INTEGRATED APPROACH FOR ACCURATE QUANTIFICATION OF METHANE GENERATION AT MUNICIPAL SOLID WASTE LANDFILLS

by

Ali Reza Abedini

M.A.Sc. Civil and Environmental Engineering, Tehran University, 2003

B.Sc., Civil Engineering, Isfahan University of Technology, 1999

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Abstract

Municipal solid waste (MSW) landfills have been identified by regulators and policy-makers as primary sources of greenhouse gas (GHG) emissions. Landfill gas (LFG) generation is best described as a first order reaction which is the basis of many LFG generation models. These models are tools to predict a landfill's lifespan methane generation, in lieu of costly full scale quantification methods. Moreover, modeling results are required to properly design LFG recovery and utilization systems. These results are also used by the GHG emission regulatory authorities to establish and enforce regulations, and modify and fine-tune the existing policies, regulations, and inventory reports. However, with a large number of variables affecting the biological decomposition process within landfills, exact quantification of methane generation and/or emission from these sources is literally impossible.

Several investigations have raised serious doubts about the accuracy of many existing models, hence, the validity of model-based emission statistics utilized by the national and international organizations. A quick modeling exercise presented in Chapter 1, involving 5 popular LFG generation models showed up to 340% variation for a single site, arguably showing the need for an advanced model which offers more realistic, consistent, and comparable results that could be used by landfill owners, engineers, and regulatory agencies.

In this research, an integrated LFG generation model was developed based on the waste decomposition principles and operational and environmental conditions. Methodologies for effective full scale quantification of fugitive methane emissions were also developed. With the unique opportunity which was made available at the Vancouver landfill (VLF), a newly

developed integrated gas generation model (iModel-110©) was calibrated and verified based on a comprehensive landfill methane mass balance investigation. The field investigations conducted at the VLF consisted of four major phases including: (i) development of an LFG recovery system database, (ii) monitoring the landfill's behavior in time and with respect to changes in ambient conditions, (iii) measurement of fugitive methane emissions through an innovative approach, and (iv) quantification of the biological methane oxidation in the landfill's cover soil using the stable isotope technique.

Preface

The overall supervision of this research was provided by Professor James W. Atwater.

Part of the work presented in this dissertation has been previously published in Journal of Waste Management and Research, is under review for publication, or has been presented at the national and international conferences. The following is a list of such manuscripts and or conference presentations:

Abedini, A. R., J. W. Atwater and G. Y. Fu (2012). "Effect of recycling activities on the heating value of solid waste: case study of the Greater Vancouver Regional District (Metro Vancouver)." Waste Management & Research 30(8): 839-848.

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List of Abbreviations

ASL	Above Sea Level
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
ATSDR	Agency for Toxic Substances and Disease Registry
BC	British Columbia
BC MOE	British Columbia Ministry of Environment
B.G.	Below Ground
BP	Barometric Pressure
CAA	Clean Air Act
CE	Collection Efficiency
COV	City of Vancouver
CRA	Conestoga-Rovers & Associates
DOC	Degradable organic carbon
ER	Emission Reduction
FID	Flame Ionization Detector
FOD	First Order Decay
FSU	Florida State University
GA	Golder Associates Ltd
GCC-IRMS	Gas Chromatograph Combustion Isotope Ratio Mass Spectrometer
GCS	Gas Collection System
GGRTA	Greenhouse Gas Reductions Target Act
GHG	Greenhouse Gas
GTE	Gas-to-Energy
GVRD	Greater Vancouver Regional District
HHV	Higher Heating Value
IPCC	Intergovernmental Panel on Climate Change
IR	Infra-red
LF	Landfill
LFG	Landfill Gas
LFGCS	Landfill gas collection system
LHV	Lower Heating Value
MAT	Mean Annual Temperature
MER	Methane Emission Rate
MOE	Ministry of Environment
MSW	Municipal Solid Waste
MV	Metro Vancouver

NHV	Net Heating Value
NMOC	Non-methane Organic Compounds
NSPS	New Source Performance Standards
OP-TDLAS	Open-path tunable diode laser absorption spectroscopy
ORS	Optical Remote Sensing
ROI	Radius of Influence
RPM	Radial Plume Mapping
SCFM	Standard Cubic Feet per Minute
SHA	Sperling Hansen Associates Inc.
SMC	Surface Methane Concentration
SWICS	Solid Waste Industry for Climate Solutions
SWMS	Solid Waste Management System
TNO	The Netherlands Organization Of Applied Scientific Research
TRI	Technology Resource Inc.
US-EPA	The United States Environmental Protection Agency
VLF	Vancouver Landfill
VOC	Volatile Organic Compounds
UV	Ultra Violet
UV-DOAS	Ultraviolet Differential Absorption Spectroscopy
WTE	Waste-to-Energy
WTEF	Waste-to-Energy Facility

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مادر دانا کند فرزند دانا تربیت هر که بر هر جا رسد از اهتمام مادر است

The best outcome from the past few years of my studies, despite all the difficulties, is the even much stronger bond I made with my best friend, my soul-mate and my love, Hamideh. There are no words to convey how much I love her. She has been a true and great supporter and has unconditionally loved me, supported me, and pushed me when necessary. I truly thank you for being such a wonderful friend for me and our kids, and for continuously being so strong and taking loads off my shoulder. I should also thank Hamideh's parents who let me take her hand in marriage and for their supports. My children, Daddy's two angels, Danial and Dina whom with I have spent less time than I have on my research. I owe you two so many hours and weekends that I should have spent with you in the past few years. Daddy loves you so much and he promises to make it up to you.

سپاس خداوند بی همتا را سزاست که همه چیز از او و به سوی اوست.

Ali Reza Abedini
December, 2014

Dedication

To the loving memory of my father who made the ultimate sacrifice for his country.

To my mother, who had the arduous task of raising me and my siblings all by herself.

To my wife, who has supported me in all my endeavors.

And

To my son and daughter who make life fun and meaningful for daddy.

Danial and Dina's Birthday, January 2014

Chapter 1: Introduction

1.1 Background

Landfilling, as the most common solid wastes disposal option worldwide, has been practiced for more than 70 years (Vesilind P. Aarne et al., 2002). Compared to other disposal options, landfills are relatively cheap, easy to operate with minimal capital costs required. While there are many initiatives to minimize the landfilling of waste, especially organic waste, the author's expectation is that landfills will remain the predominant waste disposal strategy in many solid waste management systems (SWMS). However, despite the many benefits of waste land disposal, this strategy poses significant environmental risks, including the production of landfill gas. Landfill gas (LFG) is a by-product of natural decomposition of organic materials in landfills that can create unsafe air quality, health issues, unpleasant odours, and contribute to global climate change. LFG predominantly consists of methane (CH_4) and carbon dioxide (CO_2), potent greenhouse gases (GHG). While CO_2 produced in the waste sector (e.g. municipal landfills, wastewater treatment plants, and burning of non-fossil fuel waste) is not counted as a GHG as it is of biogenic origin, the emission of CH_4 is of significant concern (IPCC, 2006).

Methane is a naturally occurring GHG with a global warming potential (GWP) 28 to 34 times greater than carbon dioxide over a 100-year timeframe (IPCC, 2013). The atmospheric concentration of methane has increased since 1750 due to human activities, such that in 2011, the concentration of this gas was 1,803 ppb, exceeding the pre-industrial levels by 150% (IPCC, 2013). Landfills are considered a major contributor, responsible for 3-7% of global methane emissions (Bogner and Matthews, 2003). In Canada, about 3% of the 2010 national GHG emissions were reported to be from the waste sector. About 91% of these emissions were

attributed to be fugitive methane emissions from landfills (Environment Canada, 2012a). The Ministry of Environment (MOE) of the province of British Columbia (BC) also concluded that 6.6% of the 2010 GHG emissions in BC were sourced from the waste sector with the primary source being methane emissions from solid waste landfills (BC MOE, 2012). The provincial government of BC, like many other countries, has recently developed a new LFG regulation targeting more LFG recovery as a mitigation measure to achieve its provincial GHG reduction goals. The BC government, in support of the *Greenhouse Gas Reductions Target Act*[1] (GGRTA), has committed to reduce its GHG emissions by at least 33% below 2007 emission levels by 2020 and achieve an 80% reduction by 2050.

There have been significant technological improvements in the LFG collection and utilization industry since the first full-scale project was implemented in Palos Verdes, California, USA. in 1975 (Spokas et al., 2006). However, an integrated approach to evaluate the production and the final fate of the generated methane is yet to be developed. The intergovernmental panel on climate change (IPCC), the world's foremost authority on climate change, issued 2007 and 2013 assessment reports (Fourth and Fifth Assessment Reports) concluding the climate is changing as a result of human activities and that it will worsen if no action is taken (Bogner et al., 2007; IPCC, 2013). With landfills being point sources of GHG emissions, it would be very easy to apply quantifiable mitigation measures (e.g. capturing LFG for energy recovery and/or the thermal or biological oxidation of methane) which can significantly change the concluded

[1] See: http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_07042_01

methane budget in the inventory reports. However, proper design and operation of such LFG recovery systems requires accurate information about the quantity, quality, and the mass balance of generated methane at the landfills. This information will also help regulatory entities enforce applicable regulations and fine-tune their GHG emission inventory reports.

There are several tools developed to predict gas generation in landfills which most commonly use first-order reaction kinetics and are based on the decay of the biodegradable materials. These models are generally developed for municipal solid waste (MSW) landfills and are heavily dependent on the availability of data on the type of landfill as well as the characteristics of the deposited waste. However, reliability and accuracy of these models have been questioned due to the discrepancy between the predicted values and actual data from the gas recovery systems (Vogt and Augenstein, 1997; Scharff and Jacobs, 2006). Vogt and Augenstein (1997) have suggested that these inaccuracies are mainly due to (i) the poor quality of data used for the development of these models, (ii) the limited time frames of available data used, (iii) the inappropriate application of available data, (iv) variable climatic conditions, and (v) variable landfill design and operation factors. Scharff and Jacobs (2006) conducted a comprehensive evaluation of six different gas generation models and showed that the minimum variation in the results in the best case scenario was between 20 - 125% while the estimation in the worst case scenario varied between 40 to 570%. These investigations raise serious doubts about the accuracy of these models as well as the precision, and even the validity, of model-based emission statistics utilized by the national and international organizations.

1.2 Landfill Gas Concept

Landfill gas (LFG) predominantly consists of methane and carbon dioxide and is a by-product of anaerobic decomposition of organic wastes deposited at the landfill. Depending on a number of factors, including waste composition and the age of the landfill, the percentage of each component of LFG varies. Typically municipal solid waste LFG consists of 45- 60% methane (CH_4), 40 - 60% carbon dioxide (CO_2), small amounts of nitrogen (N_2), oxygen (O_2), ammonia (NH_3), hydrogen sulfide (H_2S), hydrogen (H_2), reduced sulfur compounds (RS), carbon monoxide (CO), and non-methane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride (Tchobanoglous et al., 1993).

Principal substrates which are ultimately decomposed to methane are cellulose, hemicellulose, proteins, and lipids. Higler and Barlaz (2001) reported that about 90% of the biodegradable portion of the municipal solid waste (MSW) in the United States (US) is comprised of cellulose and hemicellulose. There are different types of anaerobic bacteria involved in this conversion, which occurs though a complex series of reactions explained below as four sequencing phases.

1.2.1 Biodegradation Phases

These phases are defined as aerobic, anoxic non-methanogenic, anaerobic unsteady methanogenic, and anaerobic steady methanogenic phases which are illustrated in Figure 1.1 (Farquhar and Rovers, 1973; ATSDR, 2001).

Aerobic phase (Phase I): Phase I starts with placement of waste in the landfill, resulting in the introduction of oxygen to the landfill body. In this phase, which lasts only a few days, oxygen is depleted via aerobic biodegradation and is gradually removed as CO_2.

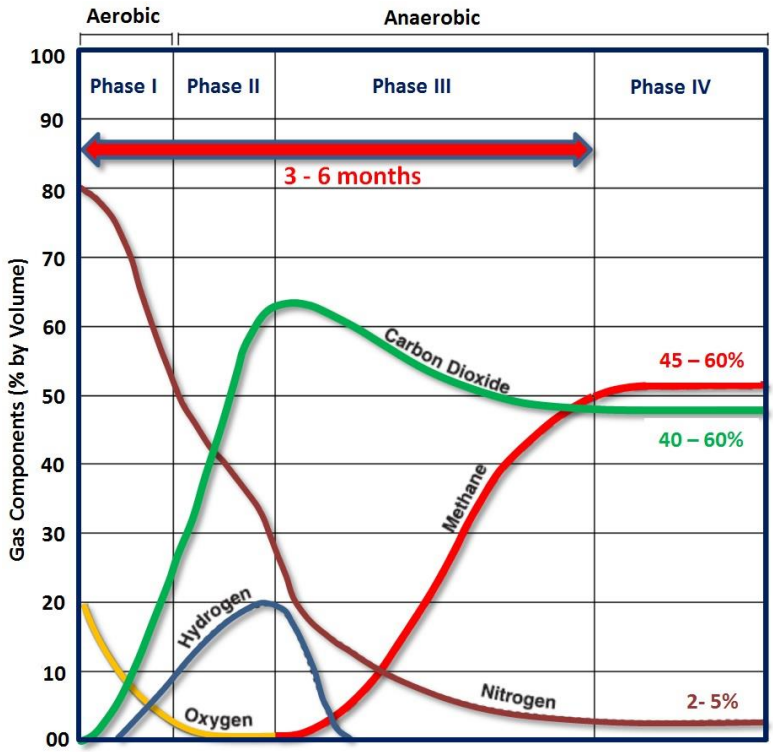


Figure 1.1 Landfill gas production phases (ATSDR, 2001)

Anoxic, Nonmethanogenic phase (Phase II): In this phase, acid fermentation occurs, resulting in a significant rise in CO_2 and H_2 production. Full establishment of this phase takes about two weeks at the end of which, and in total absence of oxygen, methane-producing bacteria begin to establish themselves.

Anaerobic, unsteady Methanogenic phase (Phase III): Methanogenesis begins but, depending on the moisture content, it takes about 3-4 months to become established. LFG generation becomes significant in this phase and it takes a few years until this generation rate stabilizes (Edward A. McBean et al., 1995; ATSDR, 2001).

Anaerobic, steady Methanogenic phase (Phase IV): Constant composition of LFG, of which 40-70% by volume consists of methane (Edward A. McBean et al., 1995), can be observed during this phase. The duration of methane production depends on the percentage of slowly degradable organic matter (e.g., paper, wood, etc.) in the landfilled waste, but in general, the rate of gas production significantly decreases after about 30 years (Edward A. McBean et al., 1995).

Normally, the duration of each phase is variable and depends on factors such as the distribution of organic components in the landfill, availability of nutrients, moisture content of the waste, moisture routing through the waste materials, and the degree of the initial compaction (Tchobanoglous and Kreith, 2002).

1.2.2 Anaerobic Digestion Principles

In the presence of enough moisture and bacteria, the anaerobic decomposition of waste starts in the complete absence of oxygen. This anaerobic decomposition of organic materials leads to the generation of methane and can be described as a simple two stage process (EMCON Associates, 1980). In this process, complex organic materials such as cellulose, fats, carbohydrates, and proteins are hydrolyzed and fermented by acid forming bacteria into organic fatty acids such as propionic and acetic acids. Products of hydrolysis also include simple sugars, amino acids, and other low molecular weight organic compounds. In the second stage organic acids are consumed by methanogenic bacteria and converted to methane and carbon dioxide (EMCON Associates, 1980).

The amount of methane generated directly depends on the level of bacterial activity in the landfill. Therefore, by providing favorable conditions for bacterial fermentation, the methane generation rate can be optimized. These conditions include sufficient moisture content, optimum temperatures (30-40˚ C for mesophilic and 50-55˚ C for thermophilic bacteria), sufficient nutrients (optimal C/N ratio of 16 (Farquhar and Rovers, 1973)), an absence of oxygen and toxic materials, pH of 6.7 - 7.2, alkalinity greater than 2000 mg/L as $CaCO_3$, and organic acid concentration of less than 3000 mg/LCH_3COOH (Schamucher, 1983). These landfill conditions provide the maximal production of methane gas.

1.2.2.1 Stoichiometric Estimate of Gas Production

The following equation describes the general transformation of organic matter in the presence of appropriate bacteria in an anaerobic environment (Tchobanoglous and Kreith, 2002).

$$\text{Organic matter} + H_2O + \text{nutrients} \rightarrow \text{new cells} + \text{resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{heat} \quad \textbf{Equation 1.1}$$

There are many references assuming a complete conversion of biodegradable matter where all the carbon content of the disposed waste is assumed to be converted to CO_2 and CH_4. This assumption results in the following stoichiometric equation to calculate the total amount of gas produced in landfills.

$$C_aH_bO_cN_d + \frac{(4a-b-2c+3d)}{4}H_2O \rightarrow \frac{(4a-b+2c+3d)}{8}CO_2 + \frac{(4a+b-2c-3d)}{8}CH_4 + dNH_3 \quad \textbf{Equation 1.2}$$

This approach has resulted in variable gas yields[2] reported in a number of studies ranging from 170 – 453 m^3 per tonne of wet waste, from which approximately 85 – 244 m^3 is reported to be the quantity of methane (Schamucher, 1983).

As an example, the following calculations show the stoichiometric estimate for the gas production from waste at the Vancouver Landfill (VLF). For the purpose of these calculations, the results of the MSW composition study conducted in 2009 by Technology Resource Inc. (TRI) in the Surrey Transfer Station were used (TRI, 2010). These values were adjusted for the wastes from demolition and land clearing (DLC), which were separately hauled to the VLF (See Table 2.3 in Page 42).

Other information required to conduct this analysis included the moisture content of different waste components (See Table 2.8 in Page 51). Furthermore, dry percentages of the chemical elements (i.e. C, H, O, N, and S) contained in the

Table 1.1 Composition of waste deposited at the Vancouver Landfill in 2009

Waste Components	Waste Composition in 2009		
	MSW	MSW + DLC	
Paper and Paperboard	21.2	17.9%	17.9%
Glass	1.7	1.4%	1.4%
Ferrous Metals	3.2	2.7%	2.7%
Non-ferrous Metals	0.8	0.7%	0.7%
Plastics	12.3	10.4%	10.4%
Organic Waste	26.6	22.5%	22.5%
Yard and Garden Waste	3.3	2.8%	2.8%
Wood and Wood Products	12.4	10.4%	21.4%
DLC	-	15.6%	-
textiles	3.1	2.6%	2.6%
Rubber	0.9	0.8%	0.8%
Nappies	2.0	1.7%	1.7%
Composite Products	4.0	3.4%	3.4%
Hazardous Wastes	4.2	3.5%	3.5%
Other	4.4	3.7%	8.4%
Total	**100.0**	**100.0%**	**100.0%**
MSW Deposited in 2009:	469,765	Tonnes	
DLC Deposited in 2009:	86,760	Tonnes	
Total Waste Deposited in 2009:	556,525	Tonnes	
Assumed Wood Content in DLC:	70%		

[2] Total amount of gases produced by unit weight of landfilled waste over the gas-generating lifespan of a landfill.

organic waste were calculated based on the typical ultimate analysis data presented in Table 2.6 (See page 46). Accordingly, the initial assessments showed that 47.5% of the waste deposited at the VLF in 2009 was dry organics and the proportion of chemical elements were 22.75%, 2.93%, 19.27%, 0.54%, and 0.10% for C, H, O, N, and S, respectively. These results, along with the determined chemical formula of the waste, are presented in Table 1.2.

Table 1.2 Chemical elements and formula of waste deposited in the VLF in 2009

Organic Waste Components	Weight in 100 kg		Chemical Elements (dry weight in 100kg)					
	Wet	Dry	**C**	**H**	**O**	**N**	**S**	**Ash**
Paper	17.9	14.3	6.21	0.86	6.28	0.04	0.03	0.86
Food Waste	22.5	11.2	5.39	0.72	4.22	0.29	0.04	0.56
Yard Waste	2.8	1.5	0.74	0.09	0.59	0.05	0.00	0.07
Wood Waste	21.4	17.5	8.67	1.05	7.48	0.04	0.02	0.26
Textile	2.6	2.2	1.23	0.15	0.70	0.10	0.00	0.06
Rubber	0.8	0.7	0.52	0.07	0.00	0.01	0.00	0.07
Total	**67.8**	**47.5**	**22.75**	**2.93**	**19.27**	**0.54**	**0.10**	**1.87**
Normalized (%)			47.94	6.18	40.60	1.13	0.21	3.95
Atomic Weight			12.00	1.00	16.00	14.00	32.10	NA
Mole Ratio			4.00	6.18	2.54	0.08	0.01	NA
Chemical Formula of Waste (N=1)			$C_{49}H_{76}O_{31}N$					

Therefore, the stoichiometric equation for this particular waste composition is as follows:

$$C_{49}H_{76}O_{31}N + 15.3 \cdot H_2O \longrightarrow 23.3 \cdot CO_2 + 26.0 \cdot CH_4 + 1 \cdot NH_3$$

When the atomic weights of the elements are used, the following equation is seen:

$$(1183) \quad + \quad (276) \quad \longrightarrow \quad (1026) \quad + \quad (416) \quad + \quad (17)$$

Therefore, methane generation potential for the wastes deposited at the VLF in 2009 is:

$M_o = (416 / 1183) \cdot (47.5 / 100) = 0.1668$ kg CH_4/ kg wet waste

Where:

M_o is the methane yield (kg CH_4/ kg wet waste),

(416 / 1183) is the molecular weight ratio of CH_4 to the deposited organics, and

(47.5 / 100) represents the amount of dry organics (presents, or kg in 100 kg of wet waste)

Considering methane density in standard conditions (i.e. 15 °C and 1 atm) equals 0.678 kg/m^3, then methane yield per tonne of waste equals:

$M_o = 0.1668 / 0.678 \cdot 1000 = 246$ m^3 CH_4 /tonne of waste

This value represents the maximum methane yield under favorable environmental conditions for bacterial activity. Comparison of the data achieved from the stoichiometric estimates with actual landfill gas measurements has absolutely proved the over-estimation of this methodology (Schamucher, 1983).

Bookter and Ham (1982) investigated the level of MSW stability in several municipal landfills across the U.S. and compared the findings with laboratory samples developed within 9 years. They observed a reduction of cellulose content, as well as a significant reduction in cellulose-to-lignin ratio over time, suggesting an overall trend of decomposition. They observed that the material decomposed more rapidly under optimum conditions; however, complete degradation was never achieved. They reported a low pH as a sign of slower degradation. Although the lab results did not show any correlation between moisture level and degradation, they concluded that landfills located in areas with more precipitation had higher level of biological degradation. This discrepancy may be due to the fact that in actual landfills the temperature in the deeper zones of

the landfill is positively regulated by bacterial metabolism, which is enhanced under optimum moisture levels. In contrast, the temperature of the lab samples was in equilibrium with ambient temperature and subject to unfavorable thermal conditions. During the course of the present study, as will be fully explained in Chapter 3, the actual temperature in the different zones and depths of the VLF was continuously monitored over different seasons and compared with fluctuations of the ambient temperature.

Eleazer et al. (1997) in a comprehensive study compared the theoretical methane yields with the actual methane generated from biodegradation of these materials under optimum conditions in the lab. They showed that the extent of decomposition in different materials varies from 28 to 94% with an average value of 58% decomposition for a typical MSW. Besides the levels of some refractory components in the waste (e.g. lignin), there are other factors resulting in inaccuracies with stoichiometric gas generation estimates. These factors include (i) moisture limitation in some parts of the landfill due to the rate of compaction, landfill depth, presence of impermeable barriers, etc., (ii) existence of plastic bags resulting in inaccessibility of some organic fractions, and (iii) presence of chemical materials in the landfills which are toxic to the gas producing bacteria, thus slowing down the biodegradation process in some sections of the landfills.

In this thesis, the author attempted the use of these variables as reduction indexes (discount factors) for the total portion of the deposited carbon which ultimately forms methane in MSW landfills.

1.3 Landfill Gas Generation Modeling

Quantitative and qualitative information about the generated gas at landfills are one the basic data required to design proper LFG recovery and utilization systems. The GHG emission regulatory authorities also need accurate information about the levels of emissions from landfills to evaluate the performance of the existing systems, establish and enforce regulations, and modify and fine-tune the existing policies and regulations. Physical measurements of emission levels from all landfills can be very costly and ineffective. Therefore, LFG generation models are often used to estimate the emissions from landfills. Using a model is particularly advantageous when the goal is to estimate the past and future LFG generation and/or emission. However, with many factors affecting methane generation at municipal landfills, it is very difficult to conduct an accurate LFG generation assessment. While there are many tools which simulate the gas generation process, a definitive and industry-accepted methodology is yet to be developed. Normally, the amount of disposed degradable waste is used as a basis in all existing methodologies, and using an empirical formula for the biodegradation of waste is one of the common ways that many researchers estimate methane generation rates from landfills (Barlaz et al., 1990; Peer et al., 1992; Bogner and Spokas, 1993; Oonk, 1994).

Landfill gas models were first developed to predict gas flow rates in the 1970's when sanitary landfilling increased and LFG utilization, as an alternative source of energy, became more popular (Walsh, 1994). While the "rule of thumb" modeling was the main basis for estimations in the LFG industry, Farquhar and Rovers (1973) developed a quantitative approach to estimate the LFG generation followed by other quantitative approaches (Robert K. Ham et al., 1979; EMCON Associates, 1980) which were developed based on limited available empirical data

(Walsh, 1994). Some of the most well-known initial models include; (i) the direct decay model, (ii) the zero order decay model, and (iii) the simplified first order decay model (EMCON Associates, 1980; Peer et al., 1992; IPCC, 1996).

With increasing concerns about GHG emissions in mid 1990's, second generation models were developed for GHG emission evaluation, regulation and control purposes. Most of the more recent LFG generation models commonly use first-order reaction kinetics, which best describe the anaerobic degradation of organic material (EMCON Associates, 1980; Hoeks, 1983; Oonk, 1994). This methodology is based on the decay of biodegradable materials and is generally developed for municipal solid waste (MSW) landfills. Unlike the direct decay and the zero-order models, the first-order methodology considered the impact of the age of waste on gas generation. Based on this model, the gas generation from each unit-mass of the deposited waste exponentially declines over time.

In the first order decay models, expression of gas generation is based on the following equation:

$$\frac{dC_t}{dt} = -kC_t \qquad \textbf{Equation 1.3}$$

Where: t = time (year)

C_t = amount of decomposable carbon available at the landfill at time t

k = decomposition rate ($year^{-1}$)

Integration of Equation 1.3 over time results:

$$C_t = C_o\, e^{-kt} \qquad \textbf{Equation 1.4}$$

Where C_o is the amount of decomposable carbon available at the landfill at time t = 0

Therefore, total (cumulative) carbon decomposed (C_{dec}) until time t is:

$$C_{dec} = C_o (1- e^{-kt}) \quad \textbf{Equation 1.5}$$

In this methodology, the total production of "carbon containing gas" (i.e. CO_2 and CH_4) is calculated based on the total carbon available for degradation at the landfill. This amount has its maximum value at the beginning, when the waste is placed in the landfill, and exponentially decreases over time. Assuming 50% (v/v) concentration of methane in the generated LFG, total methane generated due to the decomposition of the C_{dec} would be equal to:

$$M_t = C_o (1- e^{-kt}) \cdot 0.5 \cdot 16/12 \quad \textbf{Equation 1.6}$$

Where M_t is the cumulative methane generated until time t and 16/12 is the molecular weight ratio of methane to carbon.

LFG generation behavior predicted by the first order decay model has been successfully validated at landfills and through lab experiments. As such, this methodology is the basis for many current generation models used in Europe and North America, including the Netherlands Organization of Applied Scientific Research (TNO), the United States Environmental Protection Agency (US-EPA), the Intergovernmental Panel On Climate Change (IPCC), and the British Columbia Ministry of Environment (BC MOE) (Oonk and Boom, 1995; USEPA, 2005; IPCC, 2006; CRA, 2009).

There are two types of first order decay models commonly practiced: single-phase and multi-phase methodologies. The single-phase models consider all organic waste degrading at a single decay rate. This type of LFG generation modeling is widely used and is the basis of the US-EPA LandGEM model and the Dutch TNO model. These models assume a delay period in gas production, during which no methane is initially produced. An important weak point about these models is unreliable gas production estimates due to long term variations in landfill conditions and the composition of waste deposited at landfills (Huitric and Soni, 1997).

The multi-phase first order decay models are based on the same principles but differ between different types of organic wastes. This yields a more sophisticated approach which results in more reliable generation predictions (Hoeks, 1983; Oonk, 1994). This methodology considers different decay rates for different types of organic materials based on their half-lives, which is the time in which half of the initial amounts of the decomposable organics are decayed. The multi-phase models are more flexible and provide more accurate estimates for the methane generation at MSW landfills. However, this methodology requires more information about the historical and future composition of the MSW stream. Oonk and Boom (1995) conducted a comprehensive gas generation modeling study involving full scale data collection from 12 different Dutch landfills over 3 years. They showed that the multi-phase methodology best matched the actual LFG generation rates followed by the single-phase first order and zero order methodologies.

The IPCC FOD model, the British GasSim model and the BC MOE Tool are based on the multi-phase model principles. For example, the GasSim model considers three different waste types,

each with different decomposition rates, which theoretically is a good assumption of the mechanism happening in a landfill. However, the practicality of this model is highly criticized due to a lack of detailed information at most of the landfills and difficulties to break down waste composition into minor categories with appropriate modeling parameters (Huitric and Soni, 1997).

Despite all the improvement in LFG generation modeling, better projections for future LFG generation are still required. As an example, the overall kinetic parameters must still be empirically adjusted so that the current modeling results match the actual gas flow rates (Spokas et al., 2006). Considering the recent considerations and changes in waste management and organic diversion strategies worldwide, the author believes that the multi-phase first order decay methodology will provide the best approximation for methane generation at MSW landfills. However, an integrated approach using site-specific modeling parameters must be defined and incorporated into the model.

In Section 1.4 an overview of five well known models is provided. For this purpose, and considering the location of the present research (i.e. the Vancouver Landfill), two of the most well-known North American models (known and used worldwide), the methodology adopted by the Environment Canada, as well as two of the recently developed models in BC, Canada were selected. These five models are:

(i) The U.S. EPA LandGEM model (USEPA, 2005),

(ii) The IPCC FOD model (IPCC, 2006)

(iii) Environment Canada (Environment Canada, 2012a)

(iv) The inventory of BC GHG generation from landfills developed by the Golder Associates Ltd. (GA) for the BC Ministry of Environment (MOE) (Golder Associates Ltd., 2008a), and

(v) The LFG generation assessment tool "Tool" developed by Conestoga-Rovers & Associates (CRA) for the BC MOE (CRA, 2009).

1.4 Popular LFG Generation Models Overview

In this section, a comprehensive overview is conducted on four different gas generation methodologies which are most applicable to the research work site. To provide a more in-depth comparison between the selected models, LFG generation from the Phase 1 section of the VLF was estimated using these models. This phase was selected for this practice as very good knowledge about the deposited waste tonnage and composition was available for this phase, the phase has been recently completed and capped according to high engineering standards, and a well-engineered and aggressive LFG collection system was installed and operated at this phase. In fact, based on the closure system and the active LFG collection system in place at this phase of the VLF, it was expected that this area of the landfill would have a methane capture efficiency of 90% to 95%, as reported for similar landfills (Spokas et al., 2006; SCS Engineers, 2009). The suggested collection efficiency values by Spokas et al. (2006) and SCS Engineers (2009) are used as the default values for guidelines by the French Environment Agency (ADEME), and the U.S. Solid Waste Industry for Climate Solutions (SWICS), respectively. The information about the historical waste tonnages and composition deposited in this area of the landfill are provided in Table 2.3 and Table 2.7, respectively (See page 42 and page 49). The comparisons of the LFG

generation modeling results were conducted on the peak, current and total lifespan methane generation as well as the collection efficiency of the existing system in Phase 1 of the VLF. These results are summarized in Table 1.11 and illustrated in Figure 1.7.

1.4.1 U.S. EPA LandGEM

The U.S. EPA landfill gas emission model (LandGEM) determines the mass of methane generated based on the methane generation capacity (L_o) and mass of waste deposited. LandGEM was developed by the U.S. EPA in 1991 based on the first order decay methodology with pre-defined modeling parameters for different climatic conditions (i.e. k and L_o) developed based on empirical data from U.S. landfills (Debra R. Reinhart et al., 2005). The last version of LandGEM, v3.02, was released in 2005 (USEPA, 2005). The major improvement in this version is that the model calculates the gas generation from the waste deposited in 1/10th of a year (as opposed to the annual tonnage). Equation 1.7 below describes the U.S. EPA LandGEM model v3.02:

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}} \qquad \textbf{Equation 1.7}$$

Where:

Q_{CH4} = annual methane generation in the year of the calculation ($m^3\ year^{-1}$)

k = methane generation rate ($year^{-1}$)

L_o = potential methane generation capacity ($m^3\ tonne^{-1}$)

M_i = mass of waste accepted in the ith year (*tonne*)

There are two sets of modeling parameters proposed in LandGEM. (i) CAA default parameters, used when the modeling is to screen MSW landfills under the Clean Air Act (CAA) based on the maximum emissions, and (ii) AP-42 inventory default parameters, which are used to estimate emissions for inventory reports under the U.S. EPA's *Compilation of Air Pollutant Emission Factors* (USEPA, 2005). In either set, both parameters are selected based on the annual precipitation with 635 mm as the separating line between arid and conventional area. The U.S. EPA LandGEM default modeling parameters are provided in Table 1.3 below.

Table 1.3 LandGEM default modeling parameters

	k (year $^{-1}$)		L_o (m^3 $tonne^{-1}$)	
	CAA	Inventory	CAA	Inventory
Conventional	0.05	0.04	170	100
Arid Area	0.02	0.02	170	100
Wet (Bioreactor)	--	0.70	--	96

1.4.1.1 LFG Generation Modeling for VLF-Phase 1: LandGEM

Based on the data provided to the U.S. EPA LandGEM model using the CAA and inventory conventional modeling parameters, the current (i.e. 2012) methane generation rate from Phase 1 of the VLF is approximately 16,700 and 8,500 tonnes per year, respectively. The peak methane generation was in 2007, for both sets of modeling parameters, at approximately 20,400 and 9,900 tonnes per year. LandGEM also estimated that this area will generate at least 300,000 tonnes of methane during its lifespan. When the CAA default parameters were used, this amount was as high as 515,000 tonnes. Methane generation rates from the Phase 1 of the VLF estimated by the U.S. EPA LandGEM model are illustrated in Figure 1.2. Full results of this modeling practice are provided in the Appendix A.1.

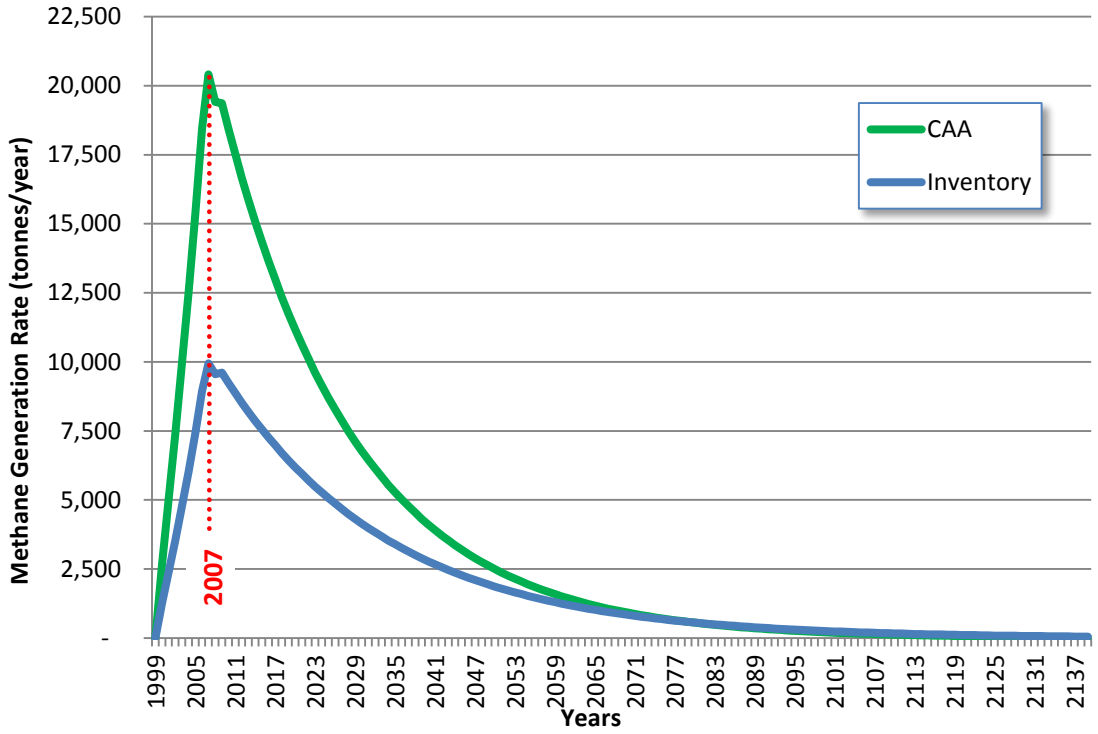


Figure 1.2 Methane generation rates at the VLF Phase 1– LandGEM v3.02

1.4.2 IPCC Model

The intergovernmental panel on climate change (IPCC) has introduced the first order decay (FOD) model, developed by an international team of experts to estimate methane emissions from individual landfills and at the national level (IPCC, 2006). The IPCC FOD model is a multi-phase first order decay model which calculates methane generation from decomposition of each waste component separately based on the respective decay rates and degradable carbon content. This model includes default decay rates for four different climatic conditions including (i) dry temperate, (ii) wet temperate, (iii) dry tropical, and (iv) moist and wet tropical. The thresholds to classify these regions are mean annual temperature (MAT) of 20°C and mean annual precipitation of 1,000 mm. The IPCC default decay rates are based on the half-lives of waste

components under different environmental conditions. These default values for different climatic regions are presented in Table 1.4 below.

Table 1.4 IPCC default decay rates for different climatic regions

Waste Components/ Types	Decay Rates (k) (years^{-1})			
	Dry		Moist and Wet	
	MAT<20°C	MAT>20°C	MAT<20°C	MAT>20°C
Food waste / Sewage sludge	0.05 - 0.08	0.07 - 0.10	0.10 - 0.20	0.17 - 0.70
Garden and park waste (non-food)	0.04 - 0.06	0.05 - 0.08	0.06 - 0.10	0.15 - 0.20
Paper and Textiles	0.03 - 0.05	0.04 - 0.06	0.05 - 0.07	0.06 - 0.085
Wood and straw	0.01 - 0.03	0.02 - 0.04	0.02 - 0.04	0.03 - 0.05
Bulk MSW or industrial waste	0.04 - 0.06	0.05 - 0.08	0.08 - 0.10	0.15 - 0.20

The IPCC model calculates methane yield based on the amount of degradable organic carbon (DOC) deposited into the landfill during its lifespan. DOC content, which is based on the composition of waste, can be calculated from the weighted average of the carbon content of various components of the waste stream. IPCC (2006) has suggested the default DOC values for the major types of waste presented in Table 1.5.

Table 1.5 IPCC default DOC content for different MSW components

Waste Stream		DOC content in % of wet waste	
		Range	Default
A.	Paper and Cardboard	36 – 45	40
B.	Textiles* and Nappies	18 – 40	24
C.	Food waste	8 – 20	15
D.	Wood	39 – 46	43
E.	Garden and park waste	18 – 22	20
F.	Rubber and Leather**	39	39
G.	Plastics, Metal, Glass and other inert materials	0	0
	Bulk MSW Waste	12 - 28	15

* 40 percent of textiles are assumed to be synthetic

** Natural rubbers would likely not degrade under anaerobic condition at landfills, hence only half is incorporated

The IPCC model also considers a correction factor for methane generation depending on the operational practices at the landfill. The methane correction factor (MCF) is defined for five different categories as presented in Table 1.6 below. In the following section the first year of operations in Phase 1 of the VLF was assumed to fall under the fourth category (i.e. MCF = 0.5) and advancing to the first category in the following years. This assumption was made based on the dimensions of this phase, disposal rate, and waste density.

Table 1.6 IPCC model methane correction factors

Landfill Operation Category		MCF
1.	Managed Anaerobic	1.0
2.	Unmanaged Deep	0.8
3.	Uncategorized	0.6
4.	Managed Semi-Aerobic	0.5
5.	Unmanaged Shallow	0.4

1.4.2.1 LFG Generation Modeling for VLF-Phase 1: IPCC Model

Based on the assumptions made and the data provided to the IPCC model using the default modeling parameters for the Vancouver region, this model estimates that the 2012 methane generation rate from the Phase 1 of the VLF is in the order of 10,100 tonnes $year^{-1}$. The peak methane generation was in 2007 at 14,000 tonnes $year^{-1}$. The IPCC model also estimated that this area will generate about 315,000 tonnes of methane during its lifespan, which considering the total tonnage of waste in place, translates to a methane yield of about 104 m^3 per tonne of waste. Methane generation rates from the Phase 1 of the VLF estimated by the IPCC model are illustrated in Figure 1.3 below. The related modeling input parameters, along with the full results are presented in the Appendix A.2.

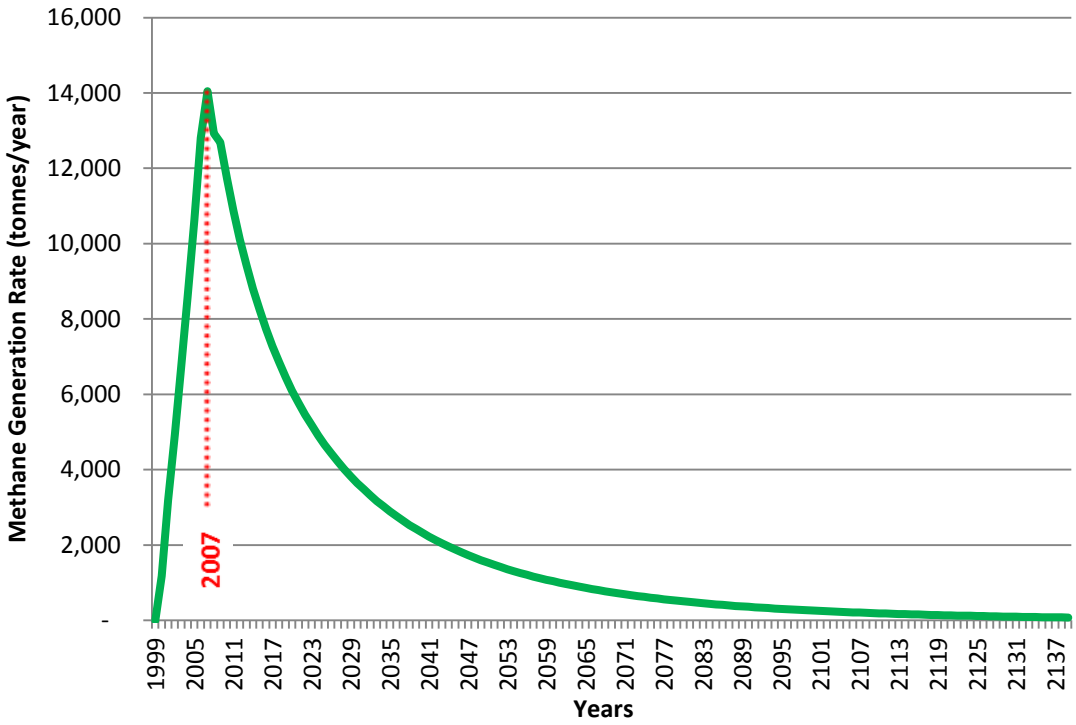


Figure 1.3 Methane generation rates at the VLF Phase 1– IPCC Model

1.4.3 Environment Canada

Environment Canada, in its inventory report for the National GHG sources and sinks between 1990 and 2010, reported that methane emission from landfills makes up about 91% of the overall emissions from the Waste Sector, which was reported at about 22 million tonnes CO_2 equivalent (CO_2-e) in 2010 (Environment Canada, 2012a). Environment Canada's LFG generation estimates are based on the first order reaction methodology using province-specific modeling parameters. The decay rates (k) are assumed to have a direct relation with landfill moisture content, which is a direct function of annual precipitation levels. Environment Canada evaluated each province based on the annual precipitation data from 1941 to 2007 and determined k values using a relationship that was developed by the Research Triangle Institute (RTI) in 2004 (Environment Canada, 2012a). The RTI-suggested k values are shown in Table 1.7. These

values show a linear relationship between decay rate and precipitation. With these data, Environment Canada has calculated provincial k values for landfills in each province based on the provincial precipitation data. For the provinces of Alberta, British Columbia and Ontario, for example, decay rates of 0.012, 0.083 and 0.046 were selected, respectively.

Table 1.7 Decay rates corresponding precipitation suggested by RTI (Environment Canada, 2012a)

Annual Precipitation (mm)		Decay Rates (k) (Year $^{-1}$)
0 - 500		0.02
500 to 1000		0.038
>1000		0.057
Provincial Values (Examples)	Alberta	0.012
	British Columbia	**0.083**
	Ontario	0.046

Environment Canada (2012a) defined methane generation potentials (L_o) for each province based on the waste composition reported for three distinct time periods (i.e. 1941-1975, 1976-1989, and 1990-2010). The values for L_o are then calculated based on the DOC content of each waste category, assuming a 50% methane concentration in the generated LFG and that 40% of the carbon content will ultimately be sequestered in the landfills. The suggested L_o values for landfills located in BC for the three time periods are respectively 161.8, 98.0, and 88 m^3 methane per tonne of waste.

1.4.3.1 LFG Generation Modeling for VLF-Phase 1: Environment Canada

Since waste disposal in Phase 1 of the VLF was started post-1990, the modeling parameters applicable to this phase based on the Environment Canada method would be k = 0.083 year $^{-1}$ (provincial value) and L_o = 88 m^3 per tonne of waste. Applying these modeling parameters to the

first order decay model resulted the 2012 methane generation rate of 10,900 tonnes per year from this phase. Also the peak methane generation rate was in 2007 at 15,700 tonnes per year. This model also estimated that this area will generate about 267,500 tonnes of methane during its lifespan. Methane generation rates from the Phase 1 of the VLF, estimated by the Environment Canada methodology, are illustrated in the Figure 1.4 below.

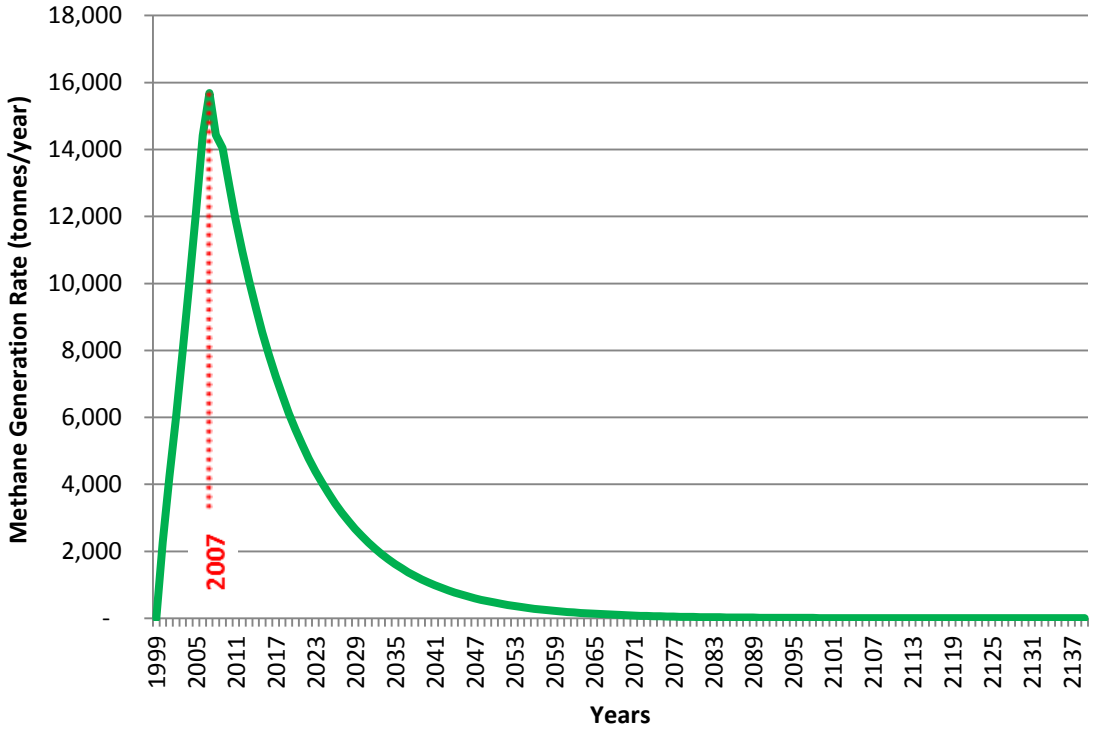


Figure 1.4 Methane generation rates at the VLF Phase 1– Environment Canada

1.4.4 Golder Model

Golder Associates Ltd. (2008b) presented an inventory of GHG emissions from landfills in BC. In this report, Golder used the LandGEM v3.02 first order decay model and found it suitable for GHG generation estimate from landfills in BC. However, Golder developed an empirical formula based on data collected from 12 landfills to better estimate the modeling parameters (i.e. k and L_o) for landfills in BC. Based on this methodology, the modeling parameters were correlated

with the average annual precipitation (mm) with an assumption that all 12 landfills had 75% methane collection efficiency. The following equations show the Golder methodology in selecting modeling parameters (Golder Associates Ltd., 2008b):

L_o (m^3 methane per tonne of waste) = 0.031 x Precipitation (mm) + 100 **Equation 1.8**

k ($year^{-1}$) = 0.00013 x Precipitation (mm) – 0.019 **Equation 1.9**

1.4.4.1 LFG Generation Modeling for VLF-Phase 1: Golder Method

The average annual precipitation value for the VLF was 1,199 mm, as reported by the Vancouver International Airport weather station (see Table 2.2 in Page 41). This value resulted in the modeling parameters of L_o = 137 (m^3 methane per tonne of waste) and k = 0.137 ($year^{-1}$) based on Equations 1.8 and 1.9, respectively. Applying these modeling parameters to LandGEM v3.02 resulted in methane generation rate of about 18,400 tonnes per year for 2012. Also, the peak methane generation rate was in 2007 at about 34,000 tonnes per year. This model also estimated that this area will generate about 416,000 tonnes of methane during its lifespan. Methane generation rates from the Phase 1 of the VLF estimated by Golder methodology are illustrated in Figure 1.5.

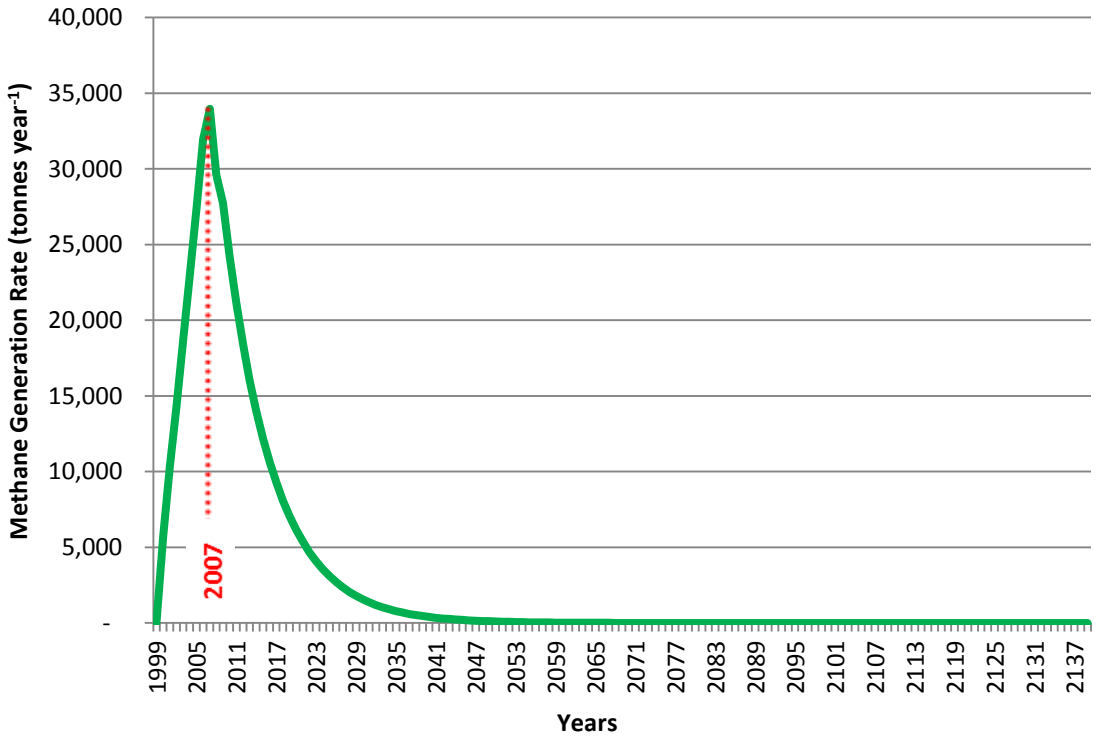


Figure 1.5 Methane generation rates at the VLF Phase 1– Golder Associates

1.4.5 BC MOE LFG Generation Assessment Tool

Conestoga-Rovers & Associates, CRA (2009) prepared the Landfill Gas Generation Assessment Procedure Guidance Report for the British Columbia Ministry of Environment (BC MOE), in accordance with the requirements of MOE's Landfill Gas Management Regulation that was approved and ordered on December 8, 2008. This was the latest regulatory requirement in BC which required landfills generating more than 1,000 tonnes of methane annually to install an active LFG collection system and a methane thermal destruction system; the MOE LFG Generation Assessment Tool (MOE Tool) was used to screen landfills in terms of their methane generation rates. CRA suggested that the first order decay model was adequate for estimating methane generation from landfills in BC and suggested that modeling parameters of L_o and k were correlated with waste composition and the climatic conditions, respectively.

As outlined in the MOE guideline, landfilled wastes are grouped into three major decomposition categories of; (i) relatively inert, (ii) moderately decomposable, and (iii) decomposable waste. Where food waste and yard waste (including grass, leaves, plant chipping and trees) are defined as decomposable and the rest of biodegradable materials (e.g. paper, newsprint, cardboard, wood, textile) are classified as moderately decomposable wastes. Different default values for L_o are assigned to each of these categories and the weighted average defines the overall methane generation potential for the landfill. The suggested L_o values in the MOE Tool are presented in Table 1.8.

Table 1.8 BC MOE tool methane generation potential values (CRA, 2009)

Waste Category	Methane Generation Potential, L_o (m^3 methane per tonne of waste)
Relatively Inert	20
Moderately Decomposable	120
Decomposable	160

MOE guidelines also defined default values for decay rates for each waste category and for different regional areas based on the reported annual precipitation (mm). These methane generation rates for each waste category and precipitation ranges are presented in Table 1.9. The MOE Tool also considers a water addition factor, a value ranging between 0.9 – 1.1 which accounts for dryness of the landfill and whether or not storm water is directed to, or diverted from, the landfill.

Table 1.9 BC MOE tool default methane generation rates (CRA, 2009)

Annual Precipitation	Methane Generation Rate (k) Values		
	Relatively Inert	Moderately Decomposable	Decomposable
<250 mm	0.01	0.01	0.03
>250 to <500 mm	0.01	0.02	0.05
>500 to <1,000 mm	0.02	0.04	0.09
>1,000 to <2,000 mm	**0.02**	**0.06**	**0.11**
>2,000 to <3,000 mm	0.03	0.07	0.12
>3,000 mm	0.03	0.08	0.13

1.4.5.1 LFG Generation Modeling for VLF-Phase 1: BC MOE Tool

Based on the waste classifications, the deposited wastes at the Phase 1 of the VLF were divided into three waste categories as presented in Table 1.10. These values are the best estimates for the composition of the waste historically deposited at this phase and include DLC waste (see Table 2.7 in Page 49).

Table 1.10 Waste composition for VLF Phase 1 based on the MOE waste categories

Year	Relatively Inert	Moderately Decomposable	Decomposable
1999	25.6%	55.1%	19.2%
2000	26.1%	56.9%	17.0%
2001	30.9%	46.6%	22.5%
2002	30.8%	49.7%	19.5%
2003	30.9%	47.7%	21.5%
2004	32.0%	48.1%	19.9%
2005	32.0%	47.8%	20.2%
2006	32.1%	47.3%	20.6%
2007			
2008	29.6%	48.3%	22.0%

Based on the assumptions made and the data provided to the BC MOE Tool using the default modeling parameters described above, this model estimated that the 2012 methane generation rate from the Phase 1 of the VLF was 11,200 tonnes year^{-1}. The peak methane generation was in

2007 at about 15,800 tonnes year^{-1}. The BC MOE model also estimated that this area will ultimately generate a total amount of 300,000 tonnes of methane, which translates to methane yield of about 99 m^3 methane per tonne of waste based on the total tonnage of waste deposited at this area. Methane generation rates from the Phase 1 of the VLF estimated by the BC MOE Tool are illustrated in Figure 1.6. The related modeling input parameters, along with the full results, are presented in the Appendix A.3.

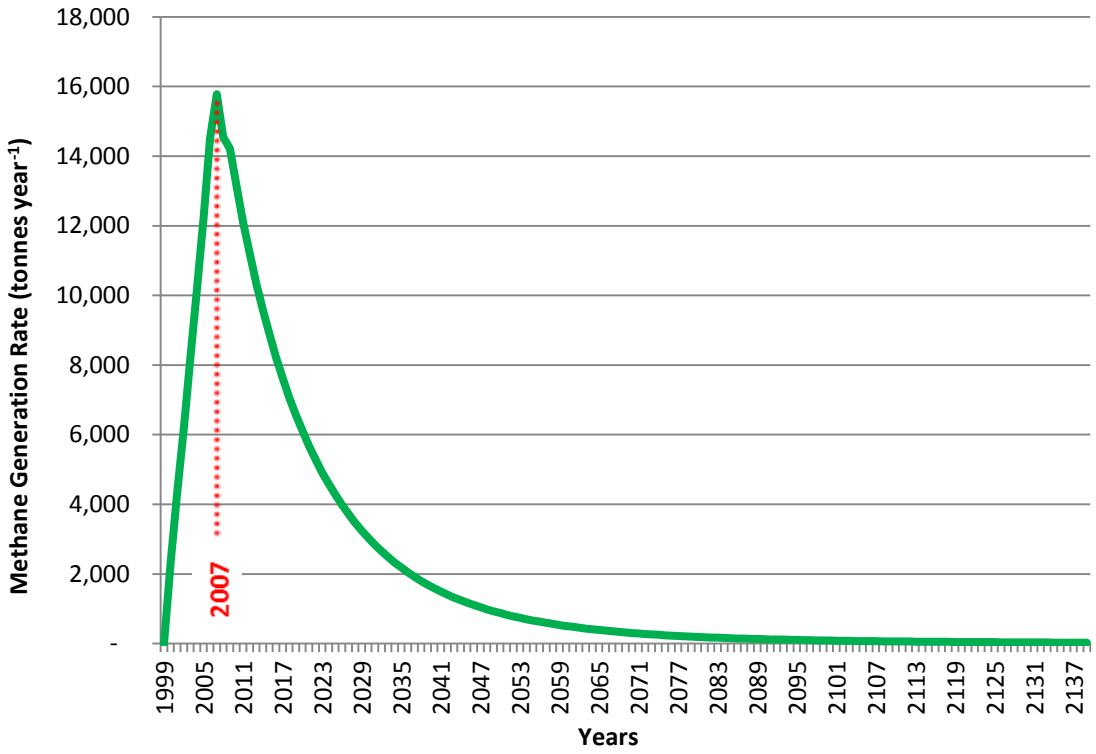


Figure 1.6 Methane generation rates at the VLF Phase 1– BC MOE Tool

1.4.6 Comparison of Different Modeling Results

The LFG generation estimates obtained from the six different methodologies are illustrated in Figure 1.7. This comparison shows the significance and magnitude of the differences between the outcomes of these modeling exercises which vary with the age of the landfill and the time

that has elapsed since closure of the site. It should be noted that this exercise was conducted for the particular environmental conditions of the VLF, and that for a different site with different climatic conditions (i.e. a dryer site) the result may be completely different. Nevertheless, this comparison shows that depending on the methodology adopted to evaluate the LFG generation, collection and/or emission from a landfill (or in a different scale) different findings will result.

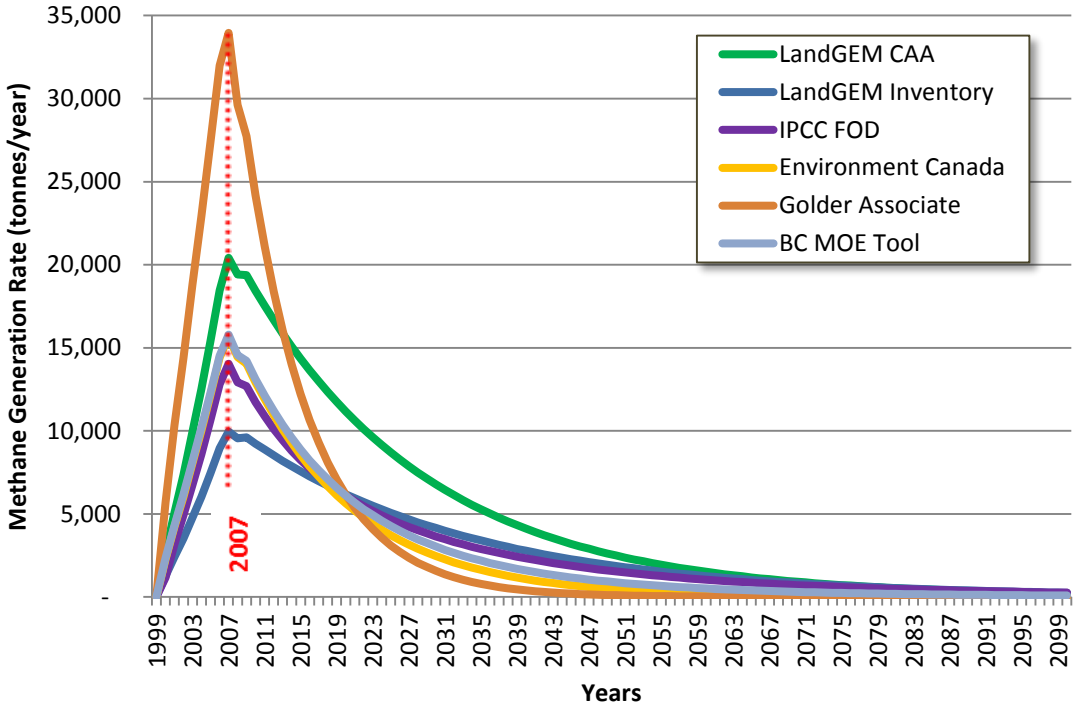


Figure 1.7 Different methodologies LFG generation modeling results_VLF Phase 1

For this particular example for the Phase 1 of the VLF, as shown in Table 1.11, the peak methane generation ranged between 10,000 to 34,000 tonnes per year. Maximum variation in the results of this evaluation occurred at the peak methane generation in 2007 and was approximately 340%, which is in agreement with pervious finding of a similar evaluation by Scharff and Jacobs (2006). Since LFG collection systems are always designed to accommodate the maximum LFG generation expected from landfills, these uncertainties on the peak generation may result in

systems significantly oversized or undersized. Furthermore on the above example, while the methane capture efficiency at Phase 1 of the VLF was expected to be between 90% and 95% (Spokas et al., 2006; SCS Engineers, 2009), the resulting values in this analysis ranged between 37% and 73%. This shows that, depending on the methodology adopted to assess the LFG generation from this phase, there would be a different understanding about the LFG collection system performance and efficiency. A summary of modeling parameters and assumptions, along with the findings for the six methodologies discussed above, are presented in Table 1.11. Full results of these analyses are provided in Appendix A.

Table 1.11 Comparison of modeling parameters and results for different methodologies_VLF Phase 1

Methodologies			CH_4 Generation (tonnes year^{-1})			Methane Yield, L_o (m^3 tonne^{-1})	Decay Rate, k (year $^{-1}$)	2012 Collection Efficiency
			Current (2012)	Peak (2007)	Lifespan Total			
1.	LandGEM	CAA	16,669	20,411	515,386	170	0.05	37%
2.		Inventory	8,520	9,947	302,038	100	0.04	73%
3.	IPCC		10,112	14,046	319,542	106	0.03-0.15	62%
4.	Environment Canada		10,949	15,683	267,524	88	0.083	57%
5.	Golder Associates		18,400	33,966	416,067	137	0.137	34%
6.	BC MOE		11,198	15,783	300,360	99	0.02-0.11	56%
							Average	**53%**
							StDev.	**±15%**

Assumptions:

Total waste tonnage: 4,470,903 tonnes
Methane Density: 0.677 kg m^{-3}
Average LFG Flow Rate in 2012: 1,239 scfm = 6,242 tonnes CH_4

1.5 Statement of the Problem

Despite all the progress that has been made in LFG generation modeling, there are still many uncertainties involved which could be reduced by more comprehensive studies conducted based on empirical data and field work results. Models are used as tools and protocols to generate GHG emission data to be disclosed to the general public and regulators. However, the results of

different modeling exercises are inconsistent. There is certainly a need for advanced, industry-accepted models offering more realistic and consistent results that could be used by the landfill owners, engineers, and national and international regulatory agencies. Whether the course of the evaluation takes place at smaller scales, such as evaluating the LFG collection efficiency in a landfill, or over larger scales, such as in national or international GHG emissions surveys, it is very important to have reliable and transparent data enabling us to make knowledgeable decisions. Such comprehensive studies shall not only look into improving modeling parameters provided based on the improved quality of data that are now available with regard to waste generation, composition, diversion, etc., but also should consider using advanced technologies to better understand and quantify methane pathways including lateral migrations, atmospheric emissions, and surface oxidations occurring at landfills.

1.6 Objectives of the Study

The main objective of this research was to develop an integrated approach to produce robust and defensible estimates for collection efficiency of existing LFG management systems and GHG emissions from municipal landfills.

The specific objective of this research was to improve the accuracy of the LFG generation estimation, incorporating fine-tuned modeling parameters which were developed based on a series of full scale field investigations. Furthermore, the approach involved verification and calibration of the results, supported with extensive field work and measurement conducted at the Vancouver Landfill (VLF). The field work consisted of four major sections including: (i) development of an LFG recovery system database as well as collection of operational data during

the course of the research, (ii) monitoring landfills behavior in time and with respect to changes in ambient conditions, (iii) measurement of fugitive methane emissions through an innovative approach, and (iv) quantification of the biological methane oxidation in landfill's cover soil using the stable isotope technique.

Chapter 2: Materials and Methods

2.1 Metro Vancouver

Metro Vancouver (MV), previously called Greater Vancouver Regional District (GVRD), is the largest regional district by population in the province of British Columbia (BC), Canada, with approximately 2.4 million residents (BC Stats, 2011). MV consists of twenty-two members and municipal cities, including Vancouver, Richmond, North Vancouver, Surrey, and Burnaby among others, with an average annual population growth rate of about 1.5%.

GVRD (2010) reported the generation of approximately 3.1 million tonnes of waste in 2010, which translates to an average per capita generation rate of roughly 3.6 kg day^{-1} or 1.3 tonnes $year^{-1}$. There are seven transfer stations in the region which receive wastes, either collected by municipalities and private haulers or directly from residents and businesses. Except for segregated materials (i.e. recyclables and yard trimmings) all wastes are sent to one of the three waste disposal facilities approved by the district. These disposal facilities are the Burnaby Incinerator, the Vancouver Landfill, and the Cache Creek Landfill (GVRD, 2010).

The records show that there have been extensive improvements in recycling in MV during the past 10 to 15 years. The rate of waste recycling was 44% in 1999, which increased to 55% by 2007. Maximizing the recycling rate is one of the major goals defined in MV's integrated waste management plan (GVRD, 2010). As shown in Table 2.1, the overall recycled waste per capita in this regional district is estimated to be 0.81 tonnes $year^{-1}$ and the disposed waste per capita is 0.66 tonnes $year^{-1}$. These values have been more or less constant since 2007 (GVRD, 2010).

Shown in Table 2.1 are the service population, per capita waste generated, recycled and disposed from 1998 through 2010, as well as estimated values for 2011. As shown in this table, and also illustrated in Figure 2.1, the overall recycling rate in MV has increased every year since 1998 to 2007 with an exception in 1999. This rate has remained more or less constant since 2007 and MV reported the same recycling rate of 55% for 2010 (GVRD, 2010). These overall recycling rates include the recycling of residential (both single-family and multi-family units), industrial, commercial and institutional (ICI), and demolition and land clearing (DLC) wastes, as well as materials recycled through "take-back" programs (industry-managed programs in which industries are fully responsible for management of goods throughout their life cycles).

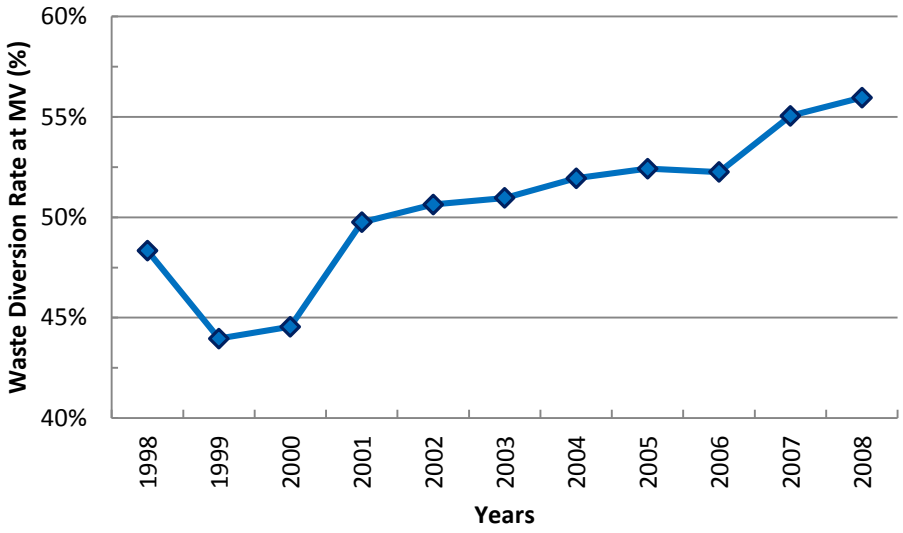


Figure 2.1 Overall historical waste diversion rates at Metro Vancouver (GVRD, 2010).

Table 2.1 Historical waste generation and disposal tonnages at Metro Vancouver

Year	Service population[a]	Annual Growth Rate	Waste Generation[a]		Recycled[a]			Disposed				
			tonnes	Per Capita	tonnes	%	Per Capita	tonnes	%	Per Capita	Waste to Energy[b]	Landfilled & other
		%		tonnes/year			tonnes/year			tonnes/year	tonnes	tonnes
1998	1,984,743		2,609,913	1.31	1,261,680	48%	0.64	1,348,233	52%	0.68	247,075	1,101,158
1999	2,013,201	1.43%	2,618,538	1.30	1,151,130	44%	0.57	1,467,408	56%	0.73	254,803	1,212,605
2000	2,041,399	1.40%	2,657,076	1.30	1,183,611	45%	0.58	1,473,465	55%	0.72	256,367	1,217,098
2001	2,073,662	1.58%	2,851,208	1.37	1,418,489	50%	0.68	1,432,719	50%	0.69	246,666	1,186,053
2002	2,102,244	1.38%	2,903,894	1.38	1,470,445	51%	0.70	1,443,449	50%	0.69	264,013	1,179,436
2003	2,128,965	1.27%	2,775,455	1.30	1,414,390	51%	0.66	1,361,065	49%	0.64	249,521	1,111,544
2004	2,153,998	1.18%	3,072,702	1.43	1,595,999	52%	0.74	1,476,703	48%	0.69	275,174	1,201,529
2005	2,188,573	1.61%	3,245,796	1.48	1,701,414	52%	0.78	1,544,382	48%	0.71	277,571	1,266,811
2006	2,218,026	1.35%	3,434,617	1.55	1,794,613	52%	0.81	1,640,004	48%	0.74	273,318	1,366,686
2007	2,251,887	1.53%	3,598,142	1.60	1,980,751	55%	0.88	1,617,391	45%	0.72	289,900	1,327,491
2008	2,273,095	0.94%	3,336,123	1.47	1,866,892	56%	0.82	1,499,231	45%	0.66	274,697	1,224,534
2009	2,314,163	1.49%	3,374,840	1.46	1,922,840	57%	0.83	1,452,001	43%	0.63	276,650	1,175,351
2010	2,351,496	1.61%	3,075,392	1.31	1,676,117	55%	0.71	1,399,275	45%	0.60	280,213	1,119,062
2011[c]	2,386,063	1.47%	3,501,921	1.47	1,927,782	55%	0.81	1,575,865	45%	0.66	280,000	1,295,865

[a] GVRD Annual Recycling and Solid Waste management Report, 2010

[b] Burnaby WTE Plant's Data

[c] Estimated Values

2.2 Vancouver Landfill

Vancouver Landfill (VLF) is located in the south-west corner of Burns Bog, 16 km south of Vancouver, serving nearly 1 million residents of the greater Vancouver area. VLF is located on a 635 ha property with a landfilling footprint of about 225 ha. This facility has been receiving waste since 1967 and currently receives about 600,000 tonnes $year^{-1}$ of MSW and DLC. Between 1967 and 2000, the VLF was developed to an elevation of 10 to 12 m above sea level (ASL). The entire landfill is divided into 7 operational areas/phases, each occupying approximately 20 to 40 hectare, measuring 800 m intervals north-south by about 200 to 500 m intervals east-west. These phases from west to east are; (i) Western 40, (ii) Phase 2, (iii) Phase 3, (iv) Area 2W, (v) Area 2E, (vi) Area 3, and (vii) Phase 1, each built separately to the originally designed level. A new plan was developed in 2000 to vertically expand the entire landfill to a maximum height of 39 m (Figure 2.2). Based on the new plan, the landfill is estimated to reach its full capacity in 2040 (SHA, 2000b). Figure 2.2 below shows the location of the Vancouver Landfill in Metro Vancouver as well as the operational phases with approximate footprint areas.

2.2.1 Gas Collection System at the VLF

The active landfill gas (LFG) management system in the VLF has been operating since 1991. The system includes horizontal and vertical collectors, lateral pipes, header and sub-headers, condensate management system, LFG extraction facility, and flare. The original system covered approximately 84 hectares of the site and included 190 vertical collection wells, however, the system has been continuously expanded and the numbers of vertical wells, blowers, and flares have increased overtime. Currently there are 330 vertical LFG wells and 30 horizontal collectors actively collecting more than 6,700 m^3 hr^{-1} LFG.

The initial goals for the City of Vancouver (COV) were the installation of the LFG management system to reduce landfill gas emissions and associated odor nuisance, as well as to conduct energy recovery from the LFG. However, the new BCMOE LFG regulation requires that the VLF actively collect and thermally oxidize at least 75% of the generated methane.

Figure 2.2 Metro Vancouver and location of Vancouver Landfill and its operational phases

2.2.2 Development of GCS Database

A large amount of historical LFG collection system data were generated by the COV over more than 20 years of operation of the LFG system. These data were collected using handheld gas analyzer devices or at the central control system at the location of the flare system. The data were stored in different formats for different reporting purposes mainly as separate Microsoft (MS) excel spreadsheets. Because there was no easy way to compile and utilize the historical data, a database in MS Access environment was developed as a part of this study, allowing a more comprehensive and meaningful mining of the existing data. Furthermore, a LANDTEC GEM2000+ LFG analyzer was used during the course of the field works to collect gas data from various locations in the collection system including LFG wellheads and manifold. These data were also added to the new LFG database. Outputs of the database provided the recovery data (R) for the METRO equation as fully presented in Chapter 6.

2.2.3 Climatic Conditions

The City of Vancouver experiences cool rainy winters and relatively warm dry summers. The monthly mean temperatures of the area between 1971 and 2000, as reported by the Vancouver International Airport weather station, ranged from a low of 3.3 ^{o}C in January to a high of 17.6 ^{o}C in August. The mean annual temperature for the same time period was 10.1 ^{o}C. Most precipitation in Vancouver Landfill falls in the form of rain. In general, the VLF has experienced at least one significant snowfall every year. The average annual precipitation in the area between 1971 and 2000 was reported to be 1,199 mm. Presented in Table 2.2 are the climate statistics for the Vancouver area between 1971 and 2000.

Table 2.2 Climate Normals 1971-2000 for the Vancouver international airport weather station

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
TEMPERATURE (°C)													
Daily Average	3.3	4.8	6.6	9.2	12.5	15.2	17.5	17.6	14.6	10.1	6.0	3.5	**10.1**
Standard Deviation	1.9	1.5	1.1	1.0	1.0	0.9	0.9	1.0	1.0	0.8	1.7	1.7	0.7
Daily Maximum	6.1	8.0	10.1	13.1	16.5	19.2	21.7	21.9	18.7	13.5	9.0	6.2	13.7
Daily Minimum	0.5	1.5	3.1	5.3	8.4	11.2	13.2	13.4	10.5	6.6	3.1	0.8	6.5
PRECIPITATION													
Rainfall (mm)	139.1	113.8	111.8	83.5	67.9	54.8	39.6	39.1	53.5	112.5	178.5	160.6	1,154.7
Snowfall (cm)	16.6	9.6	2.6	0.4	0.0	0.0	0.0	0.0	0.0	0.1	2.5	16.3	48.2
Precipitation (mm)	153.6	123.1	114.3	84.0	67.9	54.8	39.6	39.1	53.5	112.6	181.0	175.7	**1,199**

Also, a hydrogeological review by Sperling Hansen Associates Inc. (SHA) in 2008 showed that the evapotranspiration over the VLF footprint was about 416 mm, or 35% of the average precipitation in the landfill (SHA, 2008).

2.2.4 Historical Waste Tonnage at the VLF

Waste disposal at the VLF started in the Western 40 in 1967, at a rate of about 140,000 tonnes year^{-1}. Disposal progressed towards the eastern phases as the elevation of the active phase reached the original design level limit of 12 m. With the implementation of the new vertical expansion plan, waste filling in Phase 1 of the landfill continued until it reached the new permitted height of 39 m, after which waste filling continued in Phases 2 and 3 of the landfill. Table 2.3 below shows the tonnages of MSW and DLC historically deposited in each phase of the VLF.

Table 2.3 Historical waste disposal rates at different phases of the Vancouver Landfill

Year	Waste Tonnage			Waste Composition Used*	Waste Disposal History (MSW + DLC)						
					Western 40	Phase 2	Phase 3	Area 2W	Area 2E	Area 3	Phase 1
	MSW	DLC	Total		(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)
1967	136,365	0	136,365	A	136,365						
1968	169,210	0	169,210	A	169,210						
1969	199,284	0	199,284	A	199,284						
1970	196,577	0	196,577	A	196,577						
1971	206,830	0	206,830	A	206,830						
1972	193,733	0	193,733	A	193,733						
1973	217,968	0	217,968	A	217,968						
1974	223,083	0	223,083	A	223,083						
1975	219,638	0	219,638	A	219,638						
1976	215,728	0	215,728	A	215,728						
1977	196,532	0	196,532	A	196,532						
1978	187,941	0	187,941	A	187,941						
1979	185,907	0	185,907	A	185,907						
1980	213,792	0	213,792	A	213,792						
1981	199,934	0	199,934	A	199,934						
1982	259,006	0	259,006	A		259,006					
1983	328,796	0	328,796	A		328,796					
1984	511,006	0	511,006	A		511,006					
1985	588,400	0	588,400	A		588,400					
1986	678,509	0	678,509	A			678,509				
1987	762,919	0	762,919	A			762,919				
1988	591,773	0	591,773	A			591,773				
1989	467,329	0	467,329	A			467,329				
1990	468,883	0	468,883	A				468,883			
1991	464,881	0	464,881	A				464,881			
1992	453,028	0	453,028	A				453,028			
1993	461,700	162,000	623,700	B				623,700			
1994	436,800	0	436,800	B					436,800		
1995	429,700	79,700	509,400	B					509,400		
1996	401,810	102,300	504,110	B						504,110	
1997	361,600	48,450	410,050	B						410,050	
1998	350,569	101,559	452,128	B						452,128	
1999	371,005	112,567	483,572	B							483,572
2000	308,773	147,893	456,666	B							456,666
2001	383,784	70,597	454,381	C							454,381
2002	388,560	142,215	530,775	C							530,775
2003	446,034	107,918	553,951	C							553,951
2004	483,875	139,145	623,019	D							623,019
2005	545,696	146,151	691,847	D							691,847
2006	621,437	150,602	772,039	D		257,346					514,692
2007	515,043	124,709	639,752	E		639,752					
2008	512,174	145,042	657,216	E		495,216					162,000
2009	469,765	86,760	556,526	E		445,221	111,305				
2010	571,952	84,090	656,042	E			656,042				
2011	577,362	84,090	661,452	E			661,452				
Total	**17,174,690**	**2,035,786**	**19,210,476**		**2,962,522**	**3,524,742**	**3,929,329**	**2,010,492**	**946,200**	**1,366,288**	**4,470,903**

* Waste Composition Study conducted by GVRD in 1991, 1998, 2001, 2004, and 2007. Results are adjusted for DLC waste deposited at the Vancouver Landfill.

2.2.5 Research Boundary at the VLF

In order to conduct the field investigations planned for this study, four phases (areas) of the VLF were selected as the study boundary (work site). The waste filling activities were planned to be conducted at Phase 2 and Phase 3 of the VLF during the course of this research (2009 – 2014). Therefore, Area 2W, Area 2E, Area 3, and Phase 1 were selected as the study boundary. These areas were completed in 1993, 1995, 1998, and 2008, respectively. These areas have clear footprints, each with a distinct gas collection system with dedicated LFG manifolds and gas quality and quantity metering stations. Therefore, each of these four areas were treated as an individual site equipped with active LFG collection systems, as well as, with known waste in place tonnage, age, and composition (see Table 2-3).

2.3 Burnaby Waste-to-Energy Facility (WTEF)

The Burnaby Waste-to-Energy Facility (WTEF) is located in the commercial/ industrial zone of south Burnaby. The plant has been operating since 1988 and currently receives approximately 280,000 tonnes $year^{-1}$ of MSW from Burnaby, New Westminster, West Vancouver, the City of North Vancouver, and the District of North Vancouver. Since the service area covered by this plant represents the full range of housing types and social-economic neighborhoods, MV has chosen this location to conduct several waste composition analyses on a regular basis and the results are believed to accurately represent the waste generated in the MV regional district.

2.4 Municipal Solid Waste Composition and Characteristics

Metro Vancouver has conducted several waste composition studies since 1991. These physical analyses are performed in different locations but mainly at the Burnaby WTEF, where the

sampled wastes are representative of the MSW characteristics in the region and the wastes deposited at the VLF. Results of these MSW physical analyses are summarized in Table 2.4.

Table 2.4 Historical and estimated MSW composition in Metro Vancouver (1991 - 2009)

Waste Components	Waste Composition (wet %)[a]					
	A	B	C	D	E	F
	1991	1998	2001	2004	2007	2009
Paper and Paperboard	37.77	32.13	15.34	22.24	27.12	21.15
Glass	1.95	3.09	2.46	1.75	1.97	1.66
Ferrous Metals	3.49	2.57	6.51	1.82	3.23	3.20
Non-ferrous Metals	0.91	0.77	0.51	1.33	0.53	0.83
Plastics	9.19	13.98	10.46	11.76	14.83	12.32
Organic Waste	6.05	18.69	15.62	20.62	23.75	25.72
Yard and Garden Waste	14.12	5.49	10.12	4.10	3.62	3.33
Wood and Wood Products	8.19	7.38	12.05	8.46	8.10	12.37
textiles	6.42	7.61	8.15	8.25	4.10	3.08
Rubber	0.09	0.98	4.61	1.06	0.80	0.91
Nappies	1.57	2.51	2.12	1.83	2.09	2.03
Animal Litter	0.29	0.91	0.93	0.88	0.90	0.88
Composite Products	1.14	0.69	1.14	4.63	1.05	3.97
Hazardous Wastes	0.49	2.13	0.41	1.89	1.20	4.18
Other	8.33	1.07	9.57	9.38	6.71	4.37
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

[a] Data acquired directly from the Engineering & Construction Department of MV's head office.

2.4.1 Heating Value of MSW

One of the initial aims of this research was to utilize a modified version of a methodology used by Fellner et al. (2007) to separately determine the energy produced in a WTEF from incineration of the biogenic and fossil portions of MSW. Our goal was to apply this method and, using the historical plant's operational data, determine the biogenic portion of wastes historically incinerated at the Burnaby WTEF. However, due to some limitations, including lack of sufficient CO_2 readings at the plant's stacks, this method did not result in reasonable and defendable numbers.

However, the investigation produced valuable knowledge regarding the effect of historical changes in the waste management strategies in MV on the net heating value (NHV) of MSW in this regional district. The calculations were conducted using five different, widely-used formulae where heating value of MSW is derived through ultimate analysis of waste. These methods are:

(i) Boie formula used by Kathiravale (2003), and Mason and Gandhi (1983),
(ii) Dulong formula (Mason and Gandhi, 1983; Tchobanoglous et al., 1993; Tian et al., 2001; Kathiravale et al., 2003),
(iii) Mendeliev formula (Magrinho and Semiao, 2008),
(iv) Scheurer – Kestner formula (Tian et al., 2001; Kathiravale et al., 2003; Magrinho and Semiao, 2008), and
(v) Steuer formula (Tian et al., 2001; Kathiravale et al., 2003).

Some of these formulae directly calculate the NHV (also called lower heating value (LHV)) of waste while others give the higher heating value (HHV) of waste. Different available formulae are also expressed in different units of heating values, such as MJ kg^{-1}, kcal kg^{-1}, or Btu lb^{-1}. In order to be able to compare values resulted from different formulae, the author used the suggested methodology by Finet (1987) where the heat of vaporization of water is deducted and HHV is translated to NHV (or LHV). This formula is presented below as Equation 2.1. For similar purposes, we also converted all values to the common unit of kJ kg^{-1}.

(Note: 1 cal = 4.1868 Joules and 1 Btu lb^{-1} = 2.326014 kJ kg^{-1}).

$$LHV_{(kj\ kg^{-1})} = HHV\ (1 - W) - 2{,}440\ (W + 9H) \qquad \textbf{Equation 2.1}$$

Where: W is the moisture content of MSW and H is the hydrogen content of MSW (% wet basis). Table 2.5 shows the five formulae used to calculate the heating value of waste in the

MV. In this table, W is the moisture content of solid waste and C, H, O, N, and S are, respectively, the weight percentages of carbon, hydrogen, oxygen, nitrogen, and sulphur on a dry or wet basis as indicated in the second last column of the table. These values were calculated through the ultimate analysis of waste components based on the typical amounts of these elements in each organic component of waste reported by Alter (1974), Tchobanoglous (1993), and Kaiser (1966).

Table 2.5 Selected formulae for calculating heating value of MSW

Name	Value	Unit	Formula	Note	Equation
Boie	HHV	Btu lb^{-1}	151.2C + 499.77H + 45S - 47.7O + 27N	dry basis	**2.2**
Dulong	LHV	Btu lb^{-1}	145C + 610(H-O/8) +40S + 10N	wet basis	**2.3**
Mendeliev	LHV	kcal kg^{-1}	81C +300H - 26(O-S) - 6(9H+W)	wet basis	**2.4**
Scheurer - Kestner	HHV	kcal kg^{-1}	81(C-3O/4) + 342.5H + 22.5S + 57 x 3O/4 - 6(9H+W)	dry basis	**2.5**
Steuer	HHV	kcal kg^{-1}	81(C-3O/8) + 345(H-O/16) + 25S + 57 x 3O/8 - 6(9H+W)	dry basis	**2.6**

1 Btu lb-1 = 2.326014 kJ kg^{-1}

Table 2.6 Typical ultimate analysis data for combustible components of MSW[3]

Combustibles	Percent by Weight (dry basis)					
	C	**H**	**O**	**N**	**S**	**Ash**
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Plastics	60.0	7.2	22.8	-	-	10.0
Textiles	55.0	6.6	31.2	4.6	0.2	2.5
Rubber	78.0	10.0	-	2.0	-	10.0
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5

[3] (Tchobanoglous et al., 1993) (Kaiser, 1966) (Tchobanoglous et al., 1993) (Kaiser, 1966)

Investigations on the historical waste composition data, previously presented in Table 2.4, showed a 4% reduction in NHV of waste within 10 years (1998 – 2007). A comparison between these theoretical results and the actual Burnaby WTEF operational data showed a very close agreement between the actual plant's data and the predictions that resulted from the Dulong methodology. Furthermore, these analyses showed that wet percentages of C, H, O, N, S, and ash in combustible MSW in 2010 were 30.92, 6.65, 43.59, 0.63, 0.11, and 3.74, respectively. The total amount of wet combustible waste excluding ash and inert (glass, metals, etc.) in 100 kg of MSW received at WTEF in 2010 was 81.90 kg. Accordingly, the chemical formula of wet combustible MSW in MV for 2010 was $C_{748}\,H_{1,163}\,O_{449}\,N_{13}\,S$.

Also, as shown in Figure 2.3, as a result of the historical waste diversion programs in the regional district, the mass of biogenic waste (mB) in the waste stream has fluctuated between 40% and 50%. Currently, this level is higher than 45%. The overall wet weight moisture content of the waste deposited at the MV's disposal facilities was found to be between 22-24% (w/w).

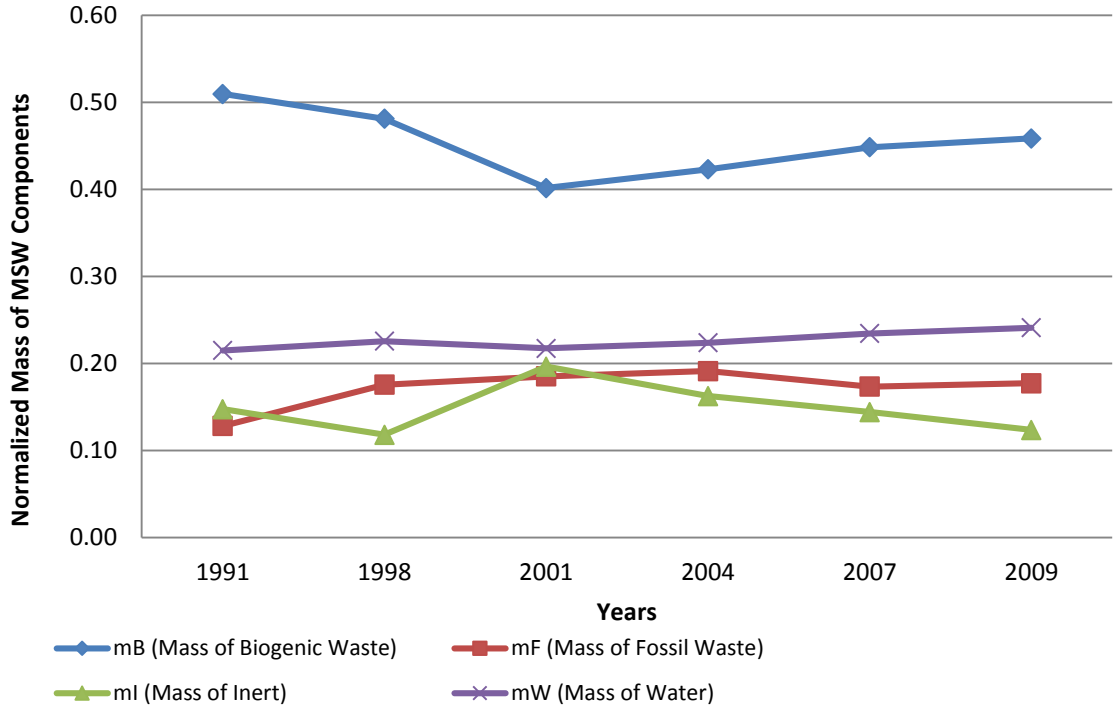


Figure 2.3 Normalized components of MSW in Metro Vancouver

2.4.2 Composition of Wastes Deposited at the VLF

Since 1993, approximately one-third of DLC wastes generated in the MV were separately hauled to the VLF (Table 2.3). Therefore, the MSW composition reported in Table 2.4 was adjusted for the DLC wastes received at the VLF each year assuming that 70% of the DLC received at this site is wood waste. Presented in Table 2.7 are the average wet weight percentages of major waste components deposited at the VLF.

Table 2.7 Composition of the waste deposited at the Vancouver Landfill (w/w%)

Study	Year	Organic waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies	Plastics & other inert
		%	%	%	%	%	%	%
Waste Composition "A"*	1967	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1968	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1969	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1970	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1971	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1972	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1973	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1974	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1975	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1976	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1977	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1978	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1979	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1980	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1981	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1982	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1983	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1984	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1985	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1986	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1987	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1988	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1989	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1990	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1991	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1992	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1993	14.5	4.1	23.8	23.6	6.4	1.9	25.8
	1994	19.6	5.5	32.1	7.4	8.6	2.5	24.3
	1995	16.5	4.6	27.1	17.2	7.2	2.1	25.2
	1996	15.6	4.4	25.6	20.1	6.8	2.0	25.5
	1997	17.3	4.8	28.3	14.8	7.6	2.2	25.0
B	**1998**	15.2	4.3	24.9	21.4	6.7	1.9	25.6
	1999	15.0	4.2	24.7	22.0	6.6	1.9	25.6
	2000	13.3	3.7	21.7	27.7	5.8	1.7	26.1
C	**2001**	14.0	8.5	13.0	21.1	10.8	1.8	30.9
	2002	12.1	7.4	11.2	27.6	9.3	1.6	30.8
	2003	13.3	8.1	12.4	23.3	10.3	1.7	30.9
D	**2004**	16.7	3.2	17.3	22.2	7.2	1.4	32.0
	2005	17.0	3.2	17.5	21.5	7.3	1.4	32.0
	2006	17.3	3.3	17.9	20.5	7.5	1.5	32.1
E	**2007**	19.8	2.9	21.8	20.2	3.9	1.7	29.6
	2008	19.2	2.8	21.1	21.8	3.8	1.6	29.6
F	**2009**	22.5	2.8	17.9	21.4	3.4	1.7	30.4
	2010	23.2	2.9	18.4	19.8	3.5	1.8	30.5
	2011	23.2	2.9	18.5	19.7	3.5	1.8	30.5

* Waste composition A through F as shown in Table 2.4

Highlighted rows indicate years in which a MSW characterization study was conducted. Other years' data are calculated based on the tonnages of MSW and DLC waste deposited at the VLF in each year.

2.4.3 Moisture Content of Municipal Solid Waste

Unfortunately, among the physical analyses conducted by MV from 1998 through 2007, the moisture content of waste was not measured. However, in 2009 Technology Resource Inc. (TRI) conducted a study in the region (Surrey Transfer Station) whereby the moisture content of each waste component was analyzed and reported (TRI, 2010). Results of these analyses (shown in Table 2.8), although not conducted at the location of interest, are believed to be fairly close to that at the Burnaby incinerator.

Furthermore, these results were compared with two other available datasets which are also shown in Table 2.8. These studies were completed by (i) Bird and Hale (1978), where similar analyses were conducted on different waste components after collection and transportation of waste, and (ii) Tchobanoglous (1993), who reported moisture contents of these components at the source, before mixed collection and transportation of waste was carried out. In general, consumption behavior, MSW collection and transportation systems, as well as climate condition are the major parameters affecting moisture content of waste. While the overall moisture content of the collected waste tends to remain more or less constant, water may move from waste components with higher moisture content to other materials with lower moisture, like papers and textiles. With the available information about the collection and transportation system in the region, along with the results of the fairly recently conducted study by TRI (2010), it was concluded that the data presented in the last column of Table 2.8 are good approximations for the moisture content of wastes deposited at the VLF. However, it should be acknowledged that in reality, more source separation and recycling of materials with lower initial moisture content and high water absorption capacity (e.g. paper and cardboard) results in less water loss of materials

with higher moisture content (e.g. food waste). For simplicity, it was assumed throughout this research that different waste components in different years would have constant moisture contents.

Table 2.8 Moisture content of different components of MSW

Waste Components	Moisture Content (% wet basis)			
	at Source*	Bird & Hale 1978	TRI 2010	This Study
Food waste	70	58.78	48	**50**
Paper	7	15	23	**20**
Cardboard	7	15	26	**20**
Plastic	2	15.48	-	**10**
Textile	4	13.41	14	**14**
Rubber	4	13.41	14	**14**
Yard Waste	50	45.12	50	**45**
Wood	15	15.01	18	**18**
DLC**	2	4	-	**5**

* (Tchobanoglous et al., 1993)
** Separately hauled (not mixed with MSW during storage and transportation)

2.5 METRO Equation

Bogner and Spokas (1993) reported that the fate of a landfill's methane would include: (i) methane fugitive emission to the atmosphere through landfill cover soil, (ii) methane oxidation by methanotrophic bacteria naturally existing in landfill cover soil, and (iii) methane capture and combustion via active LFG collection and treatment systems.

In the present study, all possible pathways for the generated methane were considered in the context of an integrated methane mass balance investigation in order to conduct a comprehensive evaluation on the fate of the generated methane at the selected work site (i.e. the Vancouver

Landfill). The following "METRO equation" was introduced, representing this comprehensive landfill methane mass balance investigation.

$$G = M + E + T + R + O$$ **Equation 2.7**

Where:

G = Generated Methane

M = Migrated Methane (i.e. lateral migration)

E = Emitted Methane (i.e. atmospheric emissions)

T = Trapped Methane

R = Recovered Methane

O = Oxidized Methane

The METRO equation considers all possible pathways for the methane generated within a landfill. However, in the particular case of the VLF, the amount of trapped methane (T) was considered insignificant and therefore was excluded from the equation. SHA (2000a), assessed the potential offsite lateral migration of LFG from the Vancouver Landfill to nearby properties and concluded that LFG migration (M) at this site is effectively blocked by the site's perimeter double ditch system (leachate and run-off ditches). Figure 2.4 shows

Figure 2.4 Double ditch system at VLF site

the double ditch system at VLF which extends around the entire site.

Therefore a "simplified METRO" equation, as presented below, was used in this study to investigate the generated methane mass balance. This is also suggested by number of recent studies, including Bogner et al. (2007).

$$G = E + R + O \qquad \textbf{Equation 2.8}$$

Based on the simplified equation, the total carbon placed in the Vancouver Landfill, if not sequestered, is ultimately either collected or emitted to the atmosphere as methane and carbon dioxide. During the course of this study, different sets of field work, measurements, calculations, and analyses were conducted between 2009 and 2013 in order to improve the estimation and/or measurement of each of these mechanisms.

The estimation of generated methane (G) utilized the widely accepted first order decay reaction. However, selection of modeling parameters was based on a series of advanced analytical methods supported by practical full scale field investigations described in Chapter 3. Methodologies to calculate variable methane generation potentials were developed in that chapter, reflecting the historical changes in waste consumption, recycling, and disposal strategies. The new modeling results were then calibrated by completing the right side of the simplified METRO equation through a comprehensive and integrated series of field investigations as described in Chapters 4, 5, and 6. These surveys were conducted at four different phases of the VLF site. These phases/areas, which form the study boundary within the

work site, are: Area 2W, Area 2E, Area 3, and Phase 1 of the Vancouver Landfill. These areas are separate filling phases/cells, which were previously shown in Figure 2.2.

Chapter 4 presents the results of the methane emission measurements (E) using a modified flux chamber technique paired with a full scale landfill surface methane concentration scan. Also, for the first time, methodologies were developed to translate qualitative methane emission data to quantitative methane flux. Chapter 5 presents the outcomes of the methane oxidation study (O) conducted using the stable isotope technique and a flux chamber. Furthermore, numerous field readings were taken from the existing LFG collection system over each area of the VLF. An LFG collection system database was also developed during the course of this study, which facilitated use of the old recovery information along with the newly collected data. A summary of the developed data base and the recovery data (R) are presented in Chapter 6.

Chapter 3: Advanced Landfill Gas Generation Modeling

3.1 Introduction

In this chapter methodologies to provide better LFG generation estimates are presented. The first order decay reaction, which is generally accepted to best describe the decomposition of the biodegradable materials in landfills, was used as the modeling basis in this study (EMCON Associates, 1980; Hoeks, 1983; Oonk, 1994; Oonk and Boom, 1995; USEPA, 2005; IPCC, 2006; CRA, 2009). However, the method of assigning values to the modeling parameters, which is in fact what differentiates various modeling methodologies, was based on a series of full-scale field investigations and the results from fundamental research studies and investigations carried out by others world-wide. Methodologies to define the values of methane generation potential (Methane Yield) and methane generation rate (Decay Rate) are discussed below. Variable methane yield, reflecting the historical changes in the waste stream, and fine-tuned decay rates, representing a landfill's actual environmental and operational conditions, allowed for a more accurate estimation of the LFG generation rates. A new integrated model (iModel-110©) was developed in the Microsoft excel environment in various (i) data input, (ii) analyses, and (iii) results output spread sheets with user friendly interfaces (See Appendix B).

This chapter includes methodologies to develop G, representing the left side of the simplified METRO equation (Equation 2.8). Generation estimates were then verified based on the field data, the parameter values on the right side of the equation (i.e. E, O, and R). The E, O, and R values were determined based on a comprehensive series of field studies conducted between 2009 to 2012 from four different filling areas of the Vancouver Landfill (VLF) as described in Chapters 4, 5, and 6, respectively. Furthermore, the new model was calibrated based on these

field data, using two different methodologies presented in Chapter 7; (i) by application of a generation calibration factor (CF_G) to fit the generation estimates for the year of study to the field data, and (ii) by fine-tuning the decay rates values within the suggested ranges and based on a sensitivity analysis presented in Chapter 8.

3.2 Methane Yield (L_o, m^3 $tonne^{-1}$)

In accurate modeling practices, the estimation of L_o is derived from the degradable organic carbon (DOC) deposited into the landfill. However, a portion of the deposited DOC will be sequestered indefinitely and only a portion will be accessible to biochemical degradation and ultimately dissimilated. The ultimate level of organic waste biodegradation and gas generation at landfills depends on various factors. Many researchers have concluded that the most important of these factors are pH, moisture, and temperature (Ham et al., 1993; Edward A. McBean et al., 1995; Eleazer et al., 1997; Ivanova et al., 2008). Methane generation is reported to be inhibited at pH levels as low as 5.5 and when alkalinity is lower than 1500 mg/l as $CaCO_3$ (Farquhar and Rovers, 1973). While methane generation occurs at MSW landfills with pH levels between 6.5 and 8 (EMCON Associates, 1980), the maximum methane production is reported to occur within the optimum pH range of 6.7 to 7.5 (Edward A. McBean et al., 1995).

Theoretical calculations presented in Section 1.2.2.1 showed that the maximum methane yield under favorable conditions for the typical MSW deposited at the VLF in 2009 was about 246 m^3 per tonne of waste. Being located in a relatively wet environment, with a mean annual precipitation of about 1,200 mm/year, and historical pH levels of approximately 6.7 to 7.3 (SHA, 2008), it appears that the decomposition of waste at the VLF occurs under near optimal

conditions. Nevertheless, the L_o values suggested by different methodologies presented in Section 1.4 ranged from 88 to 170 m^3 of methane per tonne of waste (See Table 1.11). These values are only about 35% to 70% of the maximum theoretical yield and are based on the percentage of the total DOC ultimately degraded within the landfill. Moreover, as discussed during the overview of different methodologies presented in Section 1.4, most of the models (with the exception of IPCC and BC MOE models) consider a fixed value for L_o throughout the landfill's lifespan, ignoring many variables that can affect the organic carbon balance within the waste stream, such as Metro Vancouver's aggressive waste diversion programs illustrated in Figure 2.1 in Page 36.

As part of this study, the author attempted to incorporate various index factors based on existing findings and data in the literature to calculate a more reliable methane yield based on these parameters. Among the existing models, the IPCC FOD model has the most detailed and accurate approach for defining the methane yield value. As described in Section 1.4.2, this methodology calculates methane yield based on the amount the DOC deposited in the landfill during its lifespan. The DOC value for each year is calculated based on the composition of waste and the weighted average of the carbon content of various components of the waste stream reported by Bingemer and Crutzen (1987) (See Table 1.5). Bingemer and Crutzen (1987), in order to estimate the worldwide generation of methane from municipal waste, selected the average DOC content values for each type of waste material based on the existing information reported by Mantell (1975), Bowerman et al. (1977), and Suess (1985). The IPCC model uses wet weight percentages of carbon content values for each component. While the moisture content of any particular waste component "at source" can be assumed to be somewhat constant in any

place in the world, this value can vary depending on waste composition, climatic conditions, storage, collection, and transportation methods, as well as the location where the waste physical analyses have taken place.

In the present study, a similar approach to IPCC methodology was used to calculate methane yield based on DOC. However, the dry weight percentages of the carbon content for each material was used along with the dry weight of each component deposited each year, which was calculated based on the moisture content previously presented in Table 2.8. Dry base DOC content for different waste components are presented in Table 3.1.

Table 3.1 Dry base DOC content for different MSW components

Waste Components		DOC content in % of dry waste	
		Range[4]	Default
A.	Paper and Cardboard	40 – 50	44
B.	Textiles and Nappies	25 – 50	30[5]
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
	Bulk MSW Waste (deposited at VLF)[6]	21 – 24	

[4] These ranges and defaults are based on the (IPCC, 2006) suggested based on the maximum and minimum values in consultation of (Jager and Blok, 1993; Gangdonggu Go"mi, 1997; Dehoust et al., 2002; Zeschmar-Lahl, 2002; Guendehou, 2004).

[5] It is assumed that only 60% of the textile is degradable.

[6] Calculated based on the waste composition from 1967 to 2011 presented in Table 2.7 and the waste moisture content presented in Table 2.8.

The total DOC content of the bulk MSW would depend on the composition of the waste deposited at the landfill and can be calculated for each year using the equation below:

DOC_{MSW}= 0.44(A) + 0.30(B) + 0.38(C) + 0.50(D) + 0.49(E) + 0.47(F) **Equation 3.1**

Where A, B, C, D, E, and F are the dry percentages of paper, textile, food waste, wood, yard waste and rubber in MSW, respectively.

Of the total DOC deposited in a landfill, a portion will be inaccessible. The remainder will be available DOC (DOC_a) which will be biodegraded to form LFG under optimum conditions. DOC_a is a function of DOC multiplied by correction factors selected based on the author's knowledge of landfill geometry and operations, as well as from the available studies, therefore:

$$DOC_a = DOC \times f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$$ **Equation 3.2**

Where DOC_a is the available DOC for methane generation through the landfill's lifespan and f_{dg}, f_{cl}, f_{dp}, f_{st} are the degradability, climate, depth and storage discount factors, respectively. These discount factors are equal to, or less than 1.0 and are explained in the following sections.

3.2.1 Degradability Factor (f_{dg})

Studies have shown various numbers for ultimate degradability of organic material under optimum conditions and the ultimate methane with respect to the DOC content of MSW (Ham et al., 1993; Akin et al., 1995; IPCC, 1996; Eleazer et al., 1997; Chugh et al., 1999; Ivanova et al., 2008; Wang et al., 2011). The IPCC (1996) in the GHG emission inventory guideline initially suggested 67% overall degradation and that 33% of the deposited carbon would be sequestered in the landfill, however, the revised guideline in 2006 acknowledged the overestimation resulting

from that assumption and suggested the revised value of 50% ultimate decomposition (IPCC, 2006). The IPCC FOD model applies the same default number to all waste categories regardless of the waste type and degradability, filling conditions, landfill design, etc. However, in order to improve the accuracy of methane generation estimates in the present study, different sequestration and/or degradability factors are applied to each type of waste.

The degradability of different waste components has been examined in a number of studies, showing its dependency on lignin content. These studies have shown that the average extent of degradability for main waste components can vary between 20 and 90% (Ham et al., 1993; Eleazer et al., 1997; Ivanova et al., 2008; Wang et al., 2011). Baldwin et al. (1998) was one of the first studies which reported the extent of decomposition of different waste components in MSW landfill at full scale, along with baseline data for samples. They also reported a correlation between lignin content and the rate of degradation for different types of materials. However, lignin content has not always been a good indication of the degree to which lignin inhibits the bioavailability of cellulose. A good example is a comparison between the degradability of grass and woody branches with approximately similar lignin content. The lignin in the grass does not inhibit the degradability as much as it does in branches (Akin et al., 1995; Eleazer et al., 1997).

Eleazer et al. (1997), in a comprehensive study, compared the theoretical methane yields based on the cellulose and hemicellulose contents of different waste components with the actual methane generated from biodegradation of these materials under optimum lab conditions. They showed that the extent of decomposition of different materials varied from 28% to 94%, with an

average of 58%, for the overall MSW. This study was later used as the basis for several other studies. Table 3.2 below shows more detail about the results of the study by Eleazer et al. (1997).

Table 3.2 Optimum degradability extents for different materials reported by Eleazer et al. (1997)

	Waste Components	Methane Yield (L_o)	Cellulose	Hemi-Cellulose	Lignin	Decomposition Extent
		(m^3/tonne dry)	(%)	(%)	(%)	(%)
1	Grass	144.4 ± 15.5	26.5	10.2	28.4	94.3
2	Leaves	30.6 ± 8.6	15.3	10.5	43.8	28.3
3	Branch	62.6 ± 13.3	35.4	18.4	32.6	27.8
4	Food	300.7 ± 10.6	55.4	7.2	11.4	84.1
5	Coated Paper	84.4 ± 8.1	42.3	9.4	15.0	39.2
6	Old Newsprint	74.3 ± 6.8	48.5	9.0	23.9	31.1
7	Old Corrugated Containers	152.3 ± 6.7	57.3	9.9	20.8	54.4
8	Office Paper	217.3 ± 15.0	87.4	8.4	2.3	54.6
9	MSW	92.0 ± 4.1	28.8	9.0	23.1	58.4

As shown in Table 3.2 above, Eleazer et al. (1997) reported methane yields of about 30 to 300 m^3 tonne $^{-1}$ for different waste components with an overall methane generation potential of 92 m^3 per tonne of dry MSW. Chugh et al. (1999) conducted a similar study using shredded waste (with an average particle size of 10 cm) under enhanced biodegradation conditions in batch reactors and concluded 70 – 75% overall degradability for the MSW. Their findings showed approximately 20 to 30% higher overall degradability of MSW in comparison with Eleazer et al. (1997). Staley and Barlaz (2009) used the original findings by Eleazer et al. (1997) and corrected the decomposition extent (or sequestration percentages) excluding fossil-derived materials from the calculations. They reported the methane yield for different waste components from 11 separate statewide studies conducted in different states of the USA and reported an average methane yield of 78 m^3 per tonne of dry waste, which translates to 64 m^3 methane per

tonne of wet waste. Based on the composition of waste in different states of the USA, they concluded that about 42% of the methane generated in the US landfills was from paper and cardboard, followed by 19% from food waste, with the remainder originating from yard waste, wood waste, and other organics.

Wood waste contributes a major part of the DOC deposited at landfills (Wang et al., 2011). As previously shown, about 12% of the MSW generated in MV is wood waste and this amount increases to about 20% when the amount of DLC deposited at VLF is included (See Table 2.4 and Table 2.7, respectively). Ximenes et al. (2008) compared the actual decomposition rate of up to 46 year old wood waste mined from MSW landfills with data acquired from wood waste decomposition simulations in the laboratory. Wood waste samples, which were reported to have a moisture content between 42% to 68%, were evaluated for their carbon, cellulose, hemicellulose and lignin concentrations. They concluded that their ultimate decomposition rate of less than 20% for wood waste was significantly less than the 50% default value for wood degradability used in the IPCC model. Wang et al. (2011) also conducted a comprehensive laboratory scale study on the biodegradation of different types of wood and reported carbon conversion rates between 0% and 19.9%.

In the present study, degradability factors for different waste types are selected mainly based on the decomposition extents originally reported by Eleazer et al. (1997) and the improved values reported from more recent studies by Ximenes et al. (2008), Staley and Barlaz (2009), and Wang et al. (2011). Table 3.3 below presents the selected values of the degradability factors used in this study.

Table 3.3 Degradability factor for different waste components

	Waste Components	Degradability Factor (f_{dg}) (%)
1.	Food Waste[7]	84%
2.	Paper [8]	46%
3.	Wood[9]	20%
4.	Yard Waste[10]	66%
5.	Other Organics	50%

There are other studies showing an enhancement of biodegradation through the reduction of waste particle size. However, shredding of waste is more applicable to composting processes and not normally performed before land disposal. Therefore, a correction factor for particle size was not considered in the present study. Nevertheless, there are many other factors in the real-world environment that cause the actual DOC_a for methane generation at landfills be less than what is calculated by applying the DOC and f_{dg} values. Many researchers have concluded that the most important of these factors are pH, moisture, and temperature (Farquhar and Rovers, 1973; Ham et al., 1993; Eleazer et al., 1997; Ivanova et al., 2008). In the following section, some of these factors are further explained and correction factors are assigned wherever possible.

[7] Derived based on (Eleazer et al., 1997; Chugh et al., 1999)

[8] Weighted average based on relative contribution of office paper, Newsprint, corrugated cardboard and other mixed papers reported by Metro Vancouver from 1991 to 2009 (Abedini et al., 2012).

[9] Derived in conclusion from (Kollmann and Cote, 1968; Ximenes et al., 2008; Staley and Barlaz, 2009; Wang et al., 2011).

[10] Weighted average based on relative contribution of grass, leaves, and brush reported by Oshins and Block (2000) and relative carbon sequestration factors reported by Staley and Barlaz (2009).

3.2.2 Climate Factor (f_{cl})

Among many other factors affecting the bioavailability of DOC for methane production, a landfill's water content plays a major role (Farquhar and Rovers, 1973; Ham et al., 1993; Barlaz et al., 1997; Ivanova et al., 2008). Moisture affects the availability of nutrients and bacteria for biological degradation. Therefore, a lack of moisture in the landfill may completely inhibit the biodegradation process. Many studies reported that the minimum water content required for biodegradation is between 15% and 50% dry basis (Barlaz et al., 1990; Baldwin et al., 1998; Pommier et al., 2007). However, Hartz and Ham (1983) studied MSW samples acquired from landfills under controlled moisture content and reported that methane production occurred at 10% moisture content (wet basis).

The large discrepancy between the findings of different studies on minimum moisture required for biodegradation may be due to the fact that different materials with different particle sizes and degradability were analyzed. There is also a wide range for the typical MSW moisture content. Depending on the composition of the MSW, the moisture content of waste "as generated" is historically reported to be between 25% and 65% (Pommier et al., 2007). Pommier et al. (2007) also concluded that the moisture content of a landfill not only affects the degradation rate but also greatly impacts the bioavailability of the degradable organics within the landfill, hence an effect on methane yield.

Among the models reviewed in Chapter 1, the LandGEM and Golder models consider different methane yields for different climatic zones. Golder Associates Ltd. (2008b) developed a

relationship between methane yield and precipitation based on published data and their empirical experience from various projects in BC. While sufficient data do not exist in the literature to define a clear and robust relationship between bioavailability of DOC and landfill moisture content, annual precipitation of more than 1,000 mm appears to be a good threshold that is repeatedly used to distinguish wet environments from dryer zones (CRA, 2004; IPCC, 2006; Environment Canada, 2012b).

Food waste, yard waste, paper, and wood are the major contributors to methane generation in landfills. The water contents of food and yard wastes are near their water holding capacities (Pommier et al., 2007), Therefore, unless the landfill is located in a wet environment with high levels of precipitation, hydrolysis and decomposition of other deposited organics may be limited. As previously calculated and shown in Figure 2.3 in Page 48, the overall moisture content of the generated waste in MV is approximately 22 to 25%. Nevertheless, due to the high precipitation level in this area, the VLF would be considered to be a wet landfill and exempted from the application of a reduction factor for climate (i.e. f_{cl}). However, based on author's experience and limited findings in the literature, it is suggested as a best practice approach to include the following f_{cl} values appreciating the effect of landfills moisture content on bioavailability of organic material for decomposition to form LFG.

Based on the suggested values, the 1,000 mm threshold is considered as an optimum annual precipitation level. This precipitation level is reportedly considered to provide optimum condition for decomposition of the organics in landfills, hence discount factors are suggested for precipitation levels below this threshold.

Table 3.4 Suggested climate factors for different precipitation levels

Annual Precipitation (mm)	Climate Factor (f_{cl})
0 - 500	0.5 – 0.7
500 to 1,000	0.7 - 0.9
>1,000	1

3.2.3 Depth Factor (f_{dp})

The depth of a landfill plays a major role in providing suitable conditions for anaerobic degradation of DOC placed into the landfill. Shallow landfills have more extensive oxygen infiltration into the waste mass, resulting in aerobic degradation and reduced methane generation (Vogt and Augenstein, 1997). Also, in cold climates, unless the landfill is capped with an impermeable layer (e.g. geomembrane cap), shallower sections of landfills are subject to low temperatures, which may not be optimal for bacterial activity. In such landfills, the increased depth results in a relatively higher percentage of waste mass undergoing optimum conditions for anaerobic degradation and methane generation. On the other hand, when the depth of the landfill exceeds certain levels, increased pressure due to compaction results in limited mobility of nutrients and reduced bioavailability of DOC, and methane generation (Hoeks, 1983). Based on the author's experience and available literature, landfill depth within the range of 8 m to 30 m is considered optimum for methane generation (Hoeks, 1983; Vogt and Augenstein, 1997; Howard Robinson, 2010).

Therefore, for landfills located in temperate climates, with MAT < 20 °C (e.g. all landfills in BC), the following values for depth factor are suggested. Any shallow landfill (< 8 m depth) is suggested to be assigned an f_{dp} of 0.80. For landfills exceeding that depth an f_{dp} of 0.90 is

recommended to account for the top layers. Based on this terminology, there should be a smaller discount factor for much deeper landfills (> 30 m depth) as there will be much less waste mass affected by the ambient temperature relative to the unaffected zone. However, as reported by Hoeks (1983), in very deep zones of MSW landfills less methane fermentation occurs due to the increased compaction. Therefore, a constant f_{dp} of 0.9 (i.e. discount factor of 10%) for landfills located in cold climates would conveniently account for both, (i) the top portion affected by low ambient temperatures and (ii) the pressurized bottom portion of the landfill. Obviously, the discount factor for deep landfills would apply to landfills located in any climatic condition. Table 3.5 shows the suggested depth factors assigned to landfills located in different climatic zones.

Table 3.5 Suggested depth factors for different climatic conditions

Depth of Landfill (m)	Depth Factor (f_{dp})	
	MAT < 20°C	MAT > 20°C
< 8	0.80	1
8 to 30	0.90	1
> 30	0.90	0.90

3.2.4 Other Factors

There are many other parameters which could be incorporated in fine-tuning a more accurate methane yield for LFG generation estimates. However, this requires more information to interpret suitable correction factors. Compaction rate is one of these parameters. However, calculation of the actual compaction rate (or waste density at landfills) is difficult. Available information about airspace consumption and waste-to-cover ratio may allow for a theoretical calculation of the compaction ratio, however, factors like the landfill's settlement, which itself

depends on factors such as landfill depth, waste composition, and waste type, makes it a rather complex process to predict the actual value across an entire landfill.

Deposition of toxic materials at landfills is another important factor that affects gas generation. In general, especially in wet MSW landfills, it is good practice to ensure that the naturally existing optimum conditions for methane generation are not interrupted. While the pH of MSW landfills varies by age of the landfill, it normally stabilizes within the range of 6.6 to 7.5 (Tchobanoglous et al., 1993). Maximum methane production occurs within the optimum pH range of 6.7 to 7.5 (Edward A. McBean et al., 1995). Therefore, any drift from this range can be a good indicator that the optimum conditions are interrupted and methane generation assessment should be adjusted accordingly.

Another less important factor that has an effect on the sequestration of DOC at MSW landfills is the waste storage methods practiced at the generation stage (i.e. households). While food wastes are known to be readily degradable with a half-life of about 1 year (Robert K. Ham et al., 1979; Vesilind P. Aarne et al., 2002), it has always been uncertain what percentage of these materials are isolated within plastic bags used to store the material at the generation stage. Most of the food wastes sourced from commercial and industrial zones as well as from the multi-family residential zones are stored in plastic bags before waste collection occur. That includes approximately 50% to 75% of the food waste generated in a typical municipality such as Vancouver. Depending on type of collection system as well as the disposal and compaction of the waste during disposal, most of these wastes are mixed and ‘exposed’. However, the authors visual observations from various MSW landfills have shown that about 20% of the generated food wastes remain isolated in plastic bags. This value may be much lower and closer to zero in

developing countries and where scavenging activities occur at MSW landfills. Nevertheless, as shown in the next section, it is suggested that a storage factor of f_{st} = 0.80 be assigned to the calculation of DOC_a for the food waste component of the MSW, unless any sort of waste shredder is used at the disposal site.

3.2.5 Calculated Values for Methane Yield (L_o, m^3 $tonne^{-1}$)

The DOC placed in a landfill will partly sequestrate and the rest will ultimately leave the landfill in the form of CH_4 and CO_2 and in leachate in early stages. (Note: the amount of carbon leaving the landfill in form of leachate is insignificant in comparison with the carbon released as LFG, hence ignored). For each landfill, the parameters discussed above define the ultimate amount of CH_4 generated as a result of deposition of each substance (i.e. methane yield). Table 3.6 summarizes these parameters for this study's work site (i.e. the Vancouver Landfill) as well as the methane yield calculated for each waste component based on Equation 3.3 below.

$$L_o\ (m^3\ CH_4 / \text{tonne waste}) = ½ \times DOC_a \times 16/12 \div 0.000678 \qquad \textbf{Equation 3.3}$$

Where:

"½" applies the assumption of 50% CH_4 concentration in the generated LFG,

"DOC_a" is the available DOC for ultimate CH_4 generation during landfill's lifespan (tonnes), calculated based on waste tonnage, composition, moisture content and DOC_{dry}

"16/12" applies the ratio of molecular weights of CH_4 and DOC, and

"0.000678" is the density of CH_4 (tonne/m^3) under standard conditions[11].

[11] Methane has the density of 0.677577 kg/m^3 at temperature of 15°C and pressure of 1 atm (standard condition).

Table 3.6 Methane yield for different type of organic wastes deposited at the Vancouver Landfill

Waste Components	DOC_{dry}[12]	Degradability Factor (f_{dg})	Climate Factor (f_{cl})	Depth Factor (f_{dp})	Storage Factor (f_{st})	Methane Yield (L_o) m^3/tonne
Food Waste	0.38	0.84	1.0	0.9	0.8	113
Paper Waste	0.44	0.46	1.0	0.9	1.0	143
Wood Waste	0.50	0.20	1.0	0.9	1.0	73
Yard Waste	0.49	0.66	1.0	0.9	1.0	157
Other Organics	0.30	0.50	1.0	0.9	1.0	114
2009 MSW (e.g.)	0.22[13]					76.7

Based on the composition of the waste historically deposited at the Vancouver Landfill (presented in Table 2.7) and Equation 3.3 above, the following methane generation yields presented in Table 3.7 are assigned to each year's activity of this site. Variations in L_o values reflect the changes in waste generation and recycling activities historically practiced in Metro Vancouver.

[12] See Table 3.1

[13] Calculated based on Equation 3.1 and reported waste composition in Table 2.7 and waste moisture content in Table 2.8.

Table 3.7 Calculated variable L_o values for advanced LFG generation assessment at VLF

Year	Organic waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies	DOC_{dry}	DOC_a	L_o
	%	%	%	%	%	%	%	%	m^3 $tonne^{-1}$
1967	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1968	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1969	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1970	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1971	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1972	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1973	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1974	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1975	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1976	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1977	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1978	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1979	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1980	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1981	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1982	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1983	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1984	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1985	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1986	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1987	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1988	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1989	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1990	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1991	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1992	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1993	14.5%	4.1%	23.8%	23.6%	6.4%	1.9%	24.0%	8.5%	83.4
1994	19.6%	5.5%	32.1%	7.4%	8.6%	2.5%	22.4%	9.6%	94.9
1995	16.5%	4.6%	27.1%	17.2%	7.2%	2.1%	23.4%	8.9%	88.0
1996	15.6%	4.4%	25.6%	20.1%	6.8%	2.0%	23.7%	8.7%	85.9
1997	17.3%	4.8%	28.3%	14.8%	7.6%	2.2%	23.1%	9.1%	89.6
1998	15.2%	4.3%	24.9%	21.4%	6.7%	1.9%	23.8%	8.6%	85.0
1999	15.0%	4.2%	24.7%	22.0%	6.6%	1.9%	23.9%	8.6%	84.6
2000	13.3%	3.7%	21.7%	27.7%	5.8%	1.7%	24.4%	8.2%	80.6
2001	14.0%	8.5%	13.0%	21.1%	10.8%	1.8%	21.4%	7.9%	77.4
2002	12.1%	7.4%	11.2%	27.6%	9.3%	1.6%	22.4%	7.5%	73.9
2003	13.3%	8.1%	12.4%	23.3%	10.3%	1.7%	21.7%	7.7%	76.2
2004	16.7%	3.2%	17.3%	22.2%	7.2%	1.4%	21.4%	7.6%	74.6
2005	17.0%	3.2%	17.5%	21.5%	7.3%	1.4%	21.3%	7.6%	75.0
2006	17.3%	3.3%	17.9%	20.5%	7.5%	1.5%	21.2%	7.7%	75.5
2007	19.8%	2.9%	21.8%	20.2%	3.9%	1.7%	22.0%	8.1%	79.4
2008	19.2%	2.8%	21.1%	21.8%	3.8%	1.6%	22.2%	8.0%	78.4
2009	22.5%	2.8%	17.9%	21.4%	3.4%	1.7%	21.4%	7.8%	76.7
2010	23.2%	2.9%	18.4%	19.8%	3.5%	1.8%	21.1%	7.9%	77.5
2011	23.2%	2.9%	18.5%	19.7%	3.5%	1.8%	21.1%	7.9%	77.6
								Avg.	**88.9**
								Min.	**73.9**
								Max	**94.9**

As shown in Table 3.7, the methane generation potential of waste that has been historically deposited at VLF since 1967 has varied within the range of 73.9 to 95.9 m3 methane per tonne of MSW deposited. An increase in organic waste diversion activities in MV has reduced this value to its current amount of 77.6 m^3 $tonne^{-1}$.

3.3 Decay Rate (k, year $^{-1}$)

The decay rate defines how fast the organic materials are broken down in the landfill and the rate of LFG generated. In the first order kinetic reaction, decay rate is defined as the biodegradation half-life of the organic material. Half-life ($t_{1/2}$) is the time it takes 50% of the original amount of organic material to be decomposed. Fine-tuning the value of the decay rate(s) would have a significant effect on a landfill's operation evaluation parameters, such as the LFG collection system efficiency and level of GHG emission rates from the landfill. Selecting more accurate decay rates also largely affects the LFG collection system design parameters, such as the design capacity of the extraction system (i.e. blower facility and piping network), sizing flares, and/or energy recover systems. However, the total methane generated during the landfill's lifespan is not related to the selected decay rates. For instance, as shown in Table 1.11, comparison of LFG modeling results for Phase 1 of the VLF based on different methodologies, the total lifespan methane generation resulted by LandGEM (when inventory modeling parameters were used), and BC MOE methodologies were both around 301,000 tonnes (±0.3%). However, the "current collection efficiencies" derived from these two methodologies were 73% and 56%, respectively.

The relationship between half-life and decay rate based on the fundamental first-order decay equation presented in Chapter 1 (see Equation 1.4), would be as follows:

$k\ (year^{-1}) = \ln(2) / t_{1/2}$ **Equation 3.4**

For example, a half-life of 3 years would result from a decay rate of $k = 0.23\ year^{-1}$.

In general, there are two major approaches in selecting half-lives and decay rates for predicting LFG and/or methane generation rates. Some models, such as LandGEM and Golder models, use an average k value as the decay rate of the entire MSW mass (i.e. single phase methodology). Other models, such as BC MOE tool and IPCC FOD, assign different decay rates to different types of organic materials (i.e. multi-phase methodology). As was previously discussed in Chapter 1, a comparison of these two groups of models indicated that the multi-phase first-order decay methodologies yielded more reliable methane generation predictions (Hoeks, 1983; Oonk, 1994).

There are several factors affecting the degradation rate constant. Some relate to the chemical characteristics of the waste material (e.g. lignin content), and some are based on the physical properties and environmental conditions (e.g. particle size, moisture content, temperature and pH) (Rovers et al., 1977; EMCON Associates, 1980; Bookter and Ham, 1982; Hoeks, 1983; Bingemer and Crutzen, 1987; Ham et al., 1993; Oonk, 1994; Eleazer et al., 1997; Ivanova et al., 2008).

Rovers et al. (1977) conducted one of the first studies reporting different decomposition rates for various types of organic materials in MSW landfills. They suggested that food waste and yard

wastes are among the fastest decaying materials, decomposing within 1 to 5 years. Paper wastes were the second most readily decomposable component and were reported to decompose within approximately 5 to 10 years. Finally, wood waste (excluding approximately 30% of the lignin portion) was reported to decay in 20-100 years. More detailed studies were later conducted on the decay rates and half-lives for different organic wastes. Robert K. Ham et al. (1979) estimated that the half-life of food waste was 1 year and the half -lives of paper waste, wood waste, and yard waste were about 15 years. He also concluded that the food waste decay rate under optimum conditions in landfills can be as high as 0.7 $year^{-1}$, which yields a half-life of 1 year.

While there does not appear to be a large discrepancy between the suggested values for decay rates under optimum conditions at landfills, assignment of parameters value for a particular landfill seems to be slightly different according to different models. In all methodologies, k is related to the moisture content of the landfill, which is defined by the precipitation levels in the area. However, in the IPCC model, the decay rates are also dependent on the ambient temperature. IPCC (2006) used an ambient temperature of 20 °C as a threshold, reflecting the fact that the biodegradation rate of the organic material and methane generation under anaerobic conditions slows down significantly at temperatures below 20° C (Maly and Fadrus, 1971; Debra R. Reinhart et al., 2005). Maly and Fadrus (1971) concluded that anaerobic biodegradation is enhanced at temperatures ranging from 20° to 50° C. Edward A. McBean et al. (1995) also reported the optimum temperature ranges for mesophilic and thermophilic bacterial activities within MSW landfills to be between 30° and 35°C and 45° and 65°C, respectively.

While there is enough evidence and data on the effect of temperature on the biodegradation process in landfills, there is a limited number of studies looking into the actual temperature of landfills and that how it fluctuates with the ambient temperature. Maurice and Lagerkvist (2003) studied the effects of seasonal variations on biodegradation activities and methane generation from landfills located in cold climates and concluded there were no significant variations caused by low ambient temperatures. Similarly, Bingemer and Crutzen (1987) and Thompson and Tanapat (2005) reported insignificant differences in methane generation rates between the winter and summer seasons.

In the present study, the half-lives previously developed in various studies were used as a basis for estimation of decay rate constants for the degradable components of MSW. The effects of the two major environmental affecting parameters, i.e. temperature and moisture, on the assigned k values were also considered where necessary. However, to recap the debate over the relationship between ambient temperature and internal landfill temperature, a comprehensive field investigation, presented in Section 3.3.1, was conducted to study the Vancouver Landfill temperature and its fluctuations in relation to the ambient temperature variations from the coldest to the warmest day of 2011.

3.3.1 Temperature

It is widely known that bacterial degradation is enhanced with increased temperatures within the optimum range (Maly and Fadrus, 1971; Barlaz et al., 1997; Baldwin et al., 1998). One of the most well-known equations in this regard is the van't Hoff-Arrhenius equation developed in 1884 defining the temperature dependency of the bacterial degradation process (Metcalf & Eddy,

1991). Likewise, waste mass temperature is repeatedly reported to be a major parameter affecting the rate of waste decomposition in MSW landfills. Optimum temperatures within the range of 30 to 65°C are reported for methanogenic activities, whereas, the thermophilic bacteria active in the upper end of this range are more effective in methane generation (Edward A. McBean et al., 1995).

The relationship between temperature and methane generation was also formulated by Hartz et al. (1982). They concluded that the methane generation rate was optimized at temperatures between 30° to 41°C. That study further showed that the decay rate decreased when temperature was decreased and that it tripled for each 10°C rise in the temperature (Hartz, 1983). Other studies also identified a similar range up to 45 °C as the optimum temperature range for gas production at landfills (DeWalle et al., 1978; Rees, 1980b; Mata-Alvarez and Martinez-Viturtia, 1986).

There have been only a few full-scale studies conducted on the actual temperature within landfills. Nevertheless, it is a well-known belief that landfill temperatures in central and deeper zones do not significantly fluctuate with ambient temperature (Bingemer and Crutzen, 1987; Edward A. McBean et al., 1995; Maurice and Lagerkvist, 2003; Thompson and Tanapat, 2005). Anaerobic degradation is an exothermic process, so bacterial activity continues to generate heat until optimum temperatures are reached (Maurice and Lagerkvist, 2003). Edward A. McBean et al. (1995) reported that the temperature in the top layers of a dry landfill may be more affected by ambient temperature, while deeper zones (deeper than 15 m) are unaffected by ambient air temperature. Maurice and Lagerkvist (2003), Thompson and Tanapat (2005) and Bingemer and

Crutzen (1987) all report no dependency of MSW landfill temperature on ambient air temperature. However, IPCC (2006) elected to choose different decay rates based on the ambient mean annual temperature (MAT) (See Table 1.4).

During the course of the present study, an investigation was conducted at the VLF to test the hypothesis that landfill temperatures in deeper zones are primarily driven by exothermic biodegradation reactions and not the ambient temperature. Provided that the optimum conditions were met (i.e. enough moisture content, availability of nutrients and the pH being at the optimum levels) it was believed that bacterial activity maintains the temperature at optimum levels. The landfill temperature investigations at the VLF are described in next section.

3.3.1.1 Landfill Temperature Investigations

Landfill temperature investigations were conducted at the four different phases of the VLF during a course of eight months from January to August 2011. Historical climate records show that Vancouver experiences the absolute maximum and minimum ambient temperatures within this time range. Ambient temperature was recorded with high resolution (i.e. every 10 minutes) using an S-TMB-M002, 12-Bit Temp Smart Sensors and a HOBO temperature data logger installed at the VLF site. As shown in Figure 3.1, the ambient temperature recorded during the course of the field work varied from a minimum of -8.9°C (occurred in Feb. 25th, 2011 at 7:10 AM) to a maximum of 32.5°C (occurred in Aug. 17th, 2011 at 4:50 PM). Figure 3.2 also illustrates the minimum and maximum daily temperature recorded at the Vancouver International Airport weather station, showing the ambient temperature varying from minimum of -8.1°C to maximum of 27.4°C during the course of the field work.

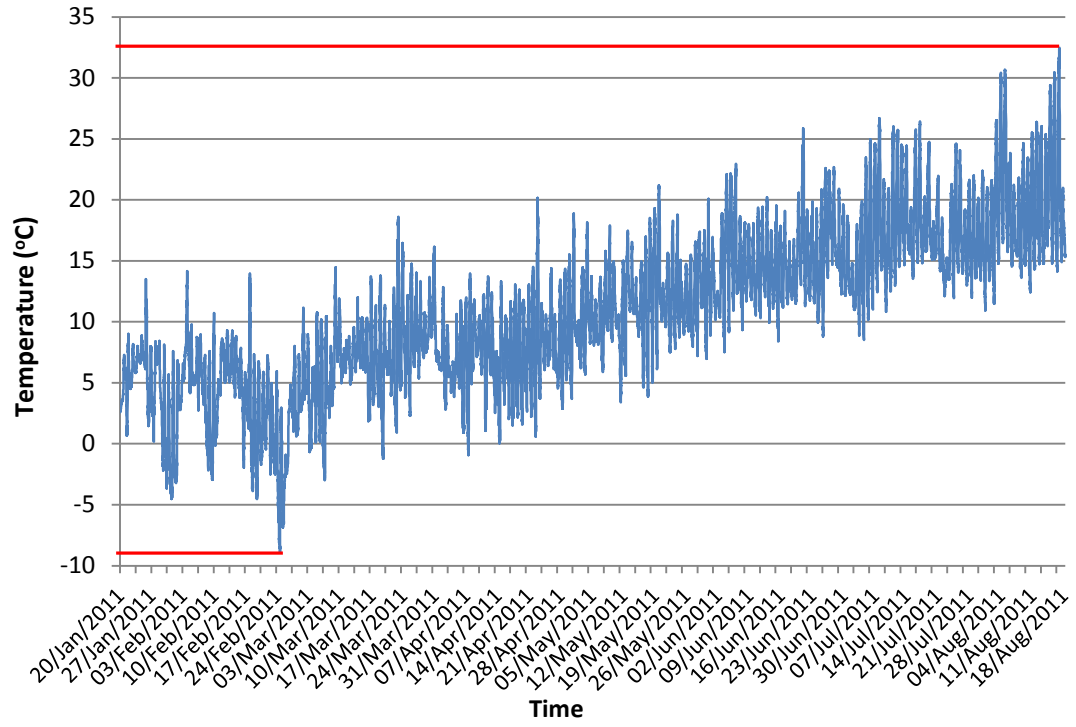


Figure 3.1 Recorded ambient temperature at the VLF site

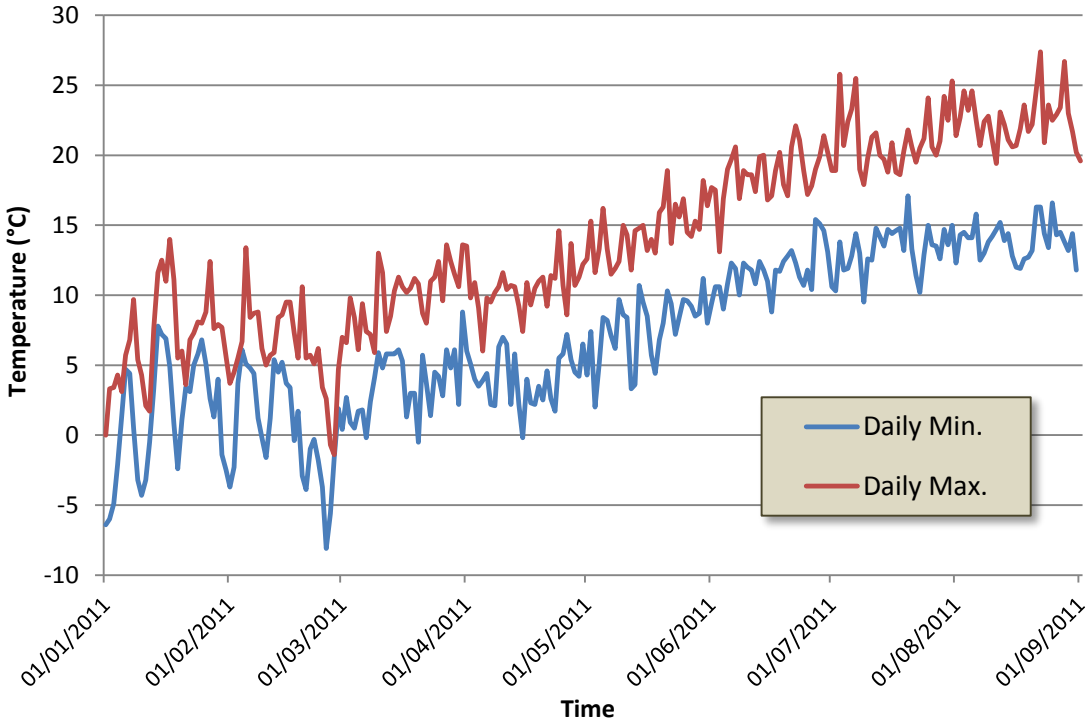


Figure 3.2 Daily min. and max. temperature recorded at the Vancouver Int'l Airport weather station

After conducting an initial wellfield survey (October to December 2010) on the existing LFG wells, 27 LFG wells were selected for the purpose of monitoring temperature at different depths of the landfill. This inspection was to study the accessibility of wells, available depths, leachate water level, and any obstruction in the wells that may have occurred due to landfill settlement (full inspection results are provided in Appendix C.1). The inspection showed that despite the expected depth of approximately 25 m for the new LFG wells installed in Phase 1, all the wells were either obstructed or flooded (i.e. filled with water and/ or leachate) at depths of approximately 10 to 12 m below ground (B.G.). Figure 3.3 below shows the location of the selected wells for temperature investigations.

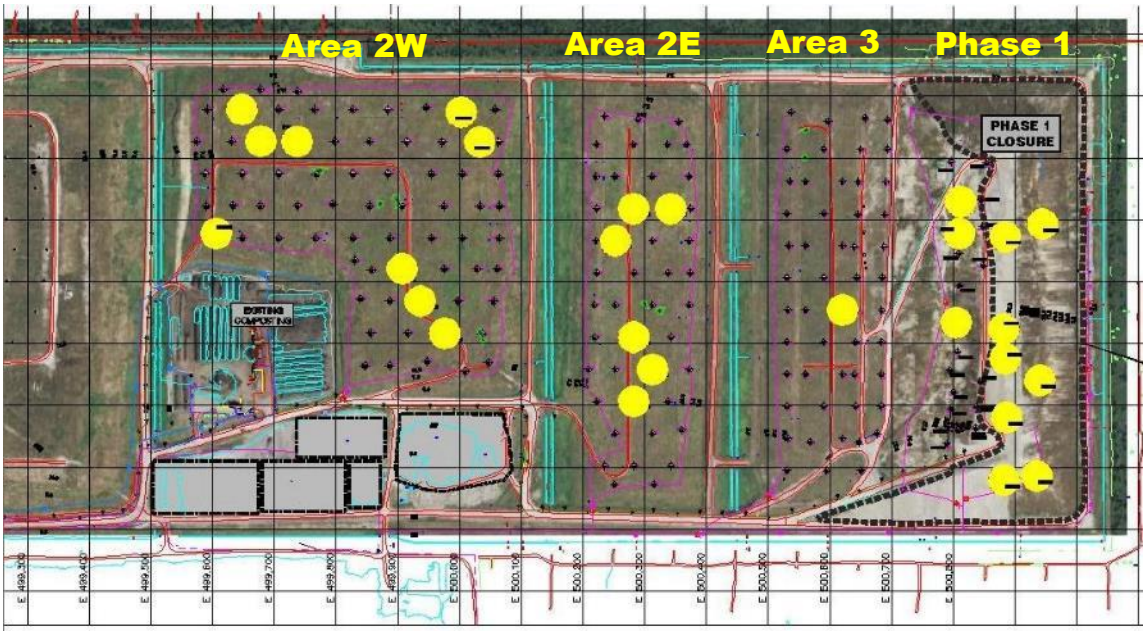


Figure 3.3 Location of selected LFG wells for landfill temperature investigations

As shown in Figure 3.3, out of a total of 27 wells, 11 wells were selected from Phase 1 of the VLF where the waste depth exceeded 30 m and was partially capped with a geomembrane cap in 2009 (extent of the geomembrane cap is shown with a dash line in the Figure). Another 16 wells

were located in the older areas of the landfill (Area 3, Area 2E and Area 2W previously shown in Figure 2.2). These areas contained older waste with a depth of 10 to 12 m and had been closed with interim cover soil in 1998, 1995, and 1993, respectively. Table 3.8 below shows a list of the selected wells, their coordinates, elevations, pipe diameters, and available depth at the time of the survey.

Table 3.8 Selected wells for the landfill's temperature investigation

	Phase 1 (11/42 Wells)			choose 11			
	WellName	Northing	Easting	Ground Elevation (m)	Top Casing Elevation (m)	Pipe ID (in)	Water Depth below ground level (m)
1	F07	5438634.3	500804.2	24.10	25.67	2.070	11.73
2	F10	5438777.7	500810.0	24.69	26.15	2.070	13.35
3	F26	5438831.8	500845.1	30.76	33.04	2.070	11.23
4	P01-V030	5438480.6	500885.9	33.21	34.47	2.070	10.60
5	P01-V031	5438540.4	500940.1	19.97	21.63	2.070	11.50
6	P01-V034	5438576.2	500883.9	35.24	36.70	2.070	11.00
7	P01-V036	5438623.7	500881.2	35.76	37.41	2.070	9.75
8	P01-V041	5438793.4	500944.3	18.48	20.35	2.070	9.80
9	P01-V042	5438773.2	500883.8	34.18	35.73	2.070	8.55
10	P01-V054	5438386.0	500934.7	19.88	21.24	2.070	13.95
11	P01-V056	5438379.3	500881.7	18.71	20.14	2.070	11.00
	Area 2W (9/70 Wells)			**choose 9**			
12	A2W-V007	5438615.7	499977.2	11.59	12.7667	2.095	9.02
13	A2W-V012	5438668.8	499937.6	12.63	13.8852	2.095	9.20
14	A2W-V018	5438720.7	499907.9	12.64	13.7835	2.095	8.56
15	A2W-V029	5438779.3	499606.6	9.81	11.0670	2.095	8.43
16	A2W-V050	5438925.9	500031.9	10.85	12.1874	2.095	8.02
17	A2W-V055	5438926.6	499738.4	13.74	15.0517	2.095	10.45
18	A2W-V056	5438926.5	499678.1	13.50	14.8397	2.095	9.05
19	A2W-V060	5438971.7	500003.0	11.26	12.5123	2.095	8.65
20	A2W-V066	5438978.4	499648.3	12.28	13.6361	2.095	11.08
	Area 2E (6/45 Wells)			**choose 6**			
21	A2E-V010	5438506.1	500282.4	12.24	13.6055	2.095	9.85
22	A2E-V013	5438558.7	500312.6	11.86	13.3392	2.095	9.90
23	A2E-V017	5438610.5	500282.8	11.92	13.2526	2.095	8.70
24	A2E-V022	5438662.3	500218.3	10.38	11.8330	2.095	6.20
25	A2E-V032	5438817.9	500342.0	10.78	12.0630	2.095	6.80
26	A2E-V033	5438818.0	500281.9	12.03	13.2470	2.095	8.20
	Area 2E (1/45 Wells)			**choose 1**			
27	A03-V019					2.095	

ACR Data Loggers (Smart Buttons) were used to log temperatures every hour at various depths of the selected LFG wells. Chambers were custom made for the smart buttons using a ½″ Brass Plug and a ½″ Brass Cap, sealed with Teflon tape and hung in wells using brass aircraft cable. Figure 3.4 below shows the smart button's chamber as well as an installed position example inside one of the LFG wells at the depth of 10 m B.G..

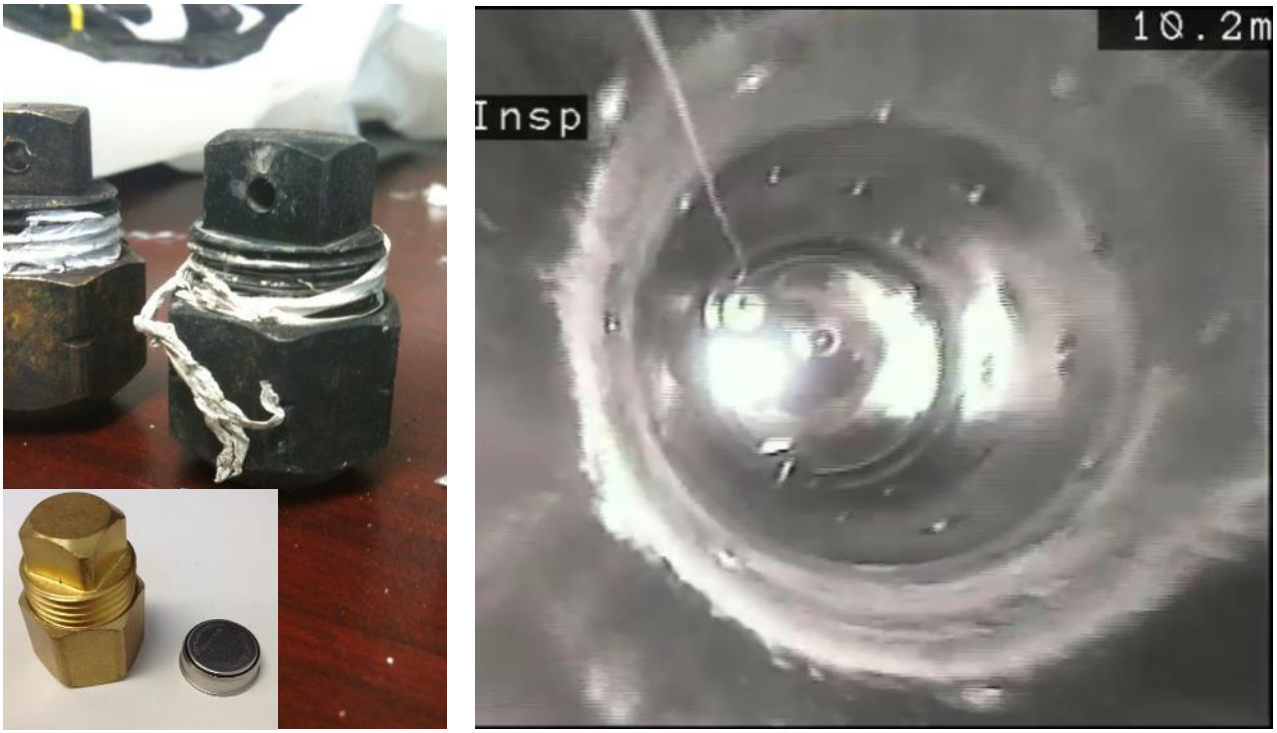


Figure 3.4 Temperature data logger and chamber (left), and installation set-up at ~10m below ground just above leachate level in an LFG well (right)

During the initial field investigation, a quick temperature survey was conducted on a limited number of selected wells on December 13th, 2010. This investigation assessed, in real-time, the temperatures inside the LFG wells at various depths while the ambient temperature was about 8° C. During this survey, the temperature profile was recorded for the total available depth of the

wells. Figures 3.5, 3.6 and 3.7 below show the temperature profiles for the LFG wells "A2W-V007", "A2W-V012" and "P01-V034", respectively.

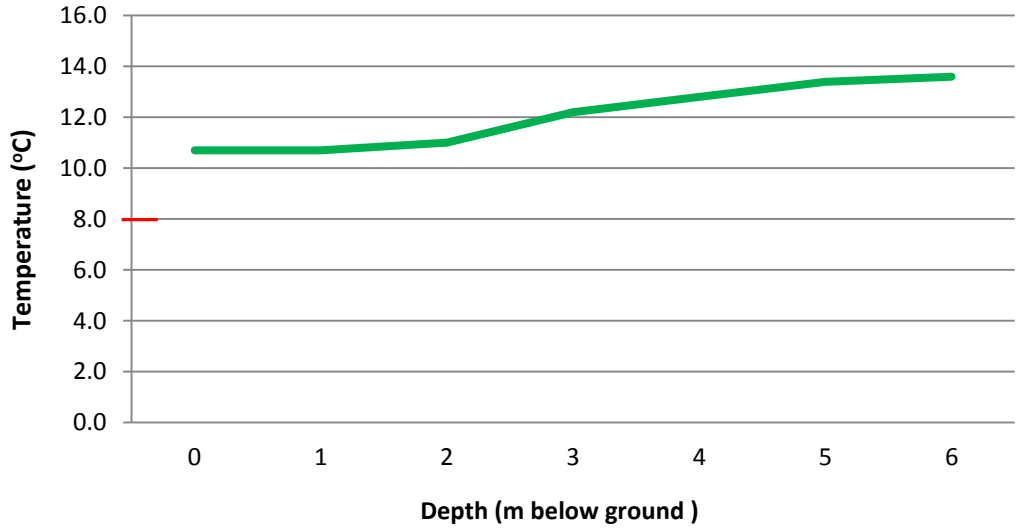


Figure 3.5 Temperature profile in LFG well "A2W-V007", December 13th, 2010 (ambient T ~8° C, depth of waste ~10m and area closed with interim cover soil since 1993)

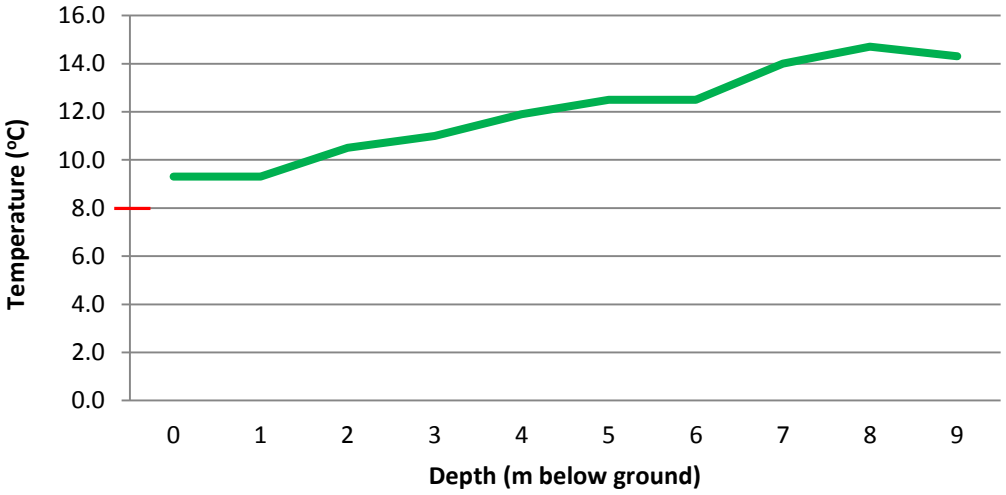


Figure 3.6 Temperature profile in LFG well "A2W-V012", December 13th, 2010 (ambient T ~8° C, depth of waste ~11m and area closed with interim cover soil since 1993)

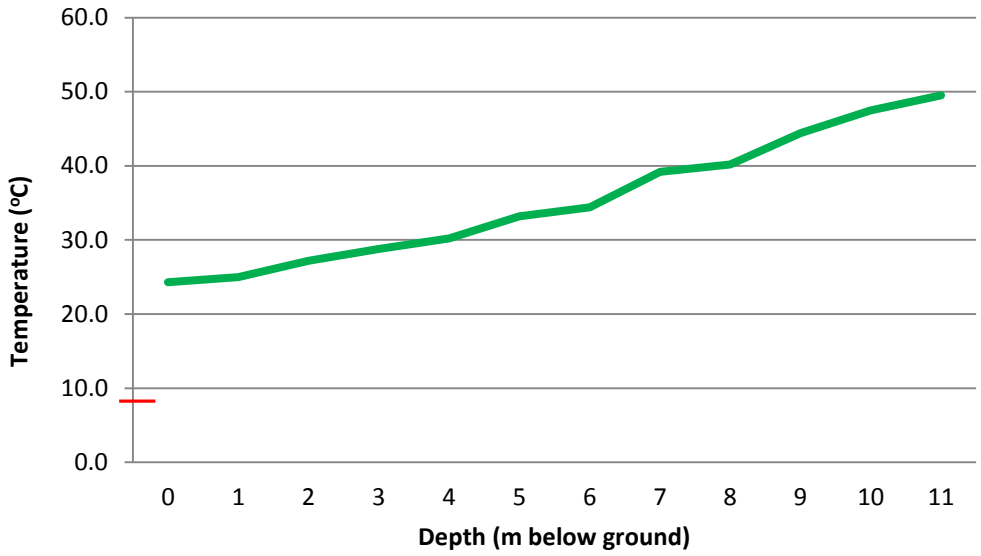


Figure 3.7 Temperature profile in Gas Well P01-V034, December 13th, 2010 (ambient T ~8° C, depth of waste ~33m and area closed with geomembrane cover since 2009)

It should be noted that while this initial survey provided useful information with regard to the temperature gradient and the temperature in deeper zones, these data would not be accurate, especially in shallower sections of the wells, as the wellhead cap had to be removed to access the well, resulting in cold air being drawn down to the well. Nevertheless, these initial investigations showed that in both cases (old phases and the recently closed Phase 1) the temperature inside the wells was higher than the ambient temperature. However, the old areas showed slight differences between ambient temperature and landfill temperature. In contrast, a significant temperature difference was observed in the new phase as shown in Figure 3.7. Since the design of the LFG vertical wells included solid PVC and/ or HDPE pipes for the first 5 meters of the well, the recorded temperature would be the temperature of the gas collected and conveyed from the depth of 5 m B.G. and below. Therefore, the reported landfill deep zone temperatures would be those recorded from the screened sections of the LFG well pipes (i.e. below 5 meter B.G.).

Based on this initial quick survey, it was decided that one temperature logger would be installed in each gas well selected in Area 3, Area 2E and Area 2W, and two data loggers would be installed in wells located in Phase 1 of the VLF. Temperatures were logged every hour at ~5 m and 10 m B.G. in Phase 1 and approximately 8 m B.G. in Areas 2W, 2E, and 3. It is worth mentioning that the total number of selected wells and temperature recording points was also limited due to limitations on available resources. Other limitations in these series of field work included limited storage capacity of the smart buttons as well as their frailty against moisture that could potentially leak into the data logger chambers. Due to these limitations, the smart buttons were replaced at least once every month during the 8 months course of these field studies. Even with frequent replacement, some of the data loggers burned out, resulting in a loss of data.

3.3.1.2 Results and Discussion

During the course of the landfill temperature field study, over 100,000 data points were collected from the selected 27 wells located in 4 different areas of VLF. Illustrations of all recorded data are provided in Appendix C.2, of which a few examples are presented below.

In general, results showed that the landfill temperature was not affected by ambient temperature fluctuations and appeared to be constant throughout the cold and warm seasons, similar to previous findings by Bingemer and Crutzen (1987), Maurice and Lagerkvist (2003) and Thompson and Tanapat (2005). However, different ranges of temperatures were observed for wastes of different ages. Areas with newer waste showed higher temperatures, representing more bacterial activity occurring in those areas. Recorded data also showed how the LFG system operational glitches can affect the landfill's temperature. Figure 3.8 below shows the recorded

data at 5 m B.G. in vertical LFG well #34 located in Phase 1 of VLF (i.e. Well "P01-V034"). An almost constant temperature of about 40 °C was recorded at this location throughout the course of the study. Also shown in the figure, three incidents of LFG collection system shut-downs occurred when cooled gas from the header pipe (buried near the ground surface) was pulled back to the fill and resulted in lower recorded temperatures (shown as operational errors, excluded from valid recorded data point).

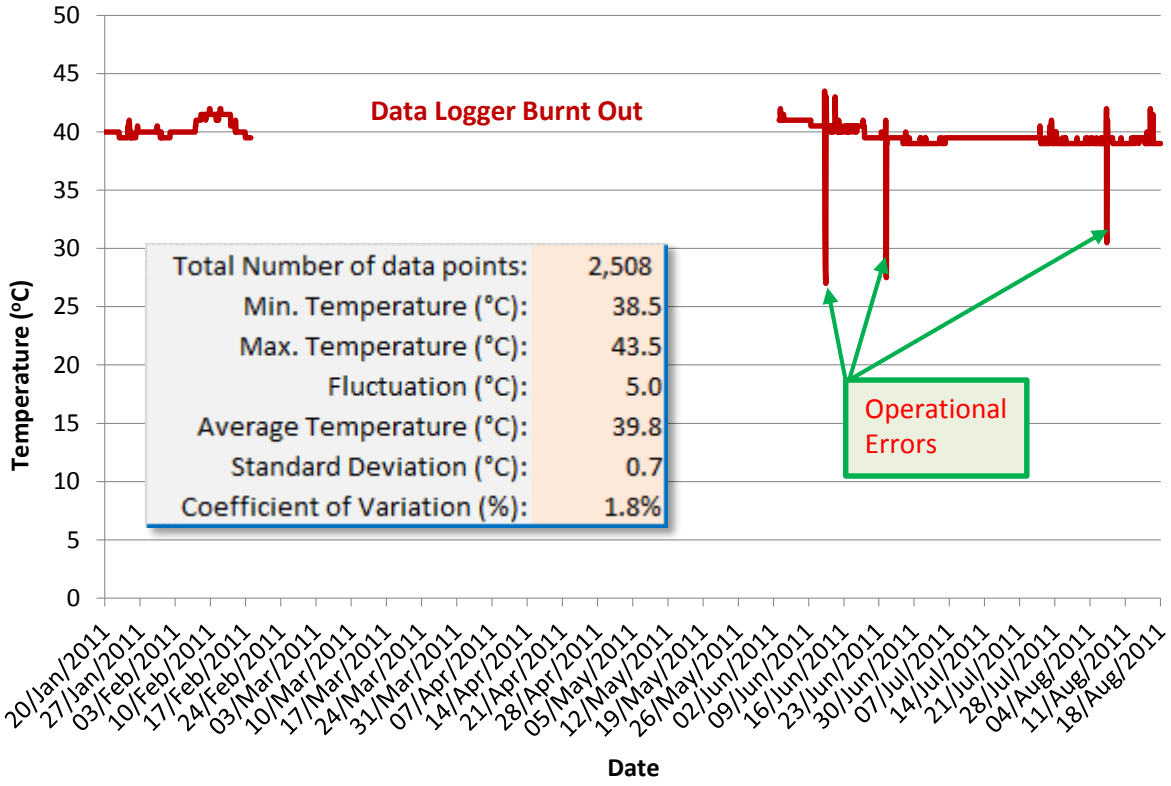


Figure 3.8 Temperature data for the LFG well "P01-V034" (5 m B.G.)

Figure 3.9 and Figure 3.10 respectively illustrate the monthly averages and hourly temperatures in this well. These data are plotted against the ambient temperature, clearly showing independency of the landfill temperature from short term and seasonal temperature variations.

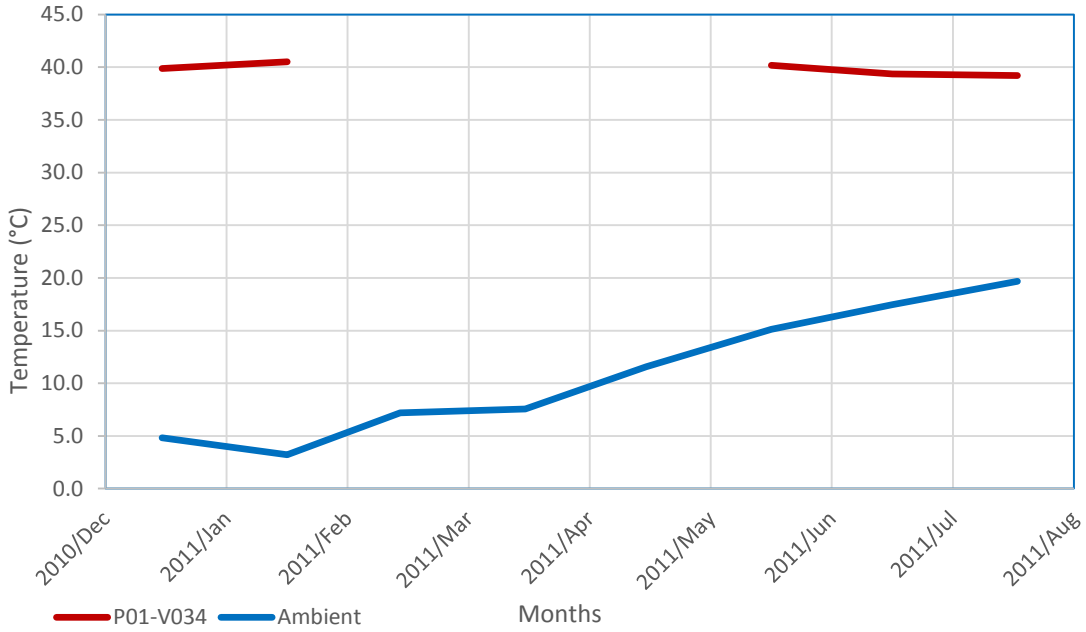


Figure 3.9 Comparison of monthly average temperature data (Ambient vs. P01-V034)

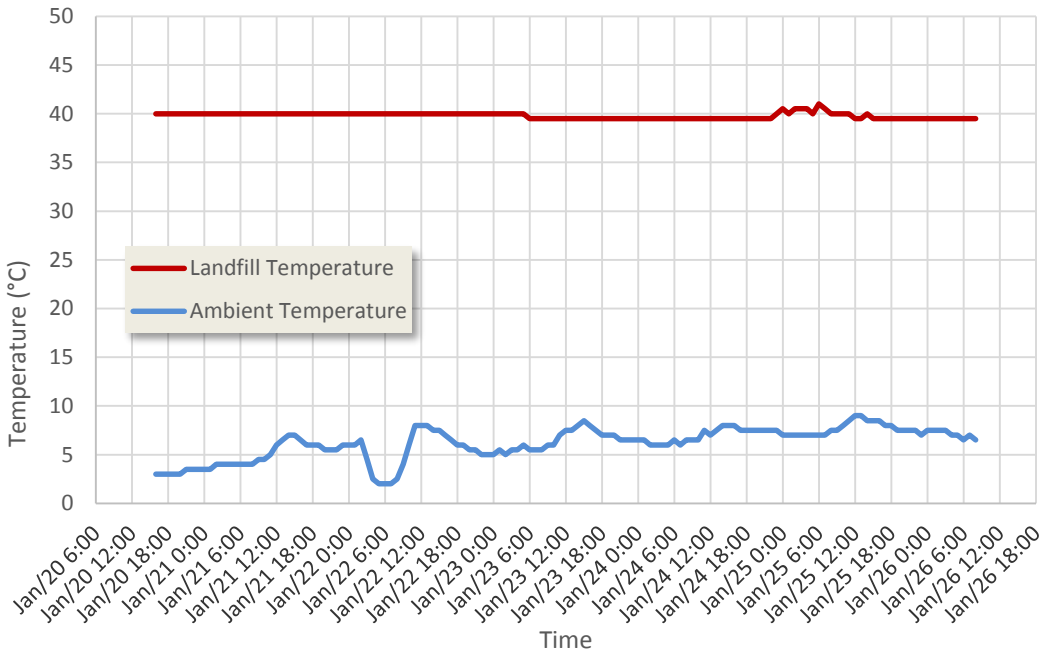


Figure 3.10 Hourly temperature fluctuations - ambient vs. landfill temperature (P01-V034)

Similarly, Figure 3.11 below is an example of the recorded temperatures in a deeper zone of the landfill at approximately 10 m below ground. When operational errors were excluded, the recorded temperature at this point showed a fluctuation of only 1 °C from mid-January to mid-June around the average temperature of 43.1 °C.

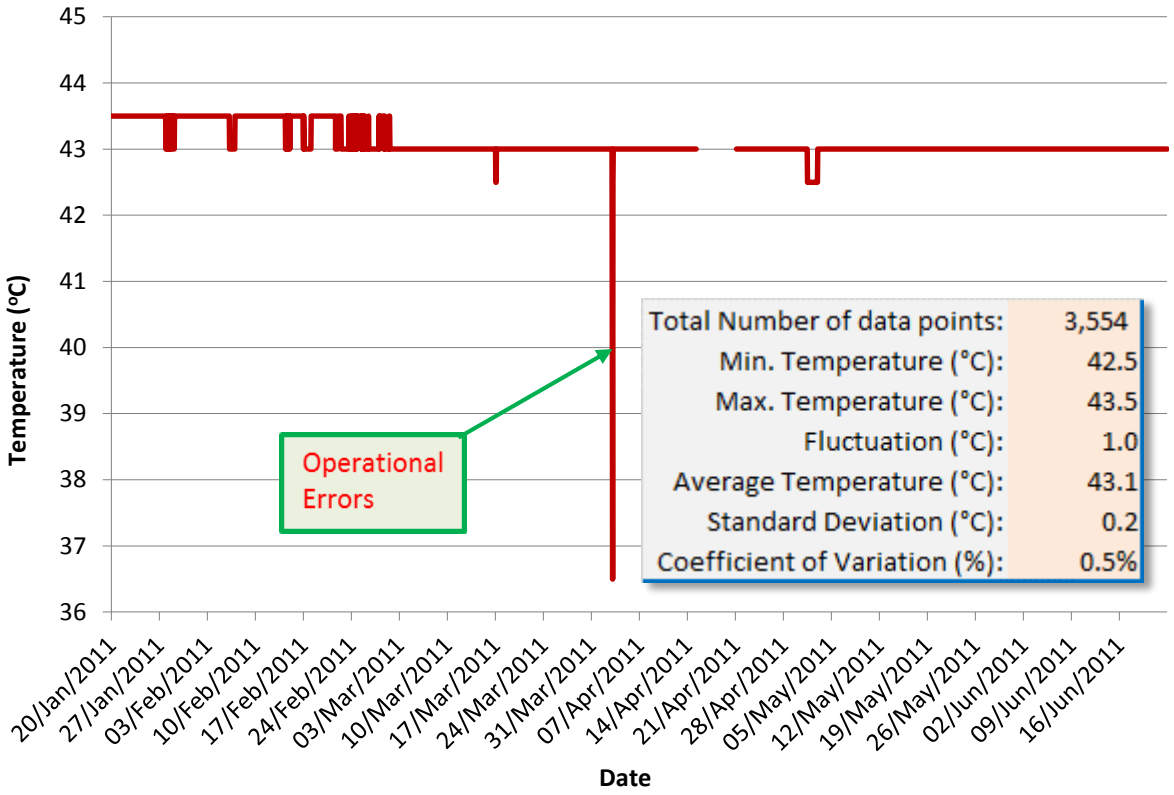


Figure 3.11 Temperature data for the LFG well "P01-V041" (9.5 m B.G.)

Figure 3.12 shows the recorded temperatures in well A2W-V056 located in the older zone of VLF. Temperatures recorded at this location were fairly constant, around 15.5 °C with a maximum fluctuation of 1 °C between mid-January to mid-June.

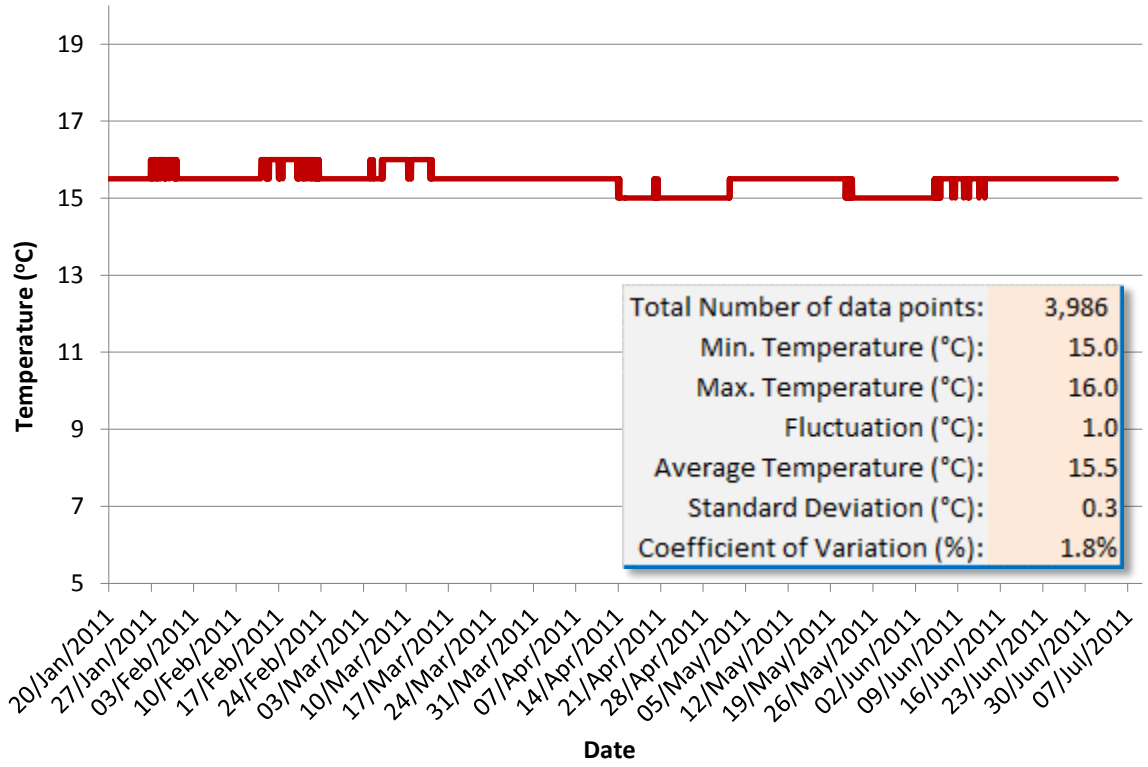


Figure 3.12 Temperature data for the LFG well "A2W-V056" (8 m B.G.)

The results of the 8 months landfill temperature investigations conducted at VLF are tabulated in Table 3.9. Well ID, depth of temperature probe, age of waste at the location, and landfill cover type are also shown, along with the average temperature, minimum and maximum values recorded, range of temperature fluctuations, standard deviation, and coefficient of variation. Out of 35 deep and shallow data recording points, four probes (3 shallow and 1 deep, data are shown in red) showed a large range of fluctuation in recorded temperatures (the red entries in Table 3.9). These variations are not correlated to the ambient temperature fluctuations and are believed to be a result of (i) faulty operation of, and/ or (ii) adjustments made to the LFG wellfield at VLF. (Note: wellfield adjustment is referred to the adjustments made to an LFG collection system to provide required amount of vacuum to each wellhead to actively collect the LFG in an

effective manner). Two examples of these "invalid" recorded data are further explained below, whereas these data are excluded from the final summary of findings and the conclusions resulting from this section of the study.

Table 3.9 Landfill temperature field investigation results (red entries represent invalid recorded data)

LFG Well ID	Depth of Probe from Surface (m)	Average Waste Age (yr)	Cover Type	No. of Valid data Points	Min. Temp. (°C)	Max. Temp. (°C)	Fluctuation Range (°C)	Average Temp. (°C)	Standard Dev. (°C)	Coef. of Variation (%)
P01-V007	5.0	7	Soil Cap	1,367	42.0	45.0	3.0	44.7	0.41	0.9%
	10.0	7	Soil Cap	1,367	46.0	47.0	1.0	46.5	0.05	0.1%
P01-V010	10.0	7	Soil Cap	1,823	42.0	47.5	5.5	45.4	1.29	2.8%
P01-V030	5.0	7	Geomem.	1,523	42.5	44.0	1.5	43.1	0.48	1.1%
	10.0	7	Geomem.	865	46.0	51.0	5.0	46.6	1.03	2.2%
P01-V031	5.0	7	Geomem.	3,051	20.5	46.0	25.5	32.4	6.94	21.4%
	10.0	7	Geomem.	1,460	29.5	37.0	7.5	33.7	1.57	4.7%
P01-V034	5.0	7	Geomem.	2,508	38.5	43.5	5.0	39.8	0.73	1.8%
	10.0	7	Geomem.	2,520	50.5	53.0	2.5	52.1	0.73	1.4%
P01-V036	5.0	7	Geomem.	2,522	42.5	45.0	2.5	43.8	0.44	1.0%
	9.5	7	Geomem.	2,522	47.5	48.5	1.0	48.4	0.25	0.5%
P01-V041	5.0	7	Geomem.	2,048	31.5	42.0	10.5	40.7	0.80	2.0%
	9.5	7	Geomem.	3,554	42.5	43.5	1.0	43.1	0.22	0.5%
P01-V042	3.5	7	Geomem.	2,673	38.5	42.0	3.5	39.6	0.30	0.8%
	8.5	7	Geomem.	1,535	48.5	52.5	4.0	50.1	0.79	1.6%
P01-V054	5.0	7	Geomem.	3,188	35.0	45.0	10.0	41.7	2.71	6.5%
	10.0	7	Geomem.	1,523	43.5	46.0	2.5	45.9	0.24	0.5%
P01-V056	10.0	7	Geomem.	3,195	43.5	45.5	2.0	45.0	0.22	0.5%
A3--V019	6.5	14	Soil Cap	1,034	20.5	21.5	1.0	21.0	0.12	0.6%
A2E-V010	8.0	16	Soil Cap	4,089	14.5	16.5	2.0	15.7	0.48	3.1%
A2E-V013	8.0	16	Soil Cap	4,090	14.0	15.0	1.0	14.6	0.35	2.4%
A2E-V017	8.0	16	Soil Cap	4,090	15.5	16.5	1.0	16.0	0.22	1.4%
A2E-V029	6.5	16	Soil Cap	4,090	14.0	16.0	2.0	15.1	0.37	2.5%
A2E-V032	6.5	16	Soil Cap	4,090	8.5	11.0	2.5	10.2	0.58	5.7%
A2E-V033	8.0	16	Soil Cap	4,090	16.5	17.5	1.0	16.9	0.23	1.4%
A2W-V007	8.0	18	Soil Cap	4,090	12.5	16.0	3.5	15.0	0.72	4.8%
A2W-V012	8.0	18	Soil Cap	4,090	16.5	18.0	1.5	17.1	0.41	2.4%
A2W-V018	8.0	18	Soil Cap	4,090	15.5	17.0	1.5	16.1	0.58	3.6%
A2W-V029	8.0	18	Soil Cap	4,088	12.5	13.5	1.0	13.3	0.25	1.9%
A2W-V050	8.0	18	Soil Cap	2,043	14.0	14.5	0.5	14.4	0.17	1.2%
A2W-V055	8.0	18	Soil Cap	4,088	12.5	16.0	3.5	14.4	0.88	6.1%
A2W-V056	8.0	18	Soil Cap	3,986	15.0	16.0	1.0	15.5	0.27	1.8%
A2W-V060	8.0	18	Soil Cap	4,090	15.5	16.5	1.0	15.8	0.31	1.9%
A2W-V066	7.5	18	Soil Cap	4,089	14.5	16.0	1.5	15.9	0.17	1.0%

Figure 3.13 is an example of how wellfield adjustments affected the recorded temperature at LFG well P01-V054. As mentioned before, the shallower probes, mainly installed at approximately 5 m B.G., were located in the section of the well with solid well piping. Therefore, the recorded temperatures were expected to be a function of the gas temperature from deeper zones (landfill temperature) and perhaps the temperature of surrounding environment which would be slightly lower than the values recorded in deeper zones. This means that there would be less difference between the temperature values recorded at shallow and deep probes in wells from which higher LFG flow rates are collected.

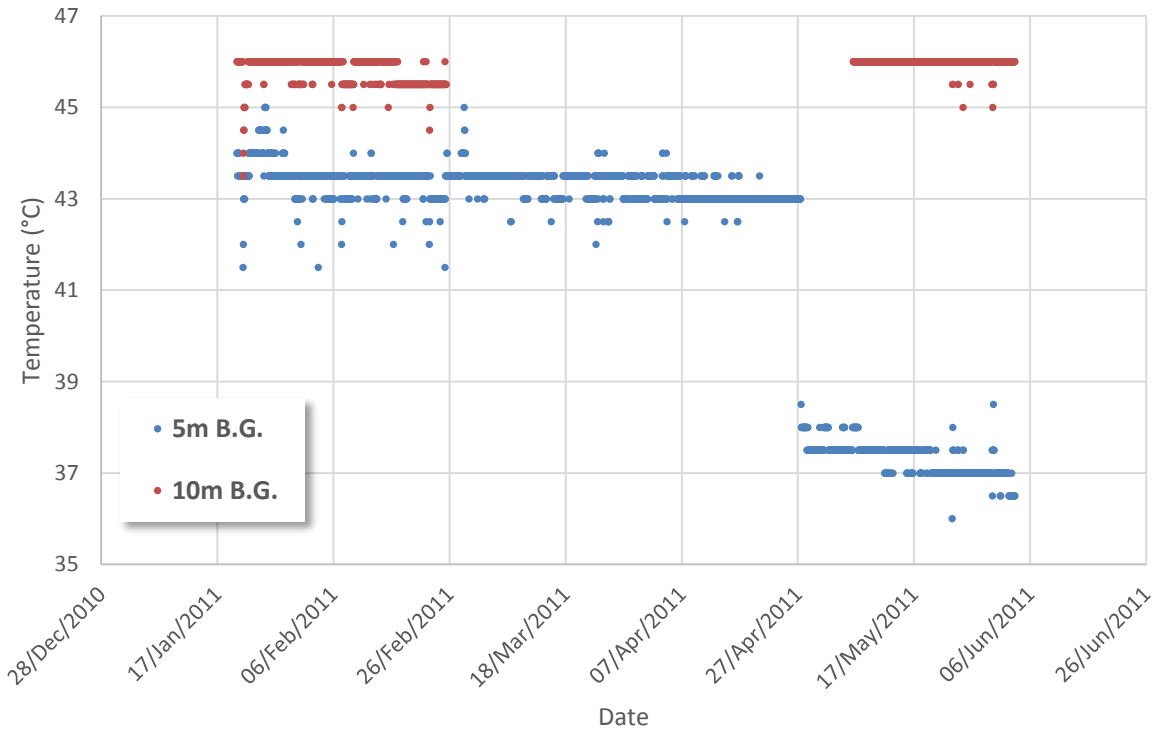


Figure 3.13 Recorded data at well "P01-V054"_example of wellfield adjustment affecting recorded temperature

In this particular example, shown above for the well P01-V054, the wellhead was turned down (i.e. applied vacuum to the well was reduced) on April 27th, 2011 resulting in a temperature decrease in the shallower section of the well, however the temperature in the deeper zone of the landfill (i.e. 10 m B.G.) remained constant at 45.9 ± 0.2 °C.

Another cause of error in the temperature data was observed in P01-V031 where the recorded temperatures showed fluctuation patterns as if the gas temperatures in the sub-surface header pipe were recorded. Figure 3.14 below shows the recorded data at this location.

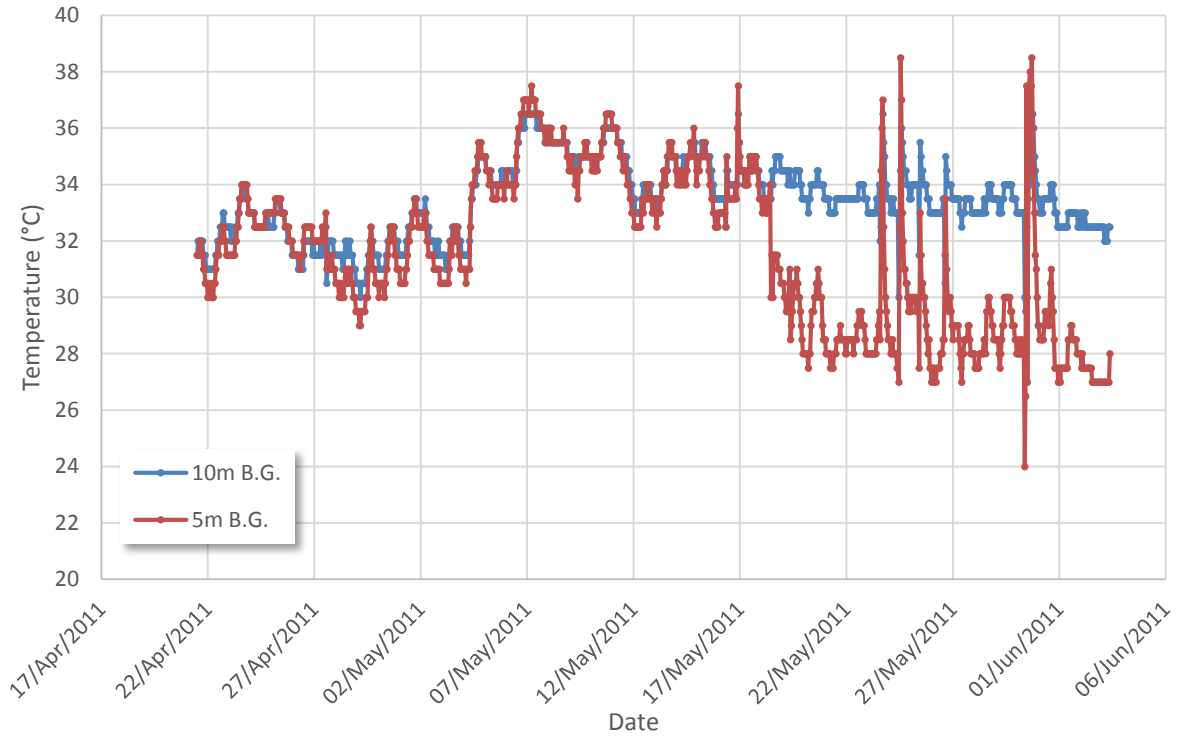


Figure 3.14 Example of faulty temperature readings at LFG well "P01-V031" Due to the LFG collection system operational issues

These temperature values recorded at P01-V031 indicated that no LFG might have been collected from this location. Zero flow situations, when the wellhead is not shut down, can stem

from two causes. The first is due to a total blockage of the well screens due to the high water table, resulting in the well screens being silted over time. This hypothesis was disproved by video inspection of the well conducted during the course of the field investigations. The second hypothesis was an application of excess vacuum in neighboring wells. The vacuum applied to LFG wells is normally defined by several parameters, including well spacing (i.e. expected radius of influence), waste compaction and/or porosity, cover system design and type, depth of well, and depth to the top of the screened section of the well pipe. Typically, 5 to 10 inches of water column is applied to LFG wells to effectively collect the generated gas at acceptable collection efficiencies. Applying too much vacuum to the LFG wells, which potentially causes air intrusion into the landfill, may result in adjacent wells overlapping each other's zone of influence to a greater extent. This is especially a concern in cold climate/ seasons and may have significant negative effects on methanogenic activity via the interruption of optimum temperatures maintained by the exothermic bacterial-mediated reactions. Nevertheless, further mining into the LFG flow rate data, which was collected from the selected wells during the course of these field investigations, supported this hypothesis. The gas flow rate data showed that although there was system vacuum provided at this gas collection point, no gas was collected from this location starting from May 2011. Figure 3.15 shows the applied vacuum and the LFG flow rate at well P01-V031. Figure 3.16 provides similar data for P01-V030, showing significantly higher gas flow rates at approximately similar system vacuum conditions as was provided to P01-V031.

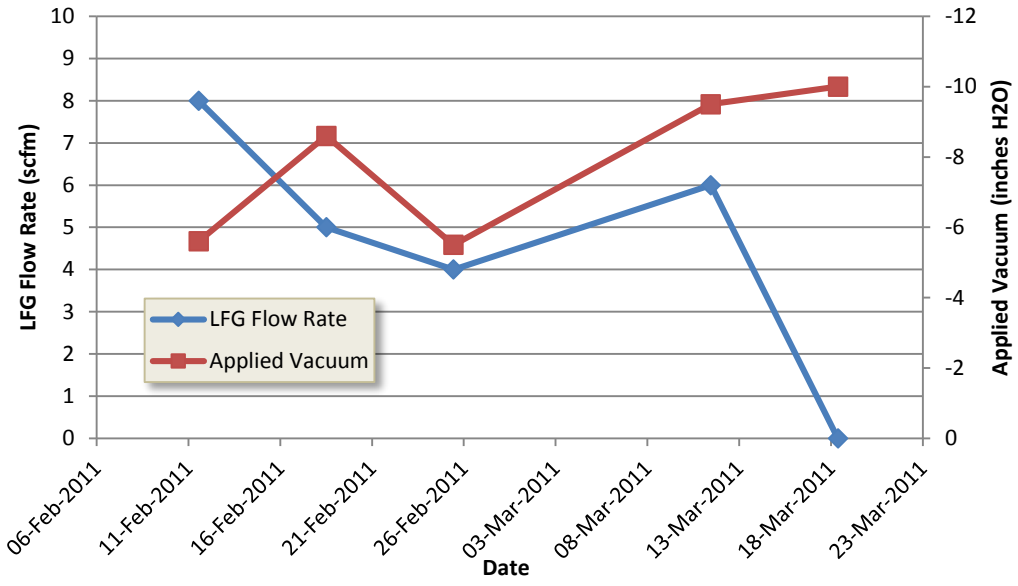


Figure 3.15 System vacuum and LFG flow rate at P01-V031

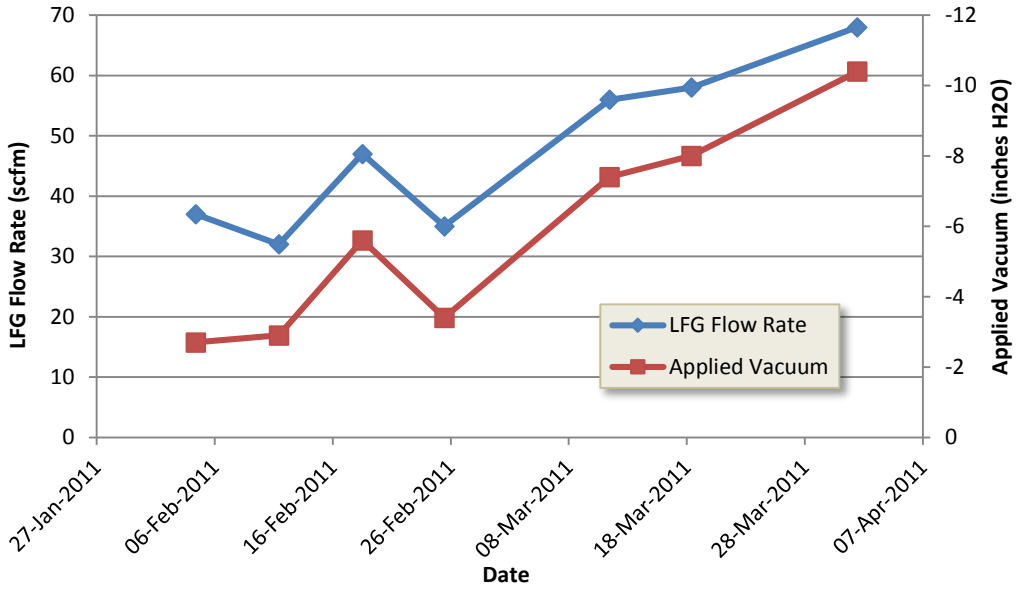


Figure 3.16 System vacuum and LFG flow rate at P01-V030

Figure 3.17 below shows wellhead P01-V054 at VLF and a Landtec. GEM™ 2000+ LFG analyzer which was used during the field investigations to monitor the collected LFG flow rate and composition from the selected wells.

Figure 3.17 LFG wellhead and LANDTEC GEM2000+ used to collect gas data at VLF

3.3.1.3 Older Temperature Study at the Vancouver Landfill

Yeşiller et al. (2005) conducted a comprehensive study on landfill temperatures at four different landfills in North America, including the VLF. That study, which was conducted at shallower areas of VLF (maximum waste depth of approximately 12 m), showed a maximum temperature of 43 °C at this site, confirming that the high temperatures recorded during the course of the present study at Phase 1 of VLF are not solely due to the greater depth of the fill in this phase. Under the study conducted by Yeşiller et al. (2005) at VLF, temperature sensors were located at various locations of the landfill, recording temperatures at various depths starting in 2004. That study continued for a number of years and the following illustration shows a snapshot of the raw recorded temperature data at representative locations from each area of the landfill at a depth of 8 m B.G. (Hanson et al., 2010).

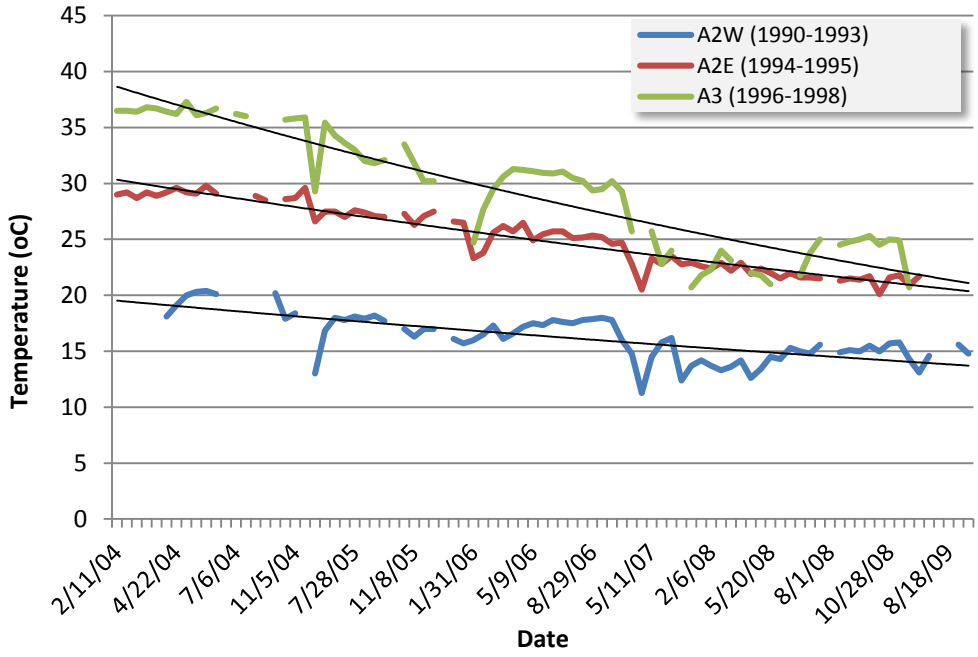


Figure 3.18 A Snapshot of other available temperature data recorded through a comprehensive study by (Hanson et al. 2010) at several landfills including VLF (8 m B.G.) (Raw data were provided by COV)

3.3.1.4 Conclusion

Approximately 100,000 landfill temperature data points were collected in different phases of VLF over a period of 8 months, covering the coldest and warmest days of 2011. Results showed no dependency of landfill temperature on ambient temperature. This is in great disagreement with methodologies that base LFG generation modeling parameters on ambient temperature. Landfill temperature fluctuations were observed to be within 0.5 to 5.5 °C, mainly due to adjustments made to the LFG extraction and collection systems. This is in contrast to the 41.4 °C fluctuation observed in ambient

Table 3.10 Summary of landfill temperature investigations (Depths 8 to 10 m B.G.)

Area	Average Waste Age (yr)	Cover Type	Average Temp. (°C)	Standard Dev. (°C)
Phase 1	7	Soil Cap	45.9	0.91
Phase 1	7	Geomem.	47.3	0.59
Area 3	14	Soil Cap	21.0	0.12
Area 2E	16	Soil Cap	15.8	0.34
Area 2W	18	Soil Cap	15.3	0.48

temperature recording. Table 3.10 shows the average values for the valid recorded temperature data in deeper zones of the Vancouver Landfill's different phases.

Similar to what was reported more than three decades ago by Rovers et al. (1977), these field investigations showed that even in temperate climates like Canada, landfill temperatures remain at optimum ranges for methane production with no significant variations due to ambient temperature fluctuations. Average temperatures of Phase 1 in areas covered with a soil cap were 45.9 ± 0.9 °C, which is slightly lower than areas covered with geomembrane cap with average temperature of 47.3 ± 0.6 °C. This may be due to the different permeability of these two types of cap systems and the effect of cold rain percolating through the soil cap to the fill. Average temperatures of the landfill in Area 3, Area 2E and Area 2W were 21.0 ± 0.1°C, 15.8 ± 0.3°C, and 15.3 ± 0.5°C, respectively.

Another very important finding of these investigations was the correlation between waste age and landfill temperature. Each phase, containing MSW with various average ages ranging between 7 to 18 years, showed a different temperature profile which remained constant throughout the study. Acknowledging the effect of temperature on biodegradation rates, these results suggest that use of a constant k value for the entire landfill's lifespan may not be an accurate choice. However, the decomposable portion of readily biodegradable organics, such as food waste and yard waste, will be almost entirely decomposed by the time the degradation process and the fill temperature decrease. Therefore, application of variable decay rates for slowly degradable waste components, such as wood waste, will likely offer little improvement to the accuracy of the long term LFG generation predictions.

While the effect of temperature fluctuation on the biodegradation process is very well known, and fundamental equations such as van't Hoff-Arrhenius equation are very well developed, application of this knowledge to the complex anaerobic process occurring at MSW landfills appears difficult. There are different types of microorganisms involved in the overall methane generation process, each with a range of optimum temperatures. Some of these microorganisms themselves also regulate and maintain landfill temperatures within a certain range. Furthermore, it must be acknowledged that "landfill temperature" is a generalized term. In reality, not only depending on the distance to the landfill surface and sides as well as many other factors, such as height of the leachate mound, the temperature of different locations of the landfill might be different. There may also be several pockets within the landfill with drastically different profiles due to the heterogeneous nature of a landfill. Therefore, relating and fine-tuning the decay rate values based on temperature and formulae such as the Arrhenius equation is not suggested. Instead, the author suggests that the concept of this knowledge be applied to an average value representing the landfill temperature, and to assign decay rates based on factors that cause a drift from optimum conditions for decomposition reactions.

3.3.2 Moisture Content

Studies have repeatedly reported that moisture is the primary limiting factor in the rate of waste decomposition and methane generation in landfills (Rees, 1980b; Rees, 1980a; Hartz and Ham, 1983; Edward A. McBean et al., 1995; Reinhart and Al-Yousfi, 1996; Barlaz et al., 1997; Baldwin et al., 1998; Wreford et al., 2000). Sufficient moisture in landfills is required for optimal hydrolysis and decomposition of complex organic materials to occur. Furthermore, moisture is

an essential element for the biodegradation process in landfills as it serves as the means of transportation for nutrients and bacteria within the landfills (Edward A. McBean et al., 1995). Therefore, increased landfill moisture enhances the anaerobic degradation process within the landfill. Also, as described in the previous section, the exothermic anaerobic degradation process increases the temperature of the landfill, which further enhances the biodegradation process.

Rowe (1998), in a comprehensive study showed that the moisture content of landfills deeper than 6 m plays a major role in temperature rise within the fill. Rees (1980b) reported that optimum gas generation conditions at a landfill occurs when the base of the landfill is fully saturated and a waste density of 1 tonne per m^3 is achieved. A different study by Hartz and Ham (1983) reported that even at moisture levels as low as 10% on a wet weight basis (% w/w) some methane production occurs. Therefore even at dry sites, and with no additional moisture added, some biodegradation is expected to occur. Similarly, Edward A. McBean et al. (1995) reported that LFG generation occurs even in very dry MSW landfills and, as the moisture content increases so do the degradation process and LFG generation. Farquhar and Rovers (1973) reported that waste decomposition and methane generation in MSW landfills slows down at field moisture levels above 80% w/w. According to Hartz and Ham (1983), this situation can only occur at landfills located in wet climates with no leachate collection system, as they concluded that free moisture conditions at landfills (i.e. field capacity threshold) occurs at approximately 40% w/w moisture content. Edward A. McBean et al. (1995) argued that even if the landfill's moisture content exceeds field capacity, the mobility of nutrients and bacteria provided by the moving liquid will further increase the gas production. Typically, the field capacity of MSW landfills has a direct relation with waste composition and compaction ratio at the time of landfilling and reported to be

within 20% to 40% w/w (Edward A. McBean et al., 1995; Yuen et al., 2001; De Velásquez et al., 2003).

MSW moisture content, as received at landfills, is reported to be somewhere between 15 to 40% w/w (Edward A. McBean et al., 1995). In Canada, the average MSW moisture content is approximately 24.4% (Levelton, 1991). As previously shown on Figure 2.3 on page 48, the moisture content of the generated MSW in Metro Vancouver in the past 20 years has been between approximately 22% to 24% w/w. Nevertheless, landfill moisture content is normally derived by the climatic conditions. Precipitation levels are typically used as an index to describe landfill moisture content and leachate generation rates. There are many LFG modeling methodologies which relate the decay rates of the organic materials deposited into the landfill to the precipitation levels in the area. The following shows a few examples where the decay rate(s) is related to the level of precipitation.

3.3.2.1 The World Bank

CRA (2004), in the LFG modeling handbook prepared for the World Bank, suggested different decay rates defined based on four different ranges of annual precipitation. These values, which were divided into three different decomposition categories, are provided in Table 3.11. These values are suggested for landfills located in Latin America and Caribbean regions.

Table 3.11 Decay rates corresponding precipitation suggested by the World Bank (CRA, 2004)

Annual Precipitation	Range of k Values (year $^{-1}$)		
	Relatively Inert	Moderately Decomposable	Highly Decomposable
<250 mm	0.01	0.02	0.03
>250 to <500 mm	0.01	0.03	0.05
>500 to <1,000 mm	0.02	0.05	0.08
>1,000 mm	0.02	0.06	0.09

3.3.2.2 Environment Canada and Golder Associates

Environment Canada (2012b) and Golder Associates Ltd. (2008b) both suggested a linear correlation between decay rate and precipitation levels. These methodologies both use single phase 1st order decay models, meaning that a single k is defined for the entire mass of MSW. Table 3.12 below shows the resulting k values for different annual precipitation levels based on these two methodologies.

Table 3.12 Decay rates based on Environment Canada and Golder Associates methods

Annual Precipitation (mm)	Decay Rates (k) (Year $^{-1}$)	
	Environment Canada	Golder Associates
0 - 500	0.020	0.023
500 to 1,000 (avg. 750)	0.038	0.079
1,000	0.057	0.111

3.3.2.3 BC Ministry of Environment

BC MOE in its LFG Generation Assessment Procedure Guidance Report prepared by CRA (2009), defined default values for decay rates for each waste category and for different regional areas based on the reported annual precipitation. These values, which were divided into three different decomposition categories, are provided in Table 3.13. According to CRA (2009),

decomposable materials include food waste, leaves, grass, plant clipping, Christmas trees, slaughterhouse waste and yard waste. Also, all different types of paper, wood waste, textile, leather and DLC waste fall into the "moderately decomposable" and the rest of materials are considered "relatively inert".

Table 3.13 Decay rates suggested by the BC MOE modeling guideline (CRA, 2009)

Annual Precipitation	Range of k Values (year $^{-1}$)		
	Relatively Inert	Moderately Decomposable	Decomposable
<250 mm	0.01	0.01	0.03
>250 to <500 mm	0.01	0.02	0.05
>500 to <1,000 mm	0.02	0.04	0.09
>1,000 to <2,000mm	0.02	0.06	0.11
>2,000 to <3,000mm	0.03	0.07	0.12
>3,000 mm	0.03	0.08	0.13

Furthermore, the BC MOE guideline has defined a "Water Addition Factor" which is a number within the range of 0.9 to 1.1, and is to be selected based on the storm water and leachate management/recirculation practices applied to the landfill. While a value of 1.0 represents the normal conditions (i.e. partial infiltration or water addition to the waste mass), values of 0.9 and 1.1 are to be applied to the k values selected for dry tomb and bioreactor landfills, respectively.

3.3.2.4 IPCC Methodology

As discussed in Section 1.4.2 in page 20, the IPCC appreciated the ambient temperature values in the selection procedure for the decay rates to be applied in the FOD model. The recommended decay values assigned to the suggested thresholds for ambient temperature (i.e. 20 °C) and annual precipitation (i.e. 1,000 mm) were previously shown in Table 1.4.

Table 3.14 IPCC default decay rates when merged over all ranges of ambient temperature

Waste Components	Decay Rates (k) (years^{-1})	
	Dry	Moist and Wet
Food waste / Sewage sludge	0.05 - 0.10	0.10 - 0.70
Garden and park waste (non-food)	0.04 - 0.08	0.06 - 0.20
Paper and Textiles	0.03 - 0.06	0.05 - 0.085
Wood and straw	0.01 - 0.04	0.02 - 0.05
Bulk MSW or industrial waste	0.04 - 0.08	0.08 - 0.20

3.3.3 Suggested Values for Decay Rates (k, year^{-1})

Most of the methodologies suggest different k values for different precipitation levels with 1,000 mm annual precipitation being the maximum level after which constant values for decay rates are proposed. This is in agreement with findings by Yeşiller et al. (2005) where annual precipitation levels beyond approximately 840 mm were found not to further elevate the landfill temperature. This is perhaps due to the limited amount of water that can be held within the waste fill (i.e. field capacity) after which it will continue to percolate through the waste mass, and may even cause solubilized material and nutrients to be washed out in the form of leachate. Therefore, the author believes that while there should be higher decay rate values adopted for higher precipitation levels, there must also be a limit to that relationship with a threshold after which the decay rates to be considered constant.

Farquhar and Rovers (1973) reported that methane generation was inhibited at landfill moisture content levels higher than 80%. Therefore, having a leachate collection system installed at a landfill may be considered as an enhancement for the biodegradation process as it will avoid the moisture content reaching levels higher than the field capacity. However, by removing the

generated leachate through the landfill's leachate collection system, a portion of the nutrients potentially available for bacterial activity will be removed (Wreford et al., 2000). Therefore, the author believes that these two factors would cancel out each other and that having a leachate collection system, especially for wet environment, would not pose a significant positive effect on the biological degradation process in the landfill. Leachate recirculation, however, can be considered as an enhancement to the overall degradation and methane formation process as long as excessive water infiltration is avoided. Rees (1980b) reported that an excessive water infiltration at landfills may result in the cooling of the waste mass, slowing down or inhibiting the degradation process.

Table 3.15 presents suggested decay rate values for different waste components assigned to different precipitation levels. These values are selected based on the fact that depending on the landfill moisture, which is primary derived by the precipitation levels in the area, bacterial activity would provide an optimum condition and the degradation process will continue at the suggested rates. However, should the landfill's conditions for any reason drift from the optimum situation (i.e. pH drifts from optimum range of 6.7 to 7.5 (Edward A. McBean et al., 1995) and /or landfill temperature drops below 30 °C (Hartz, 1983; Edward A. McBean et al., 1995)) these suggested decay rate values shall be adjusted accordingly.

Table 3.15 Suggested k values assigned to different precipitation levels for advanced LFG generation assessment

Waste Components	Decay Rates (k, year $^{-1}$)		
Annual Precipitation (mm)	< 500	500 to 1,000	> 1,000
Food Waste	0.07	0.15	0.35[14]
Yard Waste	0.04	0.08	0.14[15]
Paper and Textile	0.02	0.05	0.07[16]
Wood Waste	0.02	0.03	0.04

3.4 Delay Time

As previously shown in Figure 1.1, there is a lag time between the moments of waste placement in a landfill until steady anaerobic/ methanogenic conditions are reached. The length of this "delay time" depends on various factors including climatic condition and waste composition, and can vary between 3 months and one year (ATSDR, 2001; Gregory et al., 2003; Barlaz, 2004; USEPA, 2004). Lay et al. (1996) reported that the lag time between waste placement and methane production decreases at higher landfill moisture contents. IPCC (2006) recommended a delay time of between zero and six months. Most of the existing models, including the IPCC FOD and the US-EPA LandGEM, use the default value of six months for the delay time in all types of landfills. Considering the six month delay as an average residence time for the total

[14] Average value based on half-life of 1-3 years under optimum condition adopted in consultation of (Rovers et al., 1977; Robert K. Ham et al., 1979; Jensen and Pipatti, 2002; IPCC, 2006).

[15] Based on an average half-life of 5 years under optimum condition adopted in consultation with (Rovers et al., 1977; IPCC, 2006).

[16] Based on average half-life of 10 years under optimum condition adopted in consultation with (Rovers et al., 1977; CRA, 2004; IPCC, 2006; CRA, 2009)

mass of MSW deposited throughout year A, these models consider the steady methane generation phase to start at the beginning of year A+1.

In the current advanced modeling exercise, it is suggested that instead of a flat assumption for all landfills, the delay time to be correlated to the level of precipitation in the area. Dependency of the decay reaction rates on landfill moisture was previously shown in Section 3.3.3 and is the main driving force for this suggestion. However, should the landfill conditions for any reason drift from the optimum situation (i.e. pH drifts from optimum range of 6.7 to 7.5 (Edward A. McBean et al., 1995) and /or landfill temperature drops below 30 °C (Hartz, 1983; Edward A. McBean et al., 1995)) these suggested delay times shall be investigated and adjusted accordingly. Table 3.16 shows the suggested delay time values for different cilatic conditions.

Table 3.16 Suggested average delay time based on precipitation levels

Annual Precipitation (mm)	Average Delay Time (T_d) (months)
>1,000	4
500 to 1,000	5
< 500	6

3.5 The New Model

Based on the multi-phase first order decay methodology, an integrated LFG generation model (iModel-110©), incorporating the modeling parameters and correction factors explained above, was developed in an excel workbook. The fundamental model equation is shown in Equation 3.5:

$$\mathbf{G} = \sum_{i=1}^{n} \sum_{j=1}^{5} (\mathbf{983.2842} \times \boldsymbol{k_j} \times \boldsymbol{M_{ij}} \times \boldsymbol{w_j} \times \boldsymbol{DOC_{a_j}} \times \boldsymbol{e^{-k_j \times t_i}})$$

Equation 3.5

Where:

"G" is the methane generation rate (m^3 $year^{-1}$)

"i" represents each year of the landfill lifespan

"j" represents five different type of the organic materials deposited to the landfill

"983.2842" is a conversion factor (See Equation 3.3)

"M_{ij}" is the mass of organic waste type j disposed in year i (tonnes, wet basis)

"w_j" is the moisture content of the organic waste type j (See Table 2.8)

"$DOCa_j$" is the actual amount of organic carbon in the organic waste type j which is ultimately converted to methane (See Equations 3.2 and Table 3.6)

The model was developed with a user-friendly interface consisted of five major interlinked spread sheets and several hidden sheets for calculations. The major interface spread sheets include Parameters, MSW Tonnage, Dry Tonnages, LFG Results, and Graphics.

In the "Parameters" sheet the site-specific information such as the landfill name, opening year, site design, operational and climate factors as well as waste components characteristics such as moisture content (w_j), $DOC_{dry\text{-}j}$ and decay factors (k_j) are to be entered. Landfill activity data, including tonnages and composition of the MSW historically deposited at the landfill or expected to be landfilled in the future (M_j), are entered in the "MSW Tonnage" sheet. The total amount of

carbon annually deposited at the site is calculated based on the DOC and moisture content values in the "Dry Tonnage" sheet. The "LFG Results" sheet presents the calculated methane generation yield for each year based on the waste data, estimated annual methane generation from each waste component in tonnes per year, and the expected LFG flow rates in standard cubic feet per minute (scfm). These results, along with average waste tonnage and composition data, are graphically illustrated in "Graphics" sheet.

3.5.1 The New Model Results for the Vancouver Landfill

The iModel-110© was run separately for the VLF's four sub-areas within the boundaries of the study. One of the model's graphical outputs is the illustration of average waste composition that historically has been deposited into the landfill. These illustrations are very useful when the model is used as a tool for report preparation. Figure 3.19 a, b, c, and d shows these results for Area 2W, Area 2E, Area 3, and Phase 1 of VLF, respectively. Figure 3.20 shows annual tonnages, as well as the total tonnage of MSW historically deposited at VLF within the study boundary previously defined in Section 2.2.5. Also shown in Figure 3.21, are the initial methane generation estimates from each of the waste components historically deposited in these areas. Figure 3.22 illustrates the total methane generation rate and LFG flow rate estimated to be generated from the boundary of the study (G_i). Summary of the results are presented in Table 3.17. Full results and outputs of the models for Area 2W, Area 2E, Area 3, Phase 1, and the entire work site boundary at VLF are presented in Appendices B.1 through B.5, respectively.

Table 3.17 Summary of the initial methane generation modeling results (G_i) for the work site areas

Area/ Phase	Footprint (m^2)	Waste in Place (tonnes)	Years of Activity	Average Methane Yield, L_o (m^3 $tonne^{-1}$)	2012 CH_4 Generation (G_i), (tonnes $year^{-1}$)
Area 2W	259,700	2,010,492	1990 - 1993	91.3	1,585
Area 2E	189,010	946,200	1994 - 1995	91.1	922
Area 3	140,550	1,366,288	1996 - 1998	86.7	1,547
Phase 1	242,261	4,470,903	1999 - 2008	77.0	7,798
Total	**831,521**	**8,793,883**		**83.2**	**11,851**

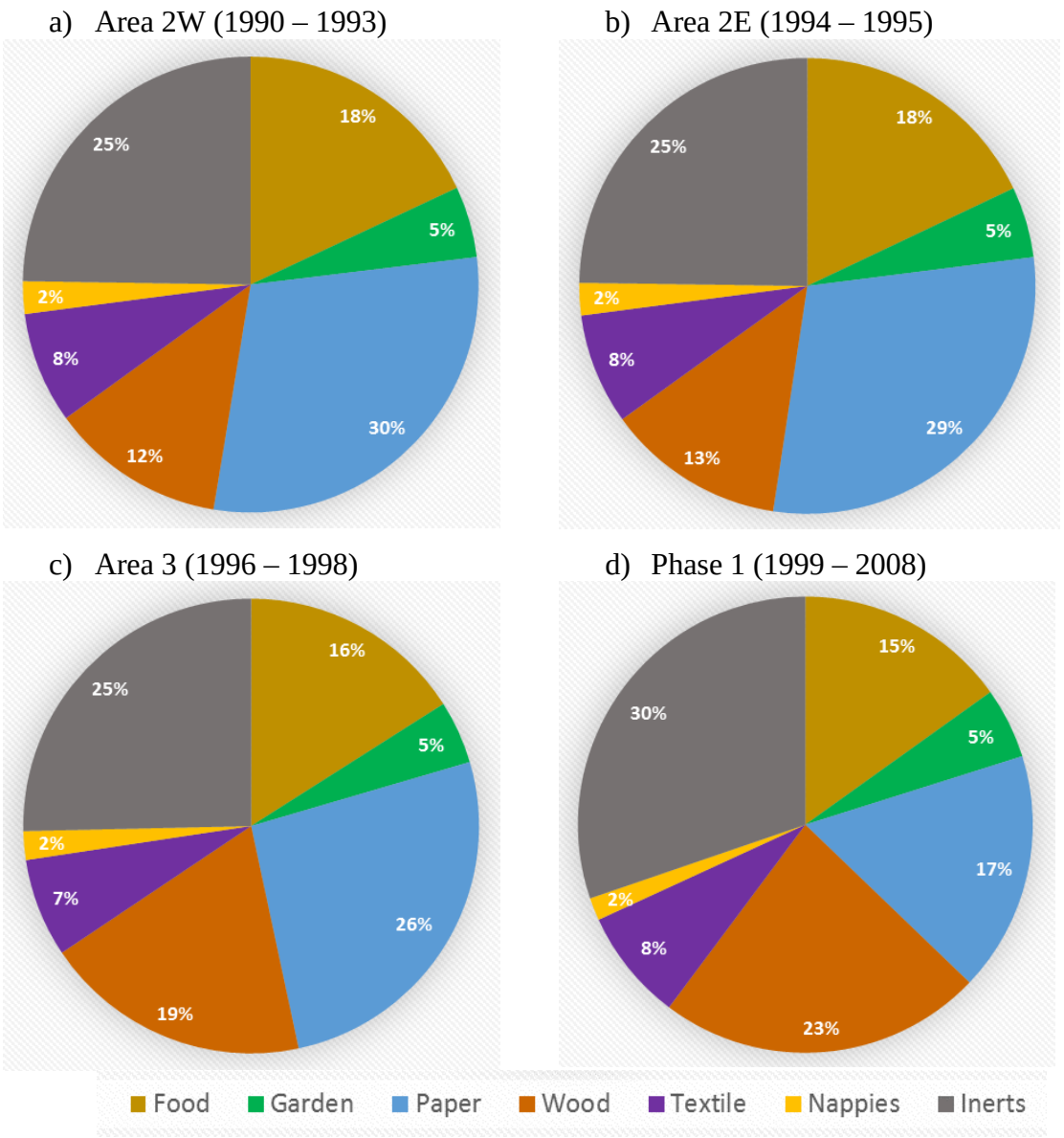


Figure 3.19 Average historical waste composition for different areas of VLF

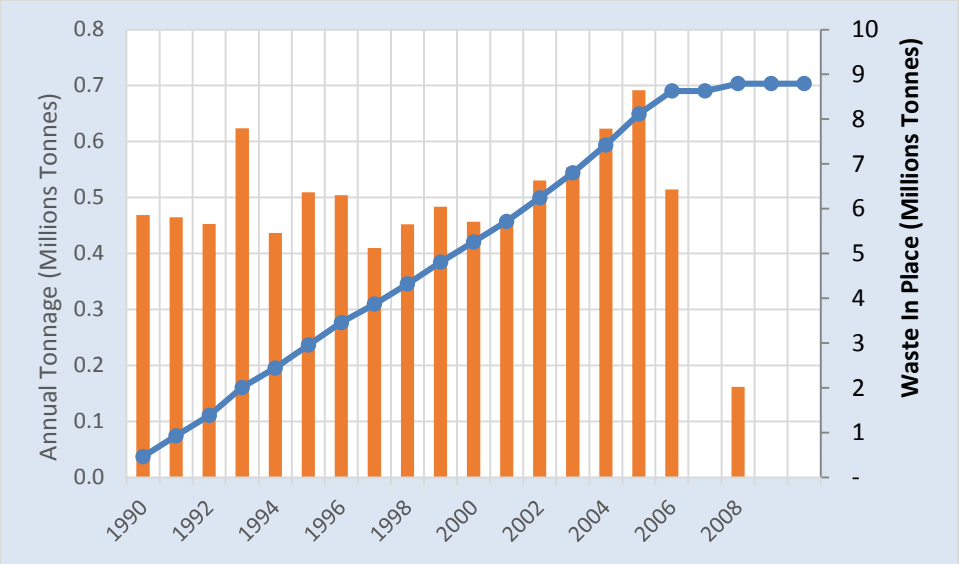


Figure 3.20 Total waste deposition rate in the four areas within the study boundary at VLF

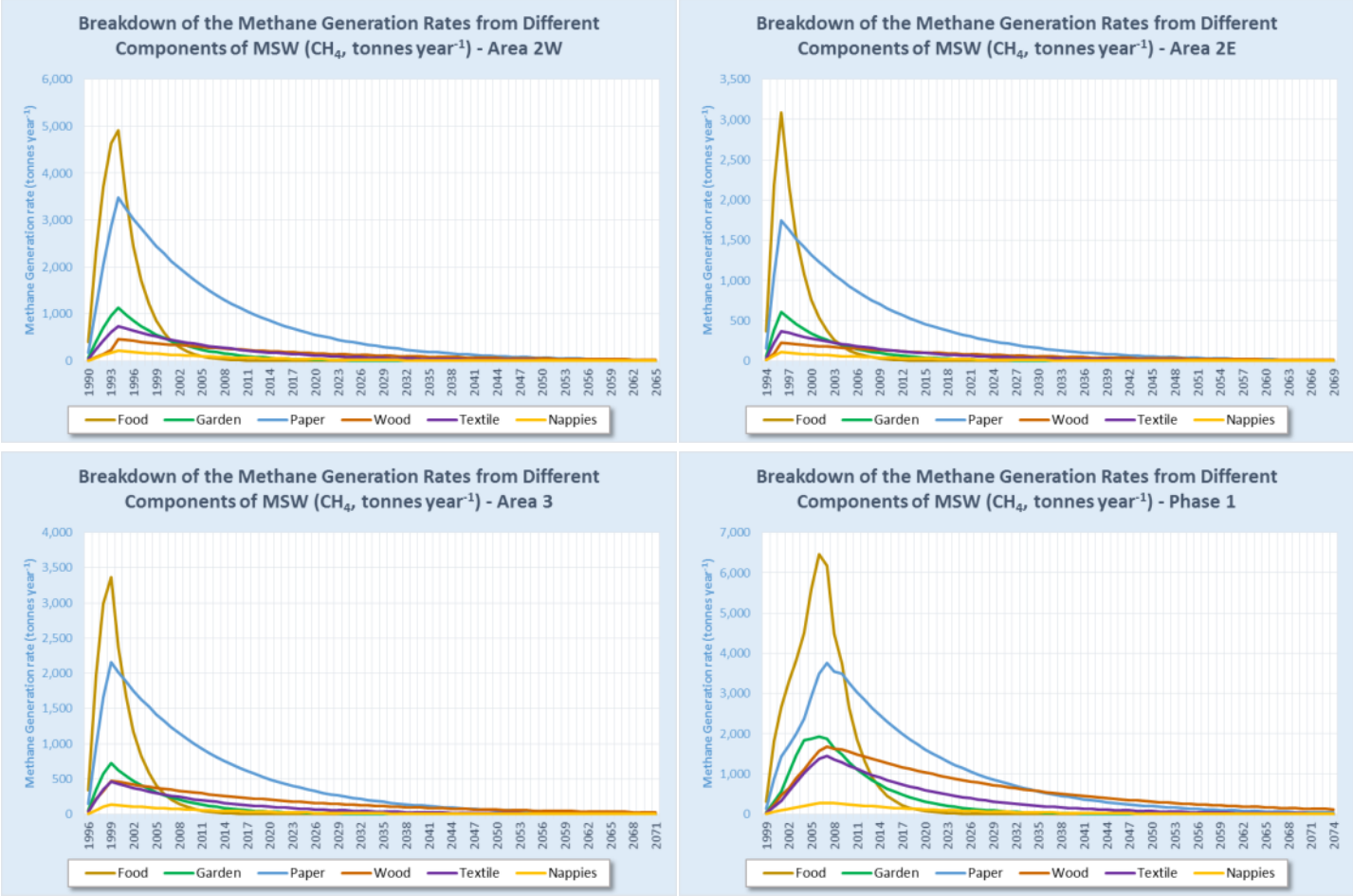


Figure 3.21 Methane generation rates from different waste components at VLF

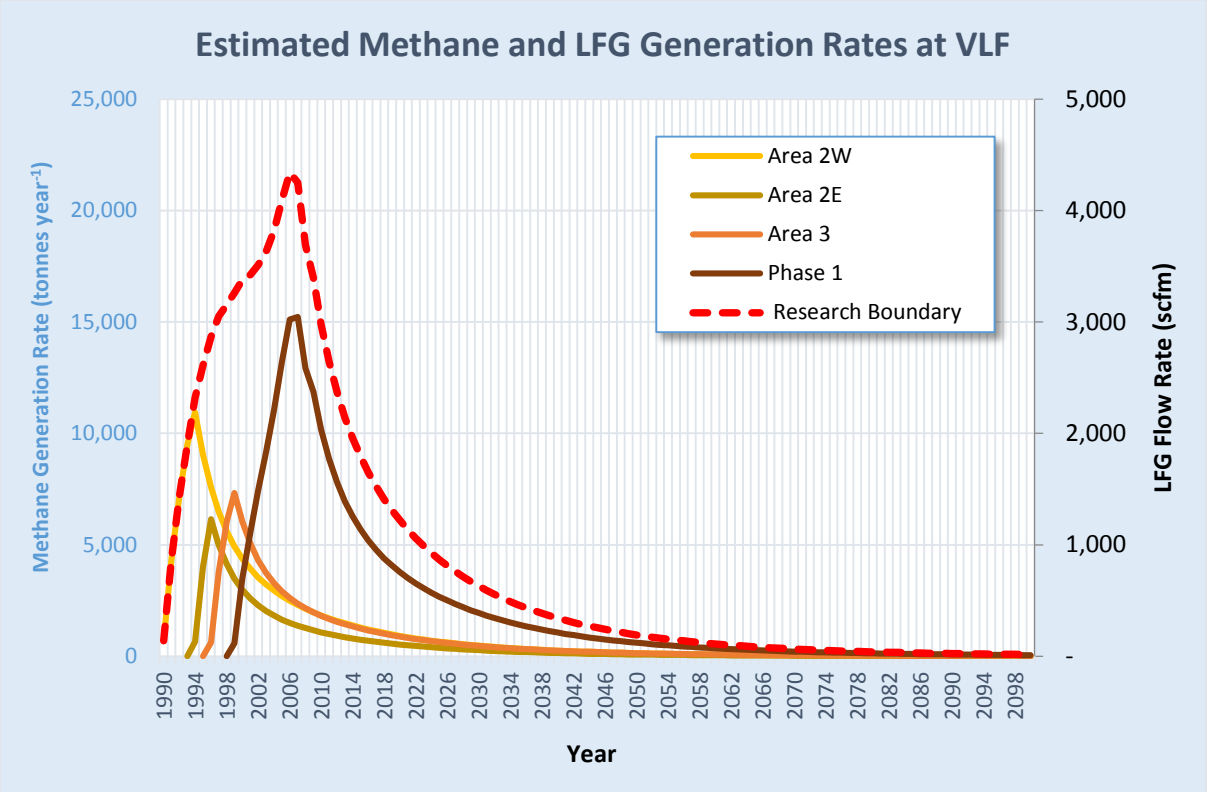


Figure 3.22 Estimated landfill gas and methane generation rates at the work site

3.6 Discussion

In order to conduct an initial comparison between the results of the new model with the popular models previously discussed in Section 1.4, the initial methane generation estimates achieved from the first run of the iModel-110© were put against the results previously presented in Table 1.11. As shown in Table 3.18 below the initial results show higher methane capture efficiency for the Phase 1 of the VLF. The overestimation of the other models in comparison to the new model is obvious and mainly due the arbitrarily assigned modeling parameters, methane yields and reaction rates, in these models. However, the magnitude of the overestimation may vary from year to year (e.g. see BC MOE and iModel-110 for years 2012 and 2007).

It is worth noting that the presented results in this chapter are the initial (raw) results and before calibration of the iModel-110©. Therefore, further discussion is presented in Chapter 7, where the new model is calibrated based on the field data and the final results are presented.

Table 3.18 Comparison between the iModel-110© initial results with the popular LFG generation models

Methodologies			CH_4 Generation (tonnes year^{-1})			Methane Yield, L_o (m^3 tonne^{-1})	Decay Rate, k (year $^{-1}$)	2012 Collection Efficiency
			Current (2012)	Peak (2007)	Lifespan Total			
1.	LandGEM	CAA	16,669	20,411	515,386	170	0.05	37%
2.		Inventory	8,520	9,947	302,038	100	0.04	73%
3.	IPCC		10,112	14,046	319,542	106	0.03-0.15	62%
4.	Environment Canada		10,949	15,683	267,524	88	0.083	57%
5.	Golder Associates		18,400	33,966	416,067	137	0.137	34%
6.	BC MOE		11,198	15,783	300,360	99	0.02-0.11	56%
7.	iModel-110		7,798	15,228	198,642	77	0.04-0.35	80%

Chapter 4: Fugitive Methane Emissions (E)

4.1 Introduction

Methane (CH_4) is an important GHG with a much shorter atmospheric lifetime (~10 years) in comparison with other greenhouse gases (Bogner and Matthews, 2003). Therefore, changes made to CH_4 emission sources can affect the atmospheric concentrations on relatively shorter timescales. In Canada, about 3% of the 2010 national GHG emissions were reported to be from the waste sector, of which about 91% was attributed to fugitive methane emissions from landfills (Environment Canada, 2012a). With landfills being point sources of CH_4 emissions, it would be easy to apply quantifiable mitigation measures. That includes capturing LFG for energy recovery and/or thermal or biological oxidation of methane which can significantly change the concluded methane budget of current inventory reports.

There have been significant technological improvements in the LFG collection and utilization industry since the first full-scale project was implemented in Palos Verdes, California, USA. in 1975 (Spokas et al., 2006). There are several regulatory requirements developed worldwide to monitor and reduce methane emissions from MSW landfills. Normally, landfills generating methane at levels higher than a defined threshold are required to capture the generated gas through active gas collection systems (GCS) and oxidize the collected methane via thermal combustion techniques. Such “regulated landfills” are also required to have a performance control and monitoring system in place to evaluate the effectiveness and efficiency of the active GCS. For example, landfill owners and/or operators in the US are required to conduct regular semi-quantitative assessments of the effectiveness of the GCS via monitoring of the landfill’s surface methane concentrations (SMC). This regulatory requirement was developed by the US-

EPA under the Clean Air Act as New Source Performance Standards (NSPS) compliance to assess the performance of the GCS of the regulated landfills. Canadian officials in BC, however, require solid quantitative measurements of GCS collection efficiency. Such assessments require nearly 100% accurate LFG generation estimates or solid fugitive methane emission numbers, along with the captured gas quantity and quality.

The adopted approach for the present study also relied on reliable quantitative information about methane emission levels (E) at VLF. This information was required to integrate the right side of the simplified METRO© equation, allowing quantification of a necessary calibration factor to be applied to generation estimates (G) on the left side of the equation.

4.2 Fugitive Emission Measurement Techniques

There are qualitative and quantitative methodologies to evaluate the efficiency of an LFG collection system. Qualitative approaches include visual observation of vegetation and/ or vegetation stress on the landfill cover, or measurement of near-ground methane concentrations. These techniques can provide valuable information about the performance of the closure and the GCS at the landfill and can identify major LFG emission "hot-spots". However, quantification of emissions (i.e. methane flux) cannot be achieved through these methodologies.

There are also various quantitative methodologies to estimate the level of methane emission from landfills. These techniques identify hot-spots at the landfill surface and then quantify methane flux from those areas. Within these methodologies, the flux chamber technique is the most well-known and widely accepted approach allowing for relatively reliable quantification of methane

emissions at landfills. The flux chamber technique is the only "approved methodology" recognized internationally and suggested by various agencies including the US-EPA, the Australian EPA and the Wales Environment Agency.

Remote sensing techniques represent a more integrated approach for quantification of methane flux. These techniques have gained popularity in recent years. One of these techniques is the Radial Plume Mapping (RPM) methodology recognized by the US-EPA as "other test method 10 (OTM-10)" since July 2006[17] (USEPA, 2006). This technique uses optical remote sensing (ORS) instrumentation to characterize gas emissions from non-point sources. Some of these ORS instruments include; (i) Open-Path Fourier Transform Infrared (OP-FTIR) spectroscopy, (ii) Ultraviolet Differential Absorption Spectroscopy (UV-DOAS), and (iii) Open-Path Tunable Diode Laser Absorption Spectroscopy (OP-TDLAS) (USEPA, 2007).

The RPM techniques carry many advantages over the "close range measurement" methodologies, such as the flux chamber technique. However, the relatively high cost of the RPM method, as well as the uncertainties associated with the possible effect of the methane plume buoyancy on the results, made the flux chamber methodology a more suitable option for the present research.

The required capital cost for the flux chamber technique is relatively low. However, the large footprint area of the work site (approximately 100 hectares for Areas 2w, 2E, 3 and Phase 1)

[17] See www.epa.gov/ttn/emc/tmethods.html

would considerably increase the required time and labour cost for the application of this method in this research project. Nevertheless, considering the availability of surface methane concentration (SMC) data, which was generated with collaboration of a third party hired by the COV, a unique approach was developed under this research allowing for quantification of the fugitive methane from the entire area at much lower cost in comparison with the above-mentioned conventional methods. This approach is fully explained in the following sections.

4.3 Surface Methane Concentration (SMC) Measurements at VLF

During the course of the present study (2010-2011), the COV hired a consultant to conduct a methane surface scan of the entire landfill site. This is a routine exercise for large landfills in the US, and is conducted based on the US-EPA's New Source Performance Standards (NSPS) for MSW landfills. In this technique, surface methane concentrations (SMC) are measured following the US-EPA's "Method 21" procedure, which is developed for measurement of volatile organic compounds (VOC) (USEPA, 1999). Under NSPS compliance, the LFG flux is not directly measured. However, the semi-quantitative information of the SMC is used to evaluate the effectiveness of the landfill's cover system and the LFG collection system in regulated landfills.

In order to conduct the present field survey, the site work (i.e. Areas 2W, 2E, 3 and Phase 1 of VLF) was divided into 101 measurement grids of about 1 hectare each as shown in Figure 4.1. Also shown in this figure, are the measurement grids and their IDs in different areas of the work site.

Figure 4.1 SMC measurement grids and IDs at the work site (VLF)

The SMC were measured using a Landtec SEM-500, a portable flame ionization detector (FID) shown in Figure 4.2.

Figure 4.2 Landtec SEM-500 (FID)

The methane concentration levels were measured within 5 to 10 cm of the landfill surface along a pattern that traversed each grid at 10 meter intervals as shown in Figure 4.3.

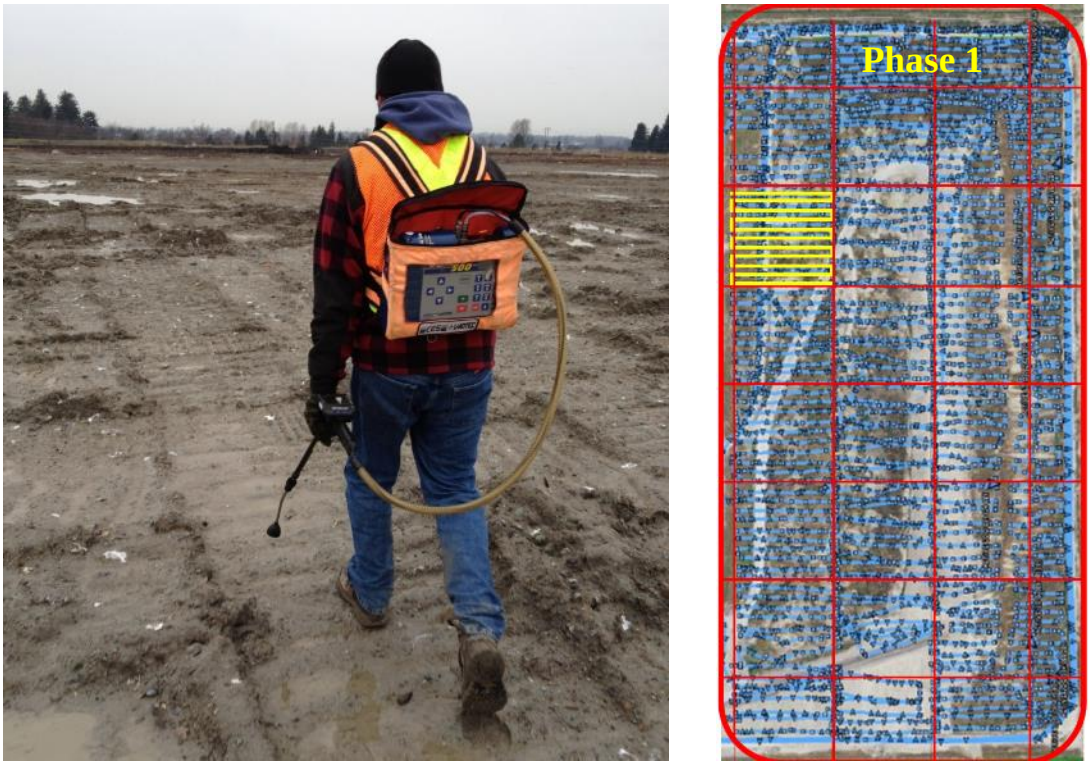


Figure 4.3 VLF surface CH_4 concentrations scan with FID (left), and Phase 1 measurement grids and scanned patterns (right)

For each grid, approximately 500 to 1000 data points were recorded to assess methane concentration at parts per million volume (ppmv) levels. The average of these readings formed a surface methane concentration number for each grid (SMC_a) which was used to categorize the work site into 5 different methane emission level zones as presented in Table 4.1. As described in the following sections, an approach was developed to translate these qualitative (semi-quantitative) SMC_a data to quantitative methane emission rates (MER) (i.e. methane flux) at VLF. This approach involved measurement of MER through application of the flux chamber

technique in a selected number of grids from each emission zone (see Section 4.4) and finding a good correlation between the MER and the SMC data.

Table 4.1 Methane emission level zones and assigned average concentrations at VLF

Codes	Emission Zones	Average Surface Methane Concentration Levels, SMC_a (ppmv)
	Zone 1	0 ppm < SMC_a < 10 ppm
	Zone 2	10 ppm < SMC_a < 20 ppm
	Zone 3	20 ppm < SMC_a < 30 ppm
	Zone 4	30 ppm < SMC_a < 40 ppm
	Zone 5	50 ppm < SMC_a

The following illustration shows the work site boundary and the SMC survey grids which are colour coded based on the surface scan results.

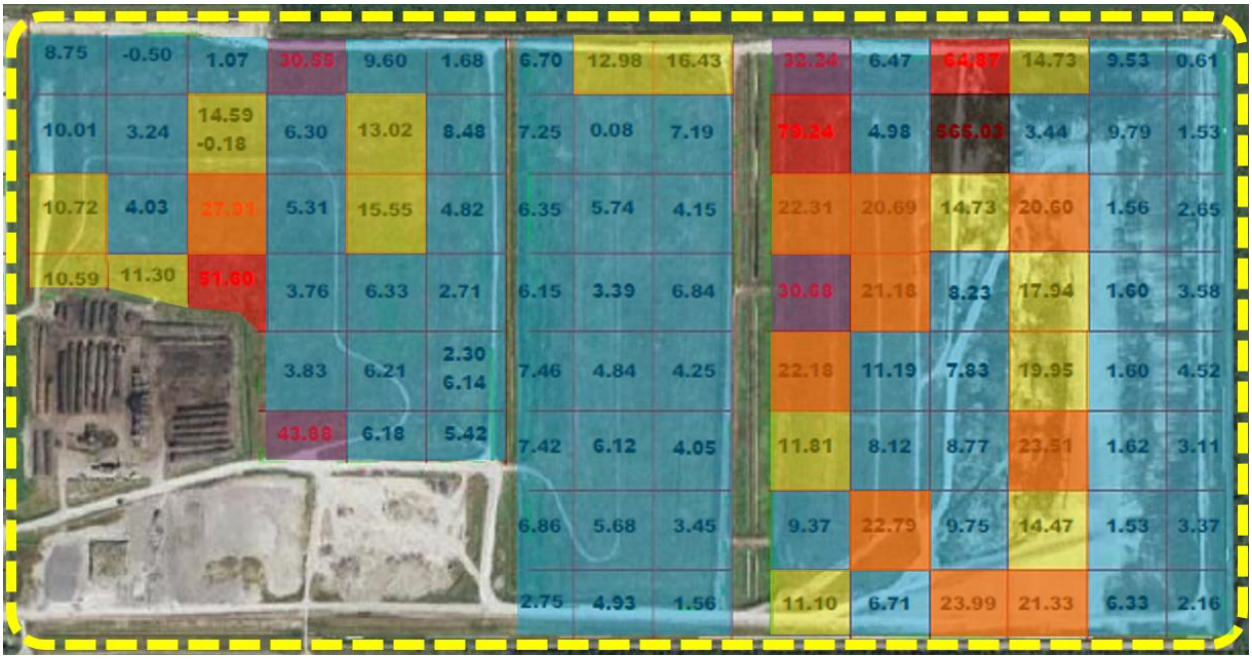


Figure 4.4 Work site divided into 5 different emission zones based on the SMC data
Note: Numbers in the grids represent the average SMC data for that grid

4.4 Flux Chamber

The application of flux chambers in landfills is a well-established method to measure fugitive emissions from a soil surface through isolating and monitoring the emitting gas from soil. This technique has been used in several LFG emission monitoring studies for the measurement of methane emissions from a section of a landfill or to estimate total emissions from an MSW landfill (Eklund, 1992; Mosher et al., 1999; Börjesson et al., 2001; Abichou et al., 2006a; Scheutz et al., 2009; Chanton et al., 2011b). The flux chamber technique includes placing a closed chamber (box) on the landfill surface and monitoring the change of methane concentration in the box over time. The rate of change in methane concentration in the chamber with time ($\Delta C/\Delta t$), chamber volume (V), and area (A) results in the methane flux emitted from landfill's surface (Spokas et al., 2006).

$$\text{Methane flux} = V/A \times (\Delta C/\Delta t) \qquad \textbf{Equation 4.1}$$

4.4.1 Dynamic and Static Flux Chambers

There are two general groups of flux chambers known as dynamic and static chambers. A dynamic flux chamber utilizes a carrier gas (sweep air) that is directed through the chamber through an inlet and outlet pipe. Samples are then acquired from the outlet pipe, or directly from a sampling port, and the change in methane concentrations is used to calculate methane flux from the landfill surface to the chamber. It should be noted that the dynamic flux chamber method requires perfect sealing of the chamber edges. This time consuming step of the test is usually completed using a penetrated collar installed on the landfill surface (to which the chamber

connects) or the application of a bentonite seal around the chamber after placement at the point(s) of interest. Because of the complete isolation applied, the gas emissions from the landfill surface entering the chamber may cause pressure build-up within the chamber, which could result in a reduction in methane flux, and thus inaccurate readings. Therefore, this method uses a pressure gauge to monitor the pressure within the chamber and ensure it is equal to the ambient pressure levels by adjusting the sweep air flow rate. It is also usually recommended to use a fan inside the chamber in order to provide enough mixing of the gas before it is sampled. However, depending on the dimensions and design of the chamber, simply directing the air flow through the chamber may provide enough turbulence and mixing.

The second type of flux chamber is known as static flux chamber. The static flux chamber method does not involve the use of a carrier gas. Instead, a small hole in the chamber's body is used to ensure that the pressure inside the chamber is maintained at atmospheric pressure levels. While it is recommended that the chamber be slightly pushed/penetrated into the soil, this method does not require the use of sealant for complete isolation. A fan is recommended inside the chamber to provide the necessary mixing of the gases. A portable gas analyzer can be used on site to measure real-time concentration of the gas of interest. Alternatively, gas samples could be stored in glass vials, Tedlar® bags, or steel canisters to be later analyzed in the laboratory.

The static flux chamber method can be completed in a matter of minutes. Consequently, it offers a relatively low-cost and low-tech solution for measurement of methane emission rates (MER) at MSW landfills. This has increased the attractiveness and popularity of the flux chamber

technique over other alternative fugitive emission measurement techniques. However, unlike air born techniques such as US-EPA's OTM-10, it is possible that the flux chamber method underestimates the level of emissions due to possible leaks from cracks, the LFG collection system piping, and other infrastructure flaws. Studies comparing these two methodologies are scarce, but available investigations have shown that the total fugitive CH_4 emission flux measured by the flux chamber technique at MSW landfills represents approximately 66% of the total actual emissions at the site (Chanton, 2011). Therefore, in order to avoid underestimating actual methane emission levels at the work site, an emission correction factor (CF_E) of CF_E = 1.52 was applied to the result of the flux chamber field work conducted at VLF.

4.4.2 Field Work Procedure

The accuracy and reliability of fugitive emission measurement studies using the flux chamber technique depend on the number of tests (flux chambers) conducted in the area of interest (Klenbusch, 1986). The guideline originally developed by the US-EPA for *"measurement of gaseous emission rates from land surfaces using an emission isolation flux chamber"* (EPA/600/8-86/008) is commonly used world-wide to define the required number of flux chamber tests based on the footprint area of the site of interest. This guideline suggests that, as a first step, the work site be divided into different zones based on the expected level of emissions. This initial "zoning" is suggested to maximize the between-zone variability while minimizing the within-zone variability in emission results (Klenbusch, 1986). Zoning can be done based on visual observations (e.g. poor vs. rich vegetation), physical properties (e.g. cover type), and design features (e.g. side slopes, crest, roads, etc.). Alternatively, if possible, results of a

preliminary site survey, similar to what was previously explained in Section 4.3, can be used to define different zones in the study site.

The next step is to determine the sample size (the required number of flux measurements) for each zone based on its size (area). The US-EPA guideline's methodology to select the sample size is based on achieving a 95% confidence that the estimated emission rates are within 20% of the true value (Klenbusch, 1986). This methodology suggests the following equation used to calculate the total number of flux measurements (n) based on each zone's footprint area:

$$n_i = 6 + 0.15 \times \sqrt{A_i}$$ **Equation 4.2**

where: n_i = sample size (required number of flux measurements) in zone i to estimate methane emission rate from that zone with 95% confidence that the results are within 20% of the true value, and

A_i (m^2) = footprint area of the zone i

Furthermore, the guideline suggests that the zones with footprint area between 0.4 ha and 3.2 ha be divided into 160 units (sub-grids), and flux measurements be randomly distributed within these units.

4.4.3 Modified Static Flux Chamber Measurements at VLF

During the course of the present study, a static flux chamber was built and used to quantify methane emission rates (MER) from the different phases of VLF. The 100 mm tall chamber was

built using a 300 mm (12″) Diameter plexiglass cylinder with sharpened edges, allowing for easy penetration into the soil, as well as a plexiglass top. The chamber was equipped with a temperature probe port which was also used as a pressure relief port at the time of chamber placement on landfill's surface. Two 1/4″ NPT quick-connect ports were also used for air recirculation and gas sampling. A portable LFG analyzer, Landtec GEM™ 2000+ was paired with the flux chamber. Connecting the inlet and outlet tubes of the GEM™ 2000+ to the chamber allowed for continuous monitoring of methane concentration at ± 0.1% resolution, while also allowing mixing of the gas inside the chamber at the same time. The temperature probe linked to the GEM™ 2000+ instrument to monitor internal gas temperature ensures that methane density is adjusted for the actual temperature at the time of sampling. Figure 4.5 shows the flux chamber test set-up built and used in this study.

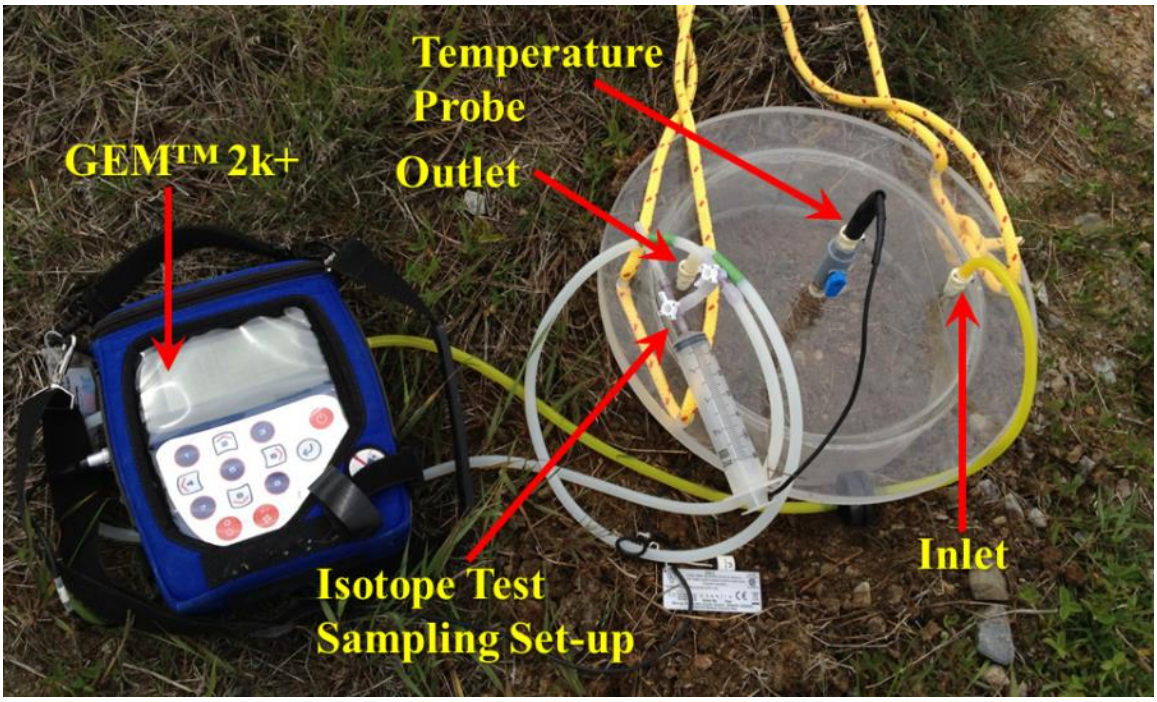


Figure 4.5 Flux Chamber and GEM™ 2000+ set-up

The sensitivity of the conventional flux chamber technique depends on the detection limit of the analytical method used in the test (Klenbusch, 1986). However, because the main purpose of the flux measurements in the present study was to find a correlation with the SMC data, it was preferred to deploy a portable and much quicker instrument (i.e. GEM™ 2000+) with relatively less sensitive measurements. With a maximum flux chamber test duration of 10 to 30 minutes, and the chamber volume of V = 0.007 m^3, as well as the gas analyzer sensitivity of ± 0.1% CH_4, the method overall detection limit was determined to be in the order of 3 to 10 g CH_4 m^{-2} d^{-1}.

Approximately 23 to 30 hectares of each defined emission zone at VLF were selected for flux chamber testing. This included 3 grids from each zone (15 grids in total), plus 1 grid from the "western 40" area of the Vancouver Landfill (Grid #11, with no LFG collection system in place) and 1 grid in Phase 1 with "suspiciously" high SMC results. The total footprint area of the selected grids was approximately 16 hectares, about 19% of the total footprint within the boundary of the study. Even though the within-zone variability was minimized by the preliminary SMC field survey, the distribution of the selected grids within each zone was set so that different possible features (e.g. access road, toe ditch, sloped vs. flat surfaces, vegetated vs. non-vegetated area, etc.) were included in the selected areas for the flux chamber survey. The minimum required number of flux measurements for each zone was determined based on Equation 4.2. Furthermore, in order to increase the accuracy of the flux chamber measurement results, instead of randomly distributing the sampling point over the entire area of each zone, all visually observable features would be sampled. For instance, if 10 flux measurements were to be made in a grid with total area consisting of 10% road, 60% side slope and 30% crest, total number of tests conducted in these three features were 1, 6 and 3, respectively. In some cases,

the total number of tests was increased to ensure that the distribution of the sampling locations in the zone of the interest resulted in estimates best representing the actual emissions in that zone. Figure 4.6 and Table 4.2 below present information about the selected grids, areas and number of flux measurements conducted.

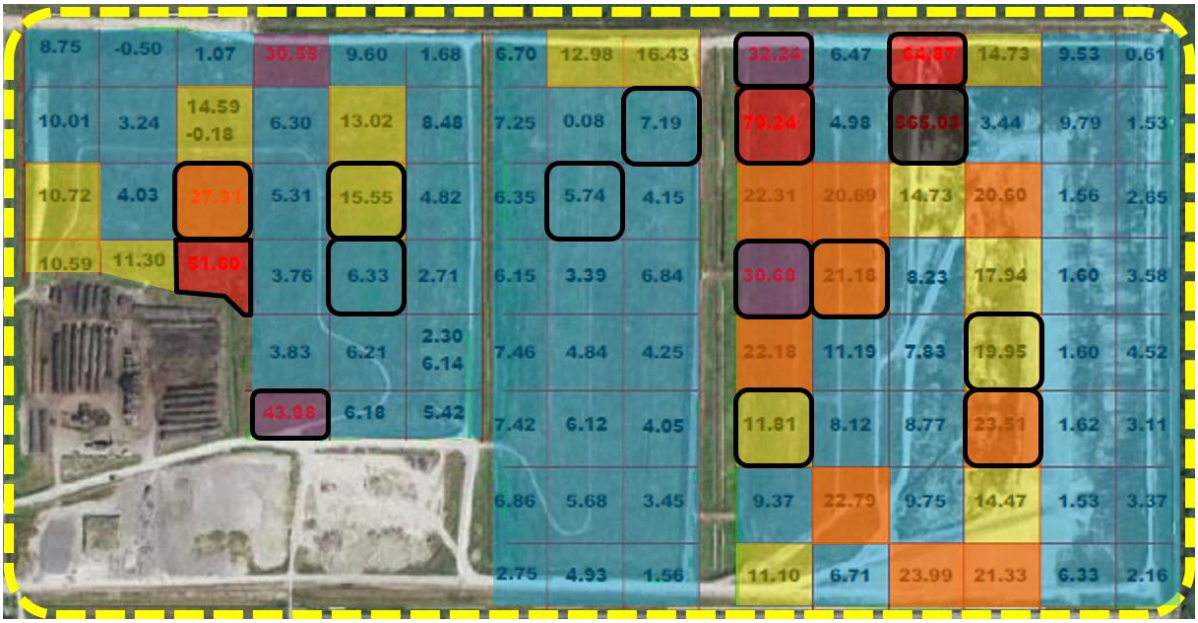


Figure 4.6 Selected grids within the study boundary for flux chamber measurements at VLF
Note: Selected grids are shown with black border lines. Numbers are avg. SMC data

Table 4.2 Selected grids for flux chamber test at VLF

	Emission Zones	Selected Grid IDs	Footprint Area (m^2)	Number of Flux Measurements (n)	
				Required	Conducted
	Zone 1	113, 135, 139	30,000	32	30
	Zone 2	112, 151, 173	30,000	32	38
	Zone 3	102, 158, 172	30,000	32	39
	Zone 4	104, 146, 149	23,000	28	30
	Zone 5	103, 147, 162	26,000	30	30
	Others	11, 163	20,000	27	22
Total			**159,000**	**181**	**189**

A total of 189 flux chamber measurements were conducted in approximately six weeks, between June and July 2012. Depending on the rate of emissions at the sampling location, the duration of each chamber test was between 5 and 30 minutes. Where methane emissions were detected, methane concentration readings were plotted against time to calculate the rate of change in methane concentration over time ($\Delta C/\Delta t$). Figure 4.7 below illustrates an example of recorded methane concentration levels increasing over time. A graphical presentation of the entire flux chamber field readings are presented in Appendix D.1.

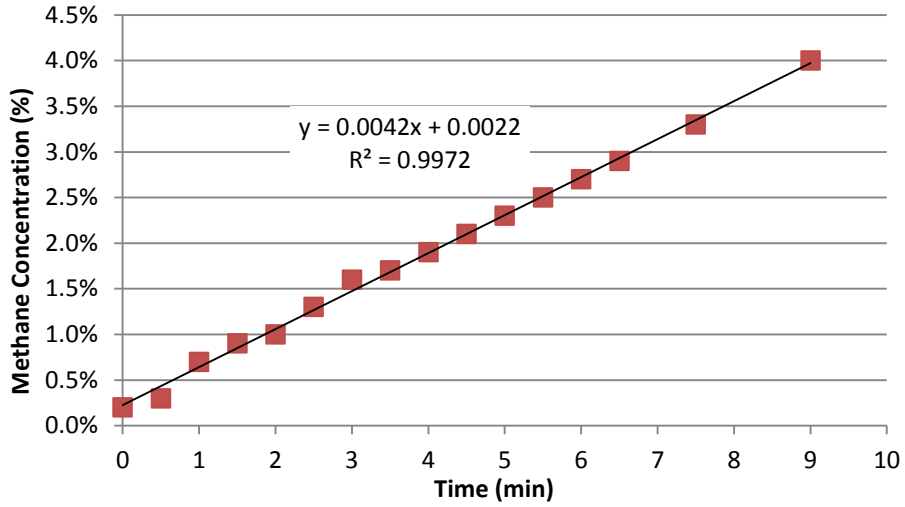


Figure 4.7 Example of recorded methane concentration levels inside the flux chamber increasing over time

The rate of change in methane concentration was then translated to methane emission rate (MER, g CH_4 m^{-2} d^{-1}) using the following equation:

$$MER\ (g\ CH_4\ m^{-2}\ d^{-1}) = V/A \times (\Delta C/\Delta t) \times \rho \qquad \textbf{Equation 4.3}$$

Where: MER = methane emission rate (methane flux)

V = chamber volume (~ 0.007 m^3 depending on chamber penetration depth)

A = landfill's surface covered by chamber (0.07 m^2)

($\Delta C/\Delta t$) = rate of change in methane concentration within chamber

ρ = methane density at the measured temperature within chamber (~ 680 – 710 g m^{-3})

Out of the 189 flux chamber measurements, only about 60 non-zero readings were acquired and the rest were classified as no emission or below detection limit (BDL). The measured non-zero MER ranged between 17 and 4,709 g CH_4 m^{-2} d^{-1} and are presented in the Appendix D.2. Table 4.3 presents a summary of results for each grid compared with SMC data.

Table 4.3 Summary of MER resulted from the flux chamber survey at selected grids at VLF

#	Emission Zones	Location at VLF	Grid Number	SMC (ppmv)	MER (g m^{-2} day^{-1})	Note
1	Other	West 40	11	52.6	19.5	
2	Zone 3	Area 2W	102	14.0	6.6	
3	Zone 5	Area 2W	103	25.8	9.8	
4*	Zone 4	Area 2W	104	22.0	4.2	Very Steep Slope
5	Zone 2	Area 2W	112	7.8	3.5	
6	Zone 1	Area 2W	113	3.9	2.8	
7	Zone 1	Area 2E	135	3.6	0.7	
8	Zone 1	Area 2E	139	3.6	2.4	
9	Zone 4	Area 3	146	16.1	5.5	
10	Zone 5	Area 3	147	39.6	12.5	
11	Zone 4	Area 3	149	15.3	3.8	
12	Zone 2	Area 3	151	5.9	4.9	
13	Zone 3	Area 3	158	10.6	8.3	
14*	Zone 5	Phase 1	162	29.7	2.0	Toe Ditch was not accessible
15*	Other	Phase 1	163	258.8	46.2	open LFG well increased SMC results
16*	Zone 3	Phase 1	172	10.8	0.0	New layer of soil cover was placed before Flux Chamber Test started
17*	Zone 2	Phase 1	173	9.1	0.0	

* these grids were excluded from data analysis due to unreliable flux chamber survey conditions as noted above

4.5 Effect of Barometric Pressure on Methane Emission Rates

Variations in the weather conditions, and in particular the barometric pressure (BP), has an impact on rate of methane fugitive emissions from landfill's surface (Prosser, 1985; Young, 1990; Poulsen et al., 2003; Scharff et al., 2003; Gebert and Groengroeft, 2006). Higher emission rates at landfills are reported to occur at lower ambient pressures (Scharff et al., 2003; Gebert and Groengroeft, 2006). In general, variations in atmospheric pressure happen due to several factors including; (i) auto oscillation of air (reported to have an insignificant effect) , (ii) daily warming and cooling of air caused by solarization (causing diurnal variations), and (iii) passage of atmospheric pressure lows and highs (leading to long term variations). Therefore, short term (daily) and long term (seasonal) variations in atmospheric pressure should be taken into account when conducting methane fugitive emission measurements at a landfill site (Poulsen et al., 2003).

Young (1990), in a comprehensive study, showed that the rate of change in atmospheric pressure, and not the pressure itself, controls the gas flux intensity. That is perhaps due to the transient effect of gas storage in landfill void spaces, such that if the BP remains constant at a certain level the landfill pressure will reach an equilibrium state and the emission flux will reach a true value driven by the LFG generation rates.

In order to study and incorporate the effect of barometric pressure variations on methane emission rates at VLF, a HOBO® Smart Barometric Pressure data logger was installed at the site. The BP and ambient temperature (T) variations were recorded at high resolution (every 10

minutes) during the initial landfill surface scan, as well as at the time of the flux measurement field work. Figure 4.8 illustrates these records for one day as an example.

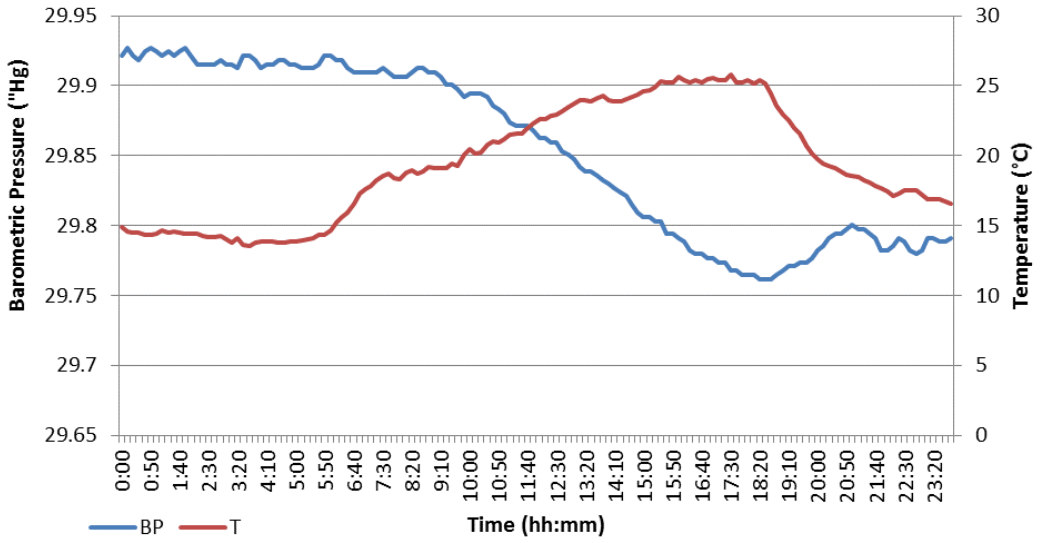


Figure 4.8 Recorded barometric pressure and temperature at the Vancouver Landfill (July 16, 2012)

As shown in the following Figure 4.9 and Figure 4.10, the recorded BP values were plotted against time, and the rate of change in atmospheric pressure (ΔP/t) at the time of conducting the field work was calculated. Depending on variations in the weather conditions at the time of flux measurement, ΔP/t could have a positive or negative value recorded in millibars per hour (mbar/hr). Graphical presentations of the recorded BP and the rate of change during emission sampling (ΔP/t) are presented in Appendix D.3.

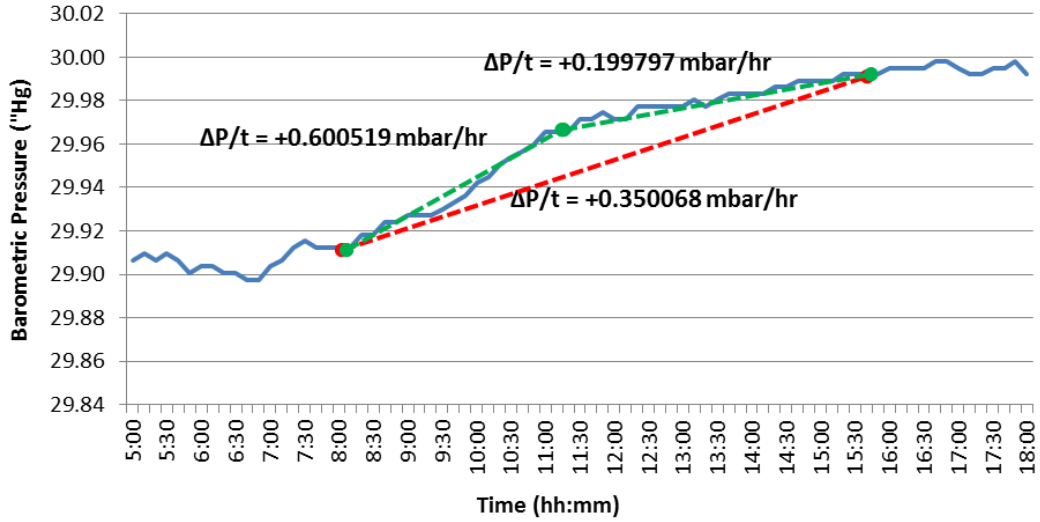


Figure 4.9 Barometric pressure at the Vancouver Landfill (June 26, 2012)

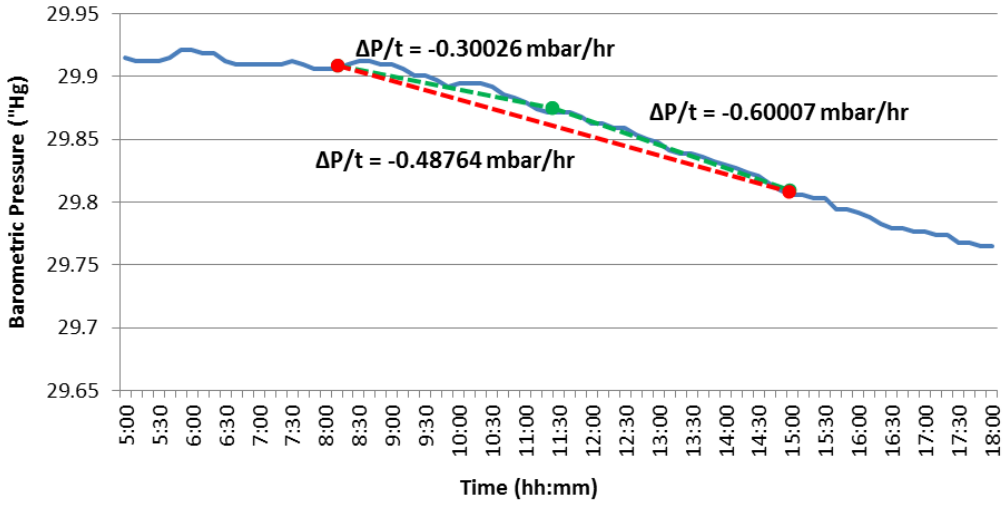


Figure 4.10 Barometric pressure at Vancouver Landfill (July 16, 2012)

The accuracy of the measured MER would depend on the sign and the magnitude of ΔP/t, with an underestimated MER(s) for positive ΔP/t and overestimated MER(s) for negative ΔP/t. In order to evaluate the accuracy of the measured MER(s), as well as to study how the magnitude of the ΔP/t would affect the recorded MER(s), two sets of duplicate flux measurements were

conducted during this part of the field work. The first set included replicates of the flux measurement at the same location and same time. Ideally, these duplicates should have resulted in the same MER for both runs of the measurements. Results showed a relative standard deviation (RDS) (also known as coefficient of variation (CV)) of between 0.2% and 7.8%, confirming the accuracy of the measurement technique. Table 4.4 below summarizes the results of the first set of flux measurement duplicates.

Table 4.4 Flux measurement duplicates for accuracy of the test

Chamber ID		#71	#56	#35	#48
ΔP/t (mbar/hr)		- 0.488	+ 0.601	- 0.138	- 0.067
MER ($g\ CH_4\ m^2\ d^{-1}$)	Run#1	388.80	204.52	4709.27	796.75
	Run#2	361.03	185.04	4698.58	890.00
Mean		374.9	194.8	4703.9	843.4
StDev		19.6	13.8	7.6	65.9
%CV		**5.2%**	**7.1%**	**0.2%**	**7.8%**

The second set of flux measurement duplicates included repeats of the test at the same locations but on a different day for each run. Therefore, for each of these locations (flux measurements) two MER values were developed, each subject to a different value of ΔP/t. The difference between the two recorded ΔP/t (i.e. $|R_{\Delta P}| = |(\Delta P/t)_1 - (\Delta P/t)_2|$) values were plotted against the magnitude of the difference between the two MER values (i.e. $|\Delta_{MER}| = |MER_2 - MER_1)/MER_1|$), resulting in a very good correlation between the absolute values of $R_{\Delta P}$ and Δ_{MER} with a coefficient of determination of $R^2 = 0.92$. Figure 4.11 shows this correlation illustrating the extent of drift in measured MER from the true value based on the magnitude of the ΔP/t at the time of the field measurement.

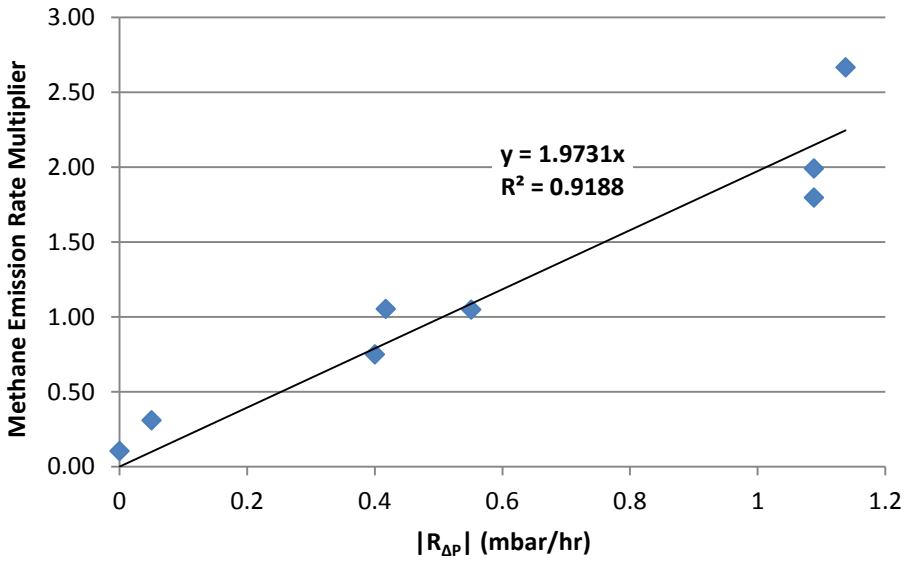


Figure 4.11 Correlation between rate of change in BP and adjusting multiplier for MER

The true value of MER at the landfill could be measured when the atmospheric pressure remained constant, causing an equilibrium condition between landfill and the surrounding environment. Therefore, all measured MER values were adjusted to the true values (MER_a) based on the recorded $\Delta P/t$ at the time of sampling relative to the equalized condition (i.e. $\Delta P/t = 0$).

Therefore, when;

(i) $\Delta P/t > 0 \rightarrow R_{\Delta P} > 0$ and $MER_a > MER$

Based on the developed correlation, for $R_{\Delta P} > 0$:

$$(MER_a - MER) / MER = 1.9731 \times R_{\Delta P}$$ **Equation 4.4**

hence;

$MER_a = MER \times (1 + 1.9731 \times \Delta P/t)$ (for $\Delta P/t > 0$) **Equation 4.5**

where; MER_a = adjusted methane emission rate (g CH_4 m^2 d^{-1})

MER = measured methane emission rate via flux chamber (g CH_4 m^2 d^{-1})

$\Delta P/t$ = rate of change in barometric pressure at the time of flux measurement (mbar/hr)

When the atmospheric pressure at the time of sampling exhibited a declining trend (i.e. $\Delta P/t < 0$), the measured MER was overestimated. That meant;

(ii) $\Delta P/t < 0 \rightarrow R_{\Delta P} < 0$ and $MER_a < MER$

therefore;

$(MER - MER_a) / MER = 1.9731 \times |R_{\Delta P}|$ **Equation 4.6**

hence;

$MER_a = MER / (1 + 1.9731 \times |\Delta P/t|)$ (for $\Delta P/t < 0$) **Equation 4.7**

By combining Equations 4.5 and 4.7, the following equations were developed to calculate the adjusted MER (MER_a) based on the magnitude and sign of the rate of change in atmospheric pressure at the time of flux measurements.

$MER_a = MER \times (1 + 1.9731 \times |\Delta P/t|)^{\wedge (\Delta P/t \,/|\Delta P/t|)}$ **Equation 4.8**

where ($\Delta P/t \,/|\Delta P/t|$) would be equal to (-1) or (+1), represent the sign of the $\Delta P/t$.

Accordingly, all the flux measurement results were adjusted for the variations of the atmospheric pressure. Similar adjustments were made to the average SMC values for each measurement grid.

4.6 Results and Discussion

Methane emission rates have been reported in several similar studies to span a wide range, depending on landfill type, waste age, cover soil type, climatic conditions etc. Bogner and Spokas (1993), reported emission rates of between 319 and 1,896 g CH_4 m^{-2} d^{-1}. Chanton and Liptay (2000), reported emission rates of about 0 to 200 g CH_4 m^{-2} d^{-1} in topsoil and 0 to 9,000 g CH_4 m^{-2} d^{-1} in clay.

In the present study, flux chamber measurements showed methane emission rates varying between 0 and 4,709 g CH_4 m^{-2} d^{-1}. Most of the emissions were observed on side slopes and areas closer to the toe of closure phases. Out of a total of 17 grids initially selected at VLF for methane flux measurements, 5 grids were excluded from the data compilation and analyses (due to reasons noted in Table 4.3). Therefore, only 12 grids were deemed to have developed representative results and qualified to be compared with the surface methane concentration survey.

The average MER_a for the five defined emission zones at VLF ranged from 1.96±1.12 g CH_4 m^2 d^{-1} to 11.14±1.87 g CH_4 m^2 d^{-1}, relative to the SMC_a values, which ranged between 3.70±0.21 ppmv and 32.70±9.77 ppmv CH_4, respectively. Table 4.5 shows the average MER_a, as well as the adjusted SMC_a values for each emission zone.

Table 4.5 Methane flux measurement results and SMC_a data for each emission zone

Zones	SMC_a [CH_4] (ppmv)	MER_a (g CH_4 m^{-2} day^{-1})
Zone 1	3.70 ± 0.21	1.96 ± 1.12
Zone 2	6.84 ± 1.32	4.22 ± 0.98
Zone 3	12.27 ± 2.38	7.44 ± 1.16
Zone 4	15.73 ± 0.55	4.67 ± 1.22
Zone 5	32.70 ± 9.77	11.14 ± 1.87
Grid#11	52.59	19.48

The average MER_a for these grids ranged from 0.7 to 19.5 g CH_4 m^2 d^{-1}, relative to the SMC_a values, which ranged between 3.57 and 52.59 ppmv CH_4, respectively. Figure 4.12 illustrates the methane flux and methane concentration for the 12 grids (approximately 11.4 ha) at VLF.

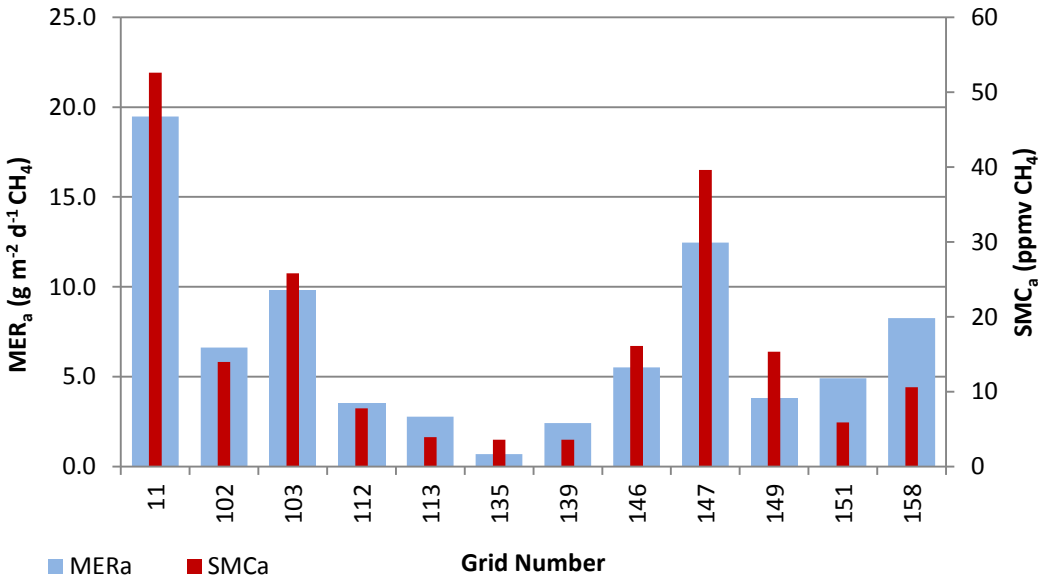


Figure 4.12 Averaged surface methane concentration (SMCa) and methane emission rate (MERa) for 12 measurement grids at VLF

As shown Figure 4.13, plotting the SMC_a data against the MER_a values showed a reasonable correlation between the measured methane fluxes and the qualitative methane concentrations. This correlation appears to be better at higher values.

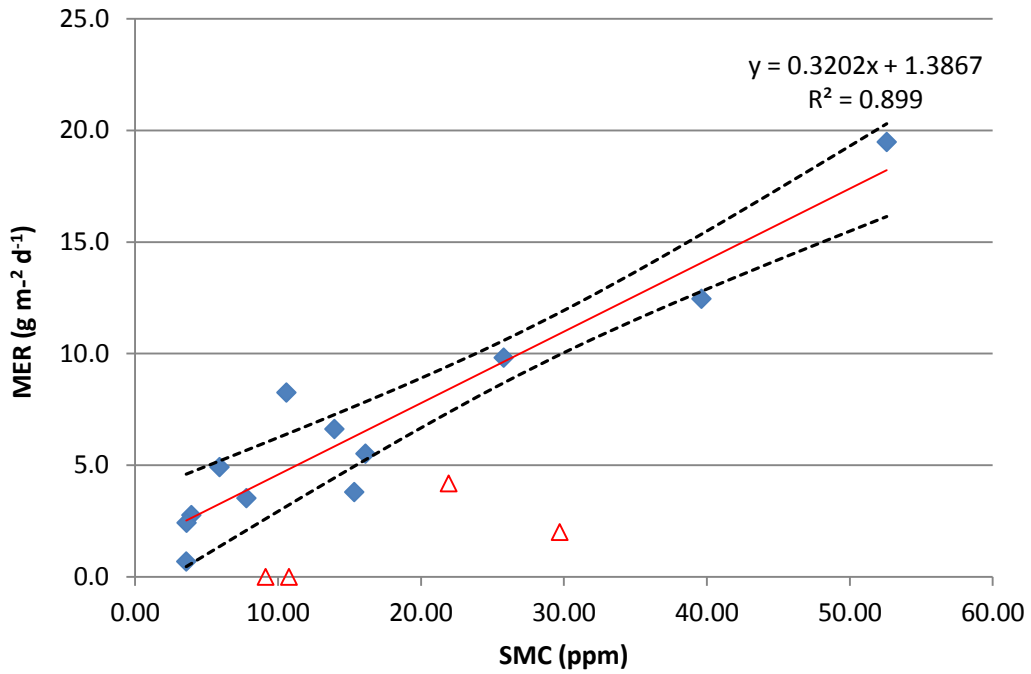


Figure 4.13 Correlation between SMC and MER values developed over 12 measurement grids at the VLF

Data points shown in Figure 4.13 with Δ represent the invalid data which were excluded from the analysis for the reasons previously noted in Table 4.3. Furthermore, the error of this developed linear regression was examined and the standard errors of the slope and y-intercept of the regression line were calculated at 95% confidence limit. Results of the error analysis are reflected in Table 4.6.

Based on this correlation;

$$MER = SMC \times (0.32 \pm 0.034) + (1.39 \pm 0.755)$$ **Equation 4.9**

where; MER = methane emission rate (g CH_4 m^2 d^{-1})

SMC = surface methane concentration (ppmv CH_4)

The development of this correlation can be practically very important in the LFG management industry, saving time and money when full scale fugitive methane emission measurements are required. This correlation may be applicable in other landfills, however, it is recommended that it be re-developed or checked for landfills with different conditions. Depending on the size of each emission zone in a particular landfill, approximately 10 to 15 flux chamber tests per hectare will be required along with a full scale SMC scan. This correlation, once developed, would allow for a quick calculation of total landfill emission through a simple methane concentration scan at the surface of any MSW landfill.

4.7 Total Fugitive Methane Emission from the Vancouver Landfill

The Equation 4.10 presented below was developed to quantify the total methane emissions within the boundary of the study (E). This equation includes all of the above mentioned findings and assumptions, where the measured SMC data would be adjusted for the effect of the barometric pressure rate of change at the time of sampling and translated to the total methane flux based on the developed correlation, as well as the total area under the study. As discussed in Section 4.4.1, the emission correction factor was also applied to account for underestimations associated with flux measurements using flux chamber technique.

$$\mathbf{E} = \mathbf{CF_E} \times \sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{A_i} \times (\mathbf{SMC_i} \times \mathbf{0.32} + \mathbf{1.39}) \times \mathbf{3.65} \times \mathbf{10^{-4}}$$ **Equation 4.10**

Where: E = total annual methane emission from each area (tonnes/year)

CF_E = 1.52, emission correction factor for flux chamber method (Chanton, 2011)

A_i = grid footprint area (m^2)

SMC_i = average surface methane concentration for each grid (ppmv CH_4)

3.65×10^{-4} = unit conversion multiplier

The sum of grid emissions from each area/phase at VLF are summarized in Table 4.6, reported as the total fugitive methane emissions from that area. Results showed that the total average methane emission from Area 2W, Area 2E, Area 3, and Phase 1 of the VLF in the year of the study were 466, 252, 367, and 396 tonnes methane $year^{-1}$, respectively. These results along with other field work results are utilized to calibrate the new model as presented in Chapter 7.

Fugitive methane emission results for all 102 grids of the VLF are provided in Appendix D.4.

Table 4.6 Total fugitive methane emissions from each area of the VLF

Area/ Phase	Number of Grids	Total Footprint Area (m^2)	Total CH_4 Emissions (tonnes $year^{-1}$)	
			(E)	St. Dev. (ΔE)
Area 2W	30	259,700	**466**	**± 137**
Area 2E	24	189,010	**252**	**± 90**
Area 3	16	140,550	**367**	**± 86**
Phase 1	32	242,261	**396**	**± 118**
Total	**102**	**831,521**	**1,481**	**± 431**

Chapter 5: Methane Oxidation in Cover Soil (O)

5.1 Introduction

Methane oxidation in landfill cover soil reduces GHG emissions from landfills, and in some cases even reduces the atmospheric methane concentration (Hilger and Barlaz, 2007). A number of studies have reported methane oxidation fractions through landfill cover soil at 22% to 55% (Whalen et al., 1990; Chanton et al., 2009; Chanton et al., 2011b). Scharff et al. (2003), in a comprehensive study on four Dutch landfills with similar climatic conditions to those of Vancouver, measured the methane oxidation fraction at about 20% to 40%. USEPA (2004), also reported an average methane oxidation fraction of 10 to 25% with lower values for clay cover soils and higher rates for topsoil. However, due to the challenges of accurately measuring methane oxidation and lack of standard quantifying methods, they recommended a default value of 10% (USEPA, 2004). Despite recent findings, the IPCC has not deviated from the default values of 0-10% proposed in 1995 (Mahieu et al., 2006; Chanton et al., 2009).

Results of recent studies using more advanced methodologies have proven the effectiveness of methanotrophic bacteria in mitigating fugitive methane emissions from landfills (Powelson et al., 2006; Huber-Humer et al., 2008; Bogner et al., 2010; Chanton et al., 2011a). These advanced methodologies allow more accurate measurements of the amount of methane oxidization in landfill cover soil, another essential element in the METRO equation required for iModel-110© calibration. One of the advanced methodologies for quantification of methane oxidation rate is the stable isotope technique. This technique is based upon the preference of methanotrophic bacteria to consume lighter isotope methane ($^{12}CH_4$) over heavier isotope methane ($^{13}CH_4$),

resulting in a shift in isotopic composition of the LFG methane as it passes through landfill cover soil and is partially oxidized (Silverman and Oyama, 1968).

The field investigations described in this chapter were conducted to quantify methane oxidation (O) naturally occurring at the work site. The stable isotope technique, paired with the flux chamber measurements described in the previous chapter, were conducted at each area of the Vancouver Landfill and methane oxidation rates (in g CH_4 m^{2-} d^{-1}) were quantified for the two different types of cover soils within the study boundaries. Other useful outputs of this portion of the study included: (i) measurement of the isotopic signature of anaerobic methane in different areas/phases of VLF, (ii) development of isotopic fractionation factor for methane oxidation for each soil type, (iii) and investigations on the effects of soil moisture content and temperature on oxidation isotopic fraction factor.

5.2 Characteristics of Cover Soils at the Vancouver Landfill

For this part of the study, the operational sub-areas/phases of VLF were grouped into two major areas of "Area A" and "Area B". Half of Area A, which included Phase 1 of VLF, was covered by geomembrane cap and the other half with till as an interim cover with no or very poor vegetation. This area had active gas collection with system vacuum of 25 to 35 inches of water column (w.c.). Area B, which consisted of Area 2W, Area 2E, and Area 3, contained older municipal waste and was covered by organically modified till and a vegetation layer. This area also had an active gas collection system applying approximately 5 to 15 inches w.c. of vacuum.

The moisture and organic content of the cover soil samples, collected from Areas A and B, were determined following the "ASTM D2974 – 07a" standard test methods. The organic content of the cover soil in Area A was in the range of 1.5 to 2.2%, with field moisture contents of 7.8 to 9.7% (samples collected in early August and tested on the same day). Soil samples from Area B had organic contents between 5.4% and 6.8% and field moisture contents between 7.1% and 11.8%. Sample no.6 from Area B had a lower organic content of 3% and moisture content of 4.1%. This sample was collected from an area which appeared to be a new layer of impermeable soil placed on top of the old soil cover, and it was not believed to represent the whole area, hence was excluded from the final analysis. Results of the soil characteristics tests are presented in Section 5.4, Table 5.1.

5.3 Stable Isotope Technique

The stable isotope technique is based upon the preference of methanotrophic bacteria to consume lighter isotope methane ($^{12}CH_4$) over heavier isotope methane ($^{13}CH_4$) resulting in a shift in isotopic composition of the LFG methane as it passes through landfill cover soil and is partially oxidized (Silverman and Oyama, 1968). Isotope quantification was accomplished using a GCC-IRMS (Finnegan Mat Delta V-gas chromatograph combustion isotope ratio mass spectrometer) as described by Popp et al. (1995).

Mahieu et al. (2006) and De Visscher et al. (2004), suggested that the stable isotope technique is a conservative approach to quantify methane oxidation rates. Underestimation of methane oxidation using the stable isotope technique is partly due to the fact that in some areas of MSW landfills no trace of the isotope and enrichment of methane in ^{13}C isotope content can be

measured due to the complete oxidation of methane in those areas. Another reason for it being considered conservative would be the isotope fractionation effect due to mass transfer (transport fractionation) which is normally disregarded. The transport fractionation effect can be correctly ignored in landfills with no active gas collection system (De Visscher et al., 2004).

During the course of the flux chamber field work, gas samples from the chamber were taken from one third of the non-zero chamber measurements, previously discussed and shown in Appendices D.1 and D.2. Based on the test procedure suggested by Chanton et al. (2011b), initial and final isotope samples were obtained during the flux chamber tests. These data are presented in Appendix E.1. Furthermore, a total number of ten methane samples from anaerobic zones of the landfill were collected directly from the gas collection system manifolds of each area/phase. Gas samples from the flux chamber and manifolds were acquired using 60 mL disposable syringes and immediately injected into 30 mL pre-evacuated glass vials. Figure 5.1 below shows the isotope sample acquisition steps.

Figure 5.1 Sampling procedure for the stable isotope tests

The isotope quantification test is an advanced and costly analysis and there are only a few laboratories in North America which are equipped with GCC-IRMS. Therefore, the isotope samples were shipped to the Department of Earth, Ocean and Atmospheric Science of the Florida State University (FSU) in order to quantify the isotope ratio (R_{sample}) of the methane samples (i.e. $^{13}C/^{12}C$). The isotopic signatures of samples were then calculated using Equation 5.1 below (Coleman et al., 1981):

$$\boldsymbol{\delta^{13}C = \left(\frac{R_{sample}}{R_{standard}} - 1\right).1000}\ ‰ \qquad \textbf{Equation 5.1}$$

Where:

$\delta^{13}C$ = isotopic signature reported in parts per thousand (ppt)

R_{sample} = isotope ratio ($^{13}C/^{12}C$) of sampled methane

$R_{standard}$ = $^{13}C/^{12}C$ ratio of the reference standard (PeeDee belemnite (PDB) standard, 0.0112372)[18]

In this methodology, $\delta^{13}C$ value of zero was assigned to the PDB standard which has a relatively high (^{13}C enriched) isotopic signature resulting in negative $\delta^{13}C$ values for most other naturally existing samples. Typical $\delta^{13}C$ values for methane sampled from LFG collection systems (anaerobic methane) are reported to be in the order of -53 to -58‰ ± 1.5‰, with no significant

[18] The common reference for $\delta^{13}C$, the Chicago PDB Marine Carbonate Standard, was obtained from a Cretaceous marine fossil, Belemnitella americana, from the PeeDee formation in South Carolina. This material has a higher $^{13}C/^{12}C$ ratio than nearly all other natural carbon-based substances; for convenience it is assigned a $\delta^{13}C$ value of zero, giving almost all other naturally-occurring samples negative δ values.

seasonal variations (Chanton et al., 1999; Chanton and Liptay, 2000; Börjesson et al., 2001; Chanton et al., 2011b). Chanton et al. (2011b), in a study involving 20 landfills across the U.S., concluded that the isotopic signature of anaerobic methane varied by region with an average value of -57.5 ± 1.5‰ for landfills in humid and cool climate regions.

A total of 38 flux chamber gas samples (residual methane), as well as 10 captured LFG samples (anaerobic methane) were analyzed. Residual methane samples were collected at the start (δ^{13}_i) and end (δ^{13}_f) of each chamber test, both with known methane concentrations, previously shown in Appendices D.1 and D.2. The ^{13}C isotope content of residual methane for each chamber test was then calculated using Equation 5.2 below (Börjesson et al., 2001; Chanton et al., 2011b):

$$\boldsymbol{\delta_R = \frac{(\delta_f \times [CH_4]_f) - (\delta_i \times [CH_4]_i)}{[CH_4]_f - [CH_4]_i}} \qquad \textbf{Equation 5.2}$$

Where:

δ_R = ^{13}C isotope content ($\delta^{13}C$ value) of residual methane

$[CH_4]_i$ = initial methane concentration in the flux chamber

$[CH_4]_f$ = final methane concentration in the flux chamber

δ_i = initial sample's $\delta^{13}C$ of methane

δ_f = final sample's $\delta^{13}C$ of methane

The oxidized fraction of methane at the location of each flux chamber test was then calculated using Equation 5.3 below (Blair et al., 1985; Liptay et al., 1998; Chanton and Liptay, 2000; Börjesson et al., 2001):

$$f_{ox} = \frac{\delta_R - \delta_a}{1000\,(\alpha_{ox} - \alpha_t)}$$ **Equation 5.3**

Where:

f_{ox} = fraction of methane oxidized

δ_a = $\delta^{13}C$ value for methane sampled from anaerobic zone of the landfill

α_{ox} = isotope fractionation factor due to oxidation (see Chapter 5.4)

α_t = isotope fractionation factor due to transport (see Chapter 5.5)

5.4 Oxidation Fractionation Factor (α_{ox})

The oxidation isotope fractionation factor (α_{ox}) defines the preference of methanotrophs in consuming lighter isotope (i.e. $^{12}CH_4$) over heavier isotopes (i.e. $^{13}CH_4$). In fact, α_{ox} is a key factor in quantifying methane oxidation using the stable isotope technique. This parameter has been found to be different in different types of landfill cover soils and varies with seasonal climate change (Chanton and Liptay, 2000; Hilger and Barlaz, 2007; Chanton et al., 2008).

Factors affecting methane oxidation within a landfill cover include soil moisture content, organic content, temperature, and pH (Chanton et al., 1999; Börjesson et al., 2001; Meraz et al., 2003) with temperature being the dominate factor (Czepiel et al., 1996; Chanton et al., 1999). Chanton et al. (1999) and Borjesson et al. (2001), reported the influence of variation in ambient temperature on methane oxidation rate in a landfill final cover. This is due to the effect of ambient temperature fluctuations on rates of enzymatic processes of methanotrophs.

Coleman et al. (1981), reported α_{ox} of 1.025 and 1.013 for 26°C and 11.5°C, respectively. King et al. (1989), observed similar patterns in the relationship between the temperature and isotope fractionation factor. Results of that study were α_{ox} of 1.027 and 1.014 for 14 and 4°C, respectively. Börjesson et al. (2001), determined α_{ox} for two temperatures of 4 and 25°C at two different landfills. The reported values were α_{ox} of 1.0270 ± 0.0039 and 1.0375 ± 0.0003 at 4°C and 1.0234 ± 0.0017 and 1.0281 ± 0.0009 at 25°C, both showing a decline in α_{ox} with a temperature increase. Chanton et al. (2008), also determined average α_{ox} values of 1.022 ± 0.0015 at 25°C that declined as the temperature increased. They showed that over the temperature range of 3°C to 35°C, α_{ox} decreases at a rate of about 0.04% for every 1°C increase in ambient temperature. Chanton and Liptay (2000), also showed that α inversely changed with temperature. While Tyler et al. (1994) showed increase in α_{ox} as a result of increased temperature at rates of 0.00043 to 0.00046/°C.

In the present study, five soil samples of the two different soil types present at VLF were taken and the isotope fractionation factor tests were conducted following the instructions provided by Chanton and Liptay (2000). Soil samples were collected from 10 cm to 15 cm below ground and incubated at two moisture levels of; (i) actual moisture content as collected (field moisture), and (ii) with added moisture. Exactly 100 g of each sample were placed in previously baked-out 1,000 mL Erlenmeyer flasks as shown in Figure 5.2. Flasks were sealed with septum/rubber corks and 50 mL of tank methane gas were injected into each flask, resulting in an initial methane concentration of approximately 4% to 5% (i.e. $[CH_4]_0$). Moisture and organic matter content of each soil sample were measured following ASTM D2974 – 07a standard test methods.

Figure 5.2 Soil sample moisture/organic content and incubation tests

Soil samples, collected from both Areas A and B, were incubated at the two moisture content levels of actual moisture content (field moisture) and increased moisture content. For the isotope fractionation factor test, the majority of the soil incubations were conducted at 25°C with two additional samples tested at 5°C. Soil sample characteristics, as well as the temperature at which each sample was incubated, are summarized in Table 5.1.

Table 5.1 Cover soil samples for incubation

Major Areas	Sample #	ID.	Temperature (°C)	Moisture (%)	Organic content (%)
Area A	1	1a	25	7.7	1.5
		1b	25	10.7	
	2	2a	25	9.7	2.2
Area B	3	3a	25	7.1	6.8
		3b	25	11.8	
	4	4a	5	7.1	6.8
		4b	5	11.8	
	5	5a	25	12.4	5.4
		5b	25	16.0	
	6	6a	25	4.2	3.0
		6b	25	14.0	

Soil incubation was completed within two consecutive days, with several "soil gas samples" collected every 1 to 3 hours, depending on the observed rate of change in concentration. Using a 50 μL gas tight syringe, samples were injected and analyzed with a gas chromatograph-flame ionization detector (GC-FID) to measure methane concentrations. When appropriate, 15 mL of the soil gas samples were injected into 10 mL pre-evacuated glass vials for $\delta^{13}C$ measurements. As shown in Figure 5.3 (a) and (b), standard curves were developed during the test for methane concentrations of more than 1% and less than 1%, respectively. These standard curves were used to convert the FID responses to volumetric methane concentrations. Figure 5.4 shows example snap shots of the chromatograms, visual observation on the screen during the test which assisted collection of the isotope samples in appropriate times.

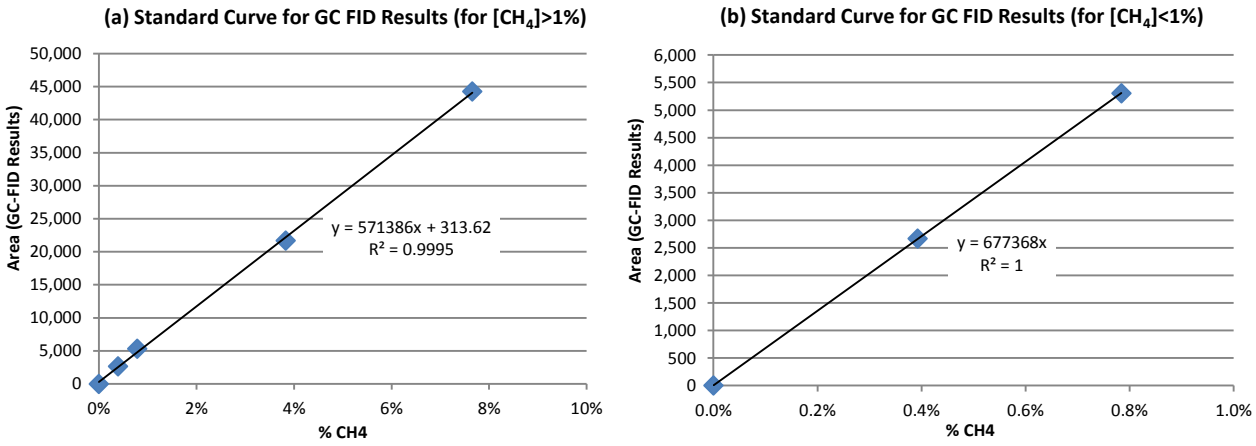


Figure 5.3 Standard curves developed during the GC-FID tests

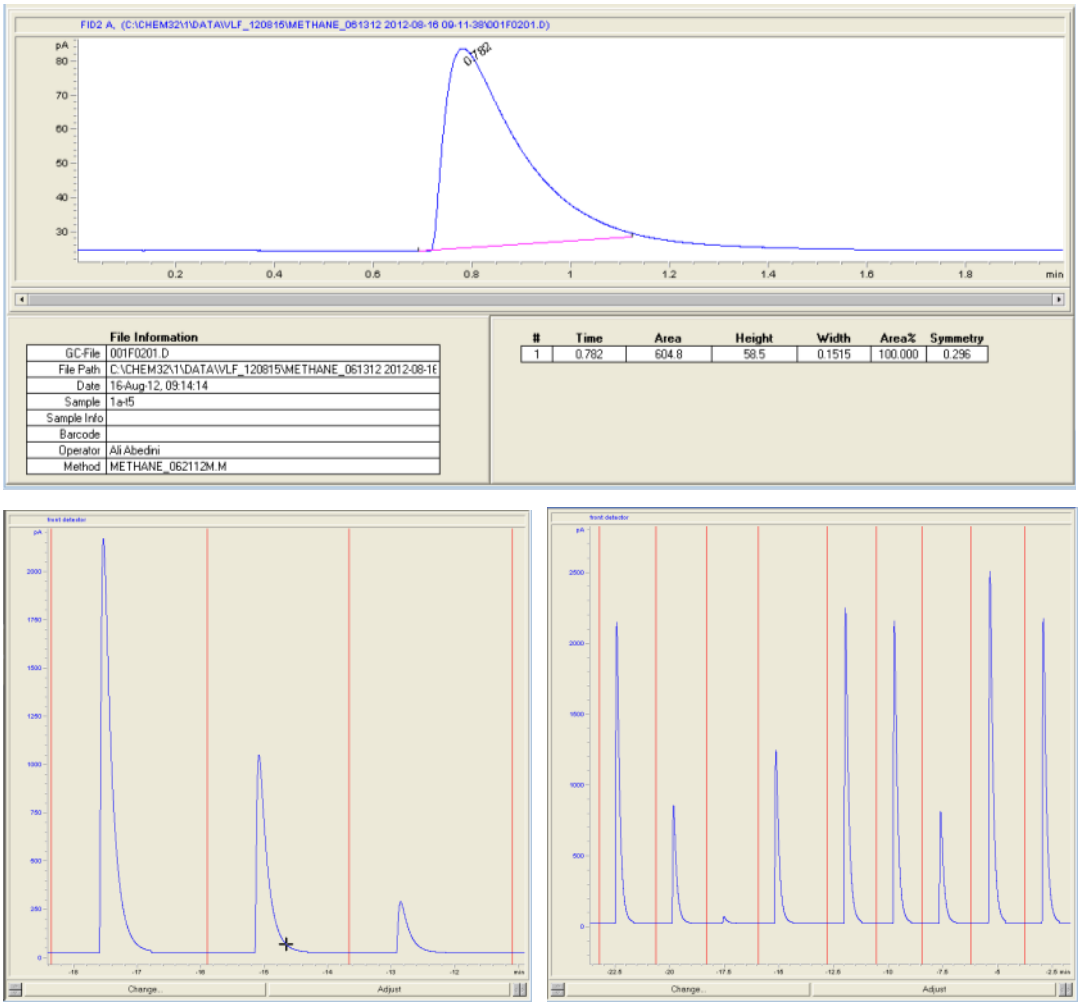


Figure 5.4 A few FID test response snap shots

A total number of 78 soil gas samples with known methane concentrations were prepared and immediately shipped to the FSU for $\delta^{13}C$ levels measurement. From the isotopic signature ($\delta^{13}C$) and the methane concentrations ($[CH_4]$), α_{ox} was calculated using the Rayleigh approach as shown in Equation 5.4 below (De Visscher et al., 2004; Mahieu et al., 2006; Chanton et al., 2008):

$$\frac{\delta^{13}C_t + 1000}{\delta^{13}C_0 + 1000} = \left(\frac{[CH_4]_t}{[CH_4]_0}\right)^{\frac{1-\alpha_{ox}}{\alpha_{ox}}} \qquad \textbf{Equation 5.4}$$

Where:

$\delta^{13}C_t$ = ^{13}C isotope content of enriched methane in soil incubation test in time t

$\delta^{13}C_0$ = ^{13}C isotope content of methane at the beginning of test (t=0)

$[CH_4]_t$ = methane concentration in incubation flask at time t

$[CH_4]_0$ = initial methane concentration in incubation flask (t=0)

5.5 Transport Fractionation Factor (α_t)

The transport fractionation factor (α_t) defines magnitude of the isotopic fractionation due to methane transport mechanism in landfill cover, advection vs. diffusion. Several similar studies have adopted the value of 1 for the transport isotope fractionation factor, suggesting that gas transport across the cover soil was dominated by advection rather than diffusion (Liptay et al., 1998; Chanton and Liptay, 2000). Although this may result in underestimation of the methane oxidation rate occurring in the landfill cover (De Visscher et al., 2004; Chanton et al., 2008), many researchers found it to be a reasonable assumption for landfills with no active gas collection system (Liptay et al., 1998; Chanton and Liptay, 2000; Abichou et al., 2006b; Stern et al., 2007; Bogner et al., 2010). This suggests that when LFG is being actively collected, α_t would

be greater than 1 and closer to the value of fractionation factor due to diffusion ($\alpha_{diffusion}$). This theoretical value is 1.0197 suggested by Marrero and Mason (1972) based on the difference between binary diffusion coefficient of $^{12}CH_4$ and $^{13}CH_4$ in air (i.e. $^{12}CH_4$ diffuses 1.0197 times faster than $^{13}CH_4$). An experiment by De Visscher et al. (2004), in a landfill in France with an active LFG collection system, resulted α_t of 1.0178 ± 0.0009. Chanton et al. (2011a), in a four year study, used this value as a base and developed α_t for 20 landfills across the U.S. Based on 155 samples, this study showed a mean value of α_t =1.0106 ± 0.007 for landfills in cool and humid climate, based on 155 samples.

In the present study, although the LFG collection system vacuum was larger in Area A comparing with Area B, the fugitive emissions were observed in locations far from the LFG collection wells. These locations were beyond the usual radius of influence of the LFG wells (normally about 25m to 30 m) and believed to be less impacted by the high applied vacuum. Therefore, a value of 1.0106 was used for α_t for both Areas A and B, in areas with active LFG collection system. For the grid# 11 in Western 40, as well as the areas where the collection system was shut down during the course of the field work, a value of α_t =1 was adopted.

5.6 Results and Discussion

As previously reported in Chapter 4, the flux chamber measurements showed methane emission rates varying from 0 to 4,709 g CH_4 m^{-2} d^{-1} within the study boundaries. Averaging the results for the two major areas defined in the present chapter, showed mean values of 744 g CH_4 m^{-2} d^{-1} and 489 g CH_4 m^{-2} d^{-1} for Area A and Area B, respectively. Median values for the two areas were 216 g CH_4 m^{-2} d^{-1} and 396 g CH_4 m^{-2} d^{-1}, respectively.

5.6.1 Residual Methane

The $\delta^{13}C$ of the residual methane emitted into chambers ranged from -34.84‰ to -55.78‰. This value averaged -47.8±7.4‰ at area A with a median value of -48.8‰. At area B, the isotopic signature of the emitted methane averaged -49.7±2.4‰ with a median value of -50.1‰. The similarity of the mean and median is the result of a normal distribution for the isotope data as reported by Abichou et al. (2011). Methane emission rate (MER) and $\delta^{13}C$ value of residual methane (δ_R) calculated with Equation 5.2 for each chamber are tabulated in Table 5.2 below.

Table 5.2 Methane emission rates (MER) and residual methane $\delta^{13}C$ values

Area	Chamber ID.	MER ($g\ CH_4\ m^{-2}\ d^{-1}$)	δ_R (‰)
Area A	44	419	-53.07
	47	37	-44.02
	48	797	-46.88
	108	18	-37.52
	91A	256	-50.67
	35	4709	-55.55
	38	135	-54.47
	300	760	-55.78
	402	130	-34.84
	406	175	-45.75
Area B	200	402	-51.87
	205	1817	-52.60
	214	444	-46.38
	309	28	-47.48
	114	82	-46.35
	91B	302	-50.46
	71	389	-50.79
	78	528	-52.36
	311	750	-49.83
	62	148	-48.59

5.6.2 Anaerobic Methane

Anaerobic methane samples collected from the LFG collection manifolds of each phase of VLF had $\delta^{13}C$ values within ranges previously reported in similar studies (Chanton et al., 1999; Chanton and Liptay, 2000; Börjesson et al., 2001; Chanton et al., 2011b). However, there was a significant difference between the two areas averaging -54.12 ± 0.06‰ for older areas (Area B) and -58.19 ± 0.05‰ for Area A, the newer one. Differences between Areas A and B included: average waste age (7 vs. 15 years), depth of waste (30 vs. 10 m), and cover system (Area A is partially capped with geomembrane while the rest of the landfill is covered with an interim cover soil and topsoil). Also, as reported in Chapter 3, Phase 1 of VLF was much warmer in comparison with other areas of the landfill with an approximate average temperature of 46°C vs. 15-21°C in the older areas. (See Table 3.10 on Page 95).

Table 5.3 below summarizes the anaerobic methane $\delta^{13}C$ value at VLF.

Table 5.3 Anaerobic methane $\delta^{13}C$ value at the Vancouver Landfill

Landfill Areas		Methane Concentration $[CH_4]$, (%)	Anaerobic Methane Isotopic Signature (δ_A), (ppt)		
			Samples	StDev.	Average
Area A	**Phase 1**	43.2	-58.17	0.003	-58.19 ± 0.05
		43.5	-58.21	0.067	
Area B	**Area 2W**	46.3	-54.23	0.058	-54.33 ± 0.05
		46.4	-54.43	0.030	
	Area 2E	45.7	-54.05	0.036	-54.04 ± 0.03
		45.9	-54.03	0.009	
	Area 3	50.6	-54.07	0.013	-53.97 ± 0.10
		50.5	-53.88	0.137	

5.6.3 Soil Incubation and Isotopic Fractionation Factor

Soil incubations were conducted at different moisture contents and temperatures. The incubation tests started at methane concentrations between 4% and 4.5%, and continued for about 1.5 days or until the concentrations dropped below 0.5%. The soil gas methane concentrations are illustrated in Figure 5.5 through Figure 5.10. These results are also presented in full in Appendix E.2.

Figure 5.5, shows the incubation results for the soil sample collected from Area A (with a lower level of organic content). This test was conducted at two different soil moisture contents of 7.7% and 10.7%, labeled (1a) and (1b), respectively. Results for this sample, showed a higher level of methanotrophic activity for the test with the lower moisture content (i.e. 1a).

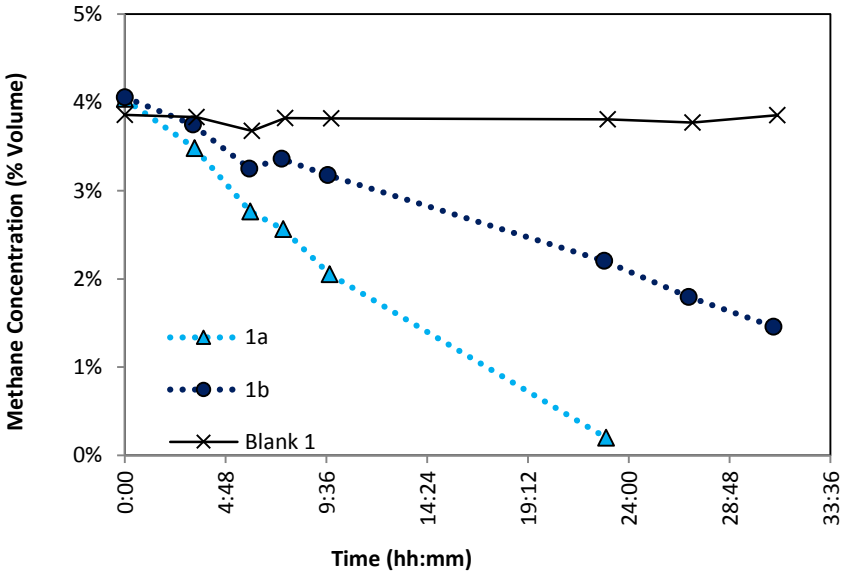


Figure 5.5 Methane concentrations during the soil incubation tests for soil sample collected from Area A with 1.5% organic content, incubated at 25°C at two moisture content levels of 7.7% (1a) and 10.7% (1b)

Figure 5.6 below shows the results for the soil sample collected from Area B, which had a higher organic content of about 6.8%. This time an opposite behaviour was observed with a lower level of methanotrophic activity observed for the test with lower soil moisture content.

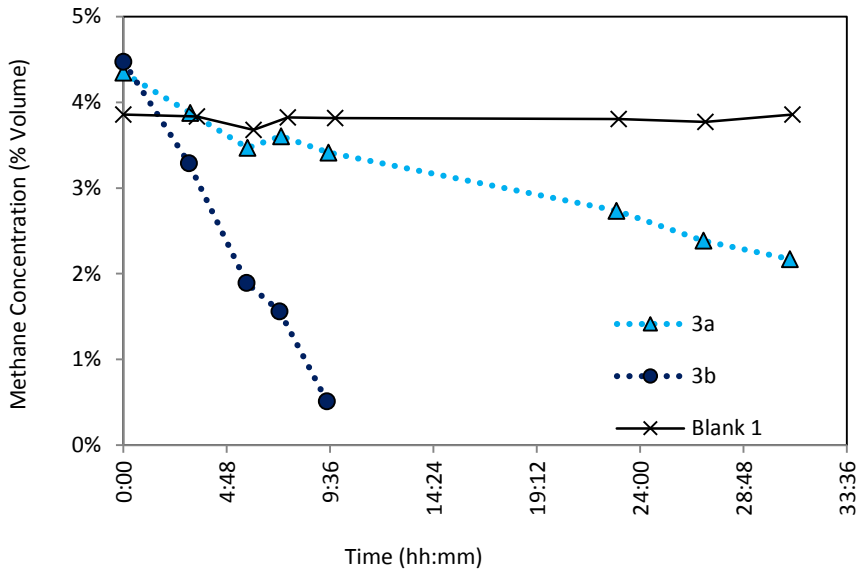


Figure 5.6 Methane concentrations during the soil incubation tests for soil sample collected from Area B with 6.8% organic content, Incubated at 25°C at two moisture content levels of 7.1% (3a) and 11.8% (3b)

The same soil sample acquired from Area B at the initial moisture content of 7.1% showed almost no methanotrophic activity at temperature equal to 5°C. However, at a moisture content of 11.8%, these activities proceeded at slightly higher rates in comparison with the same sample at the initial moisture content and at 25°C (see Figure 5.7 below). As the VLF is located in an area with daily average temperatures of 4 and 17 °C in winter and summer months respectively, as well as monthly precipitation of 151 and 45 mm during these two seasons, these results may suggest similar oxidation rates for wet winters as for dryer summers.

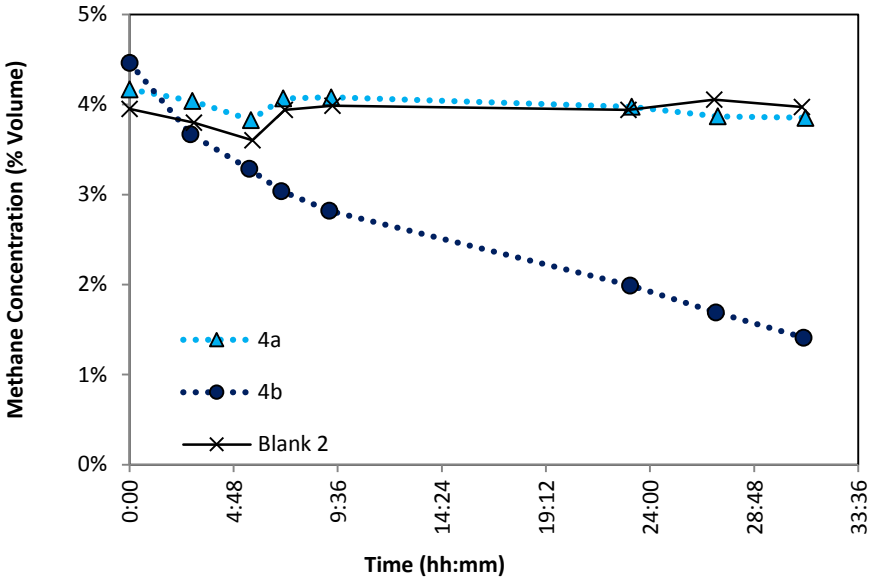


Figure 5.7 Methane concentrations during the soil incubation tests for soil sample collected from Area B with 6.8% organic content, incubated at 5°C at two moisture content levels of 7.1% (4a) and 11.8% (4b)

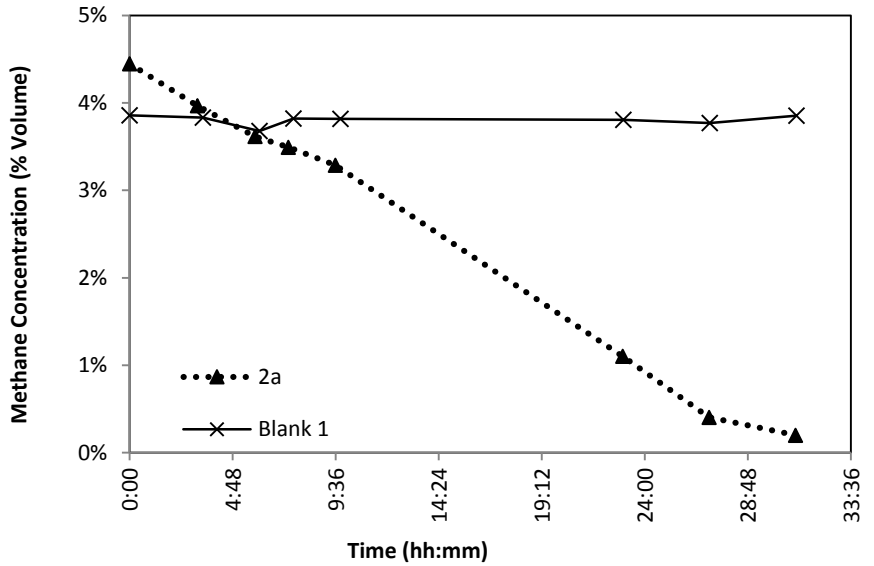


Figure 5.8 Methane concentrations during the soil incubation tests for soil sample collected from Area A with 2.2% organic content and 9.7% moisture content (2a), incubated at 25°C

Soil sample no.5 acquired from Area B, with a relatively high organic content of about 5.4% and field moisture content of about 12%, already had a high level of methanotrophic activity and adding more moisture to this soil sample did not significantly change the oxidation rate (See Figure 5.9 below).

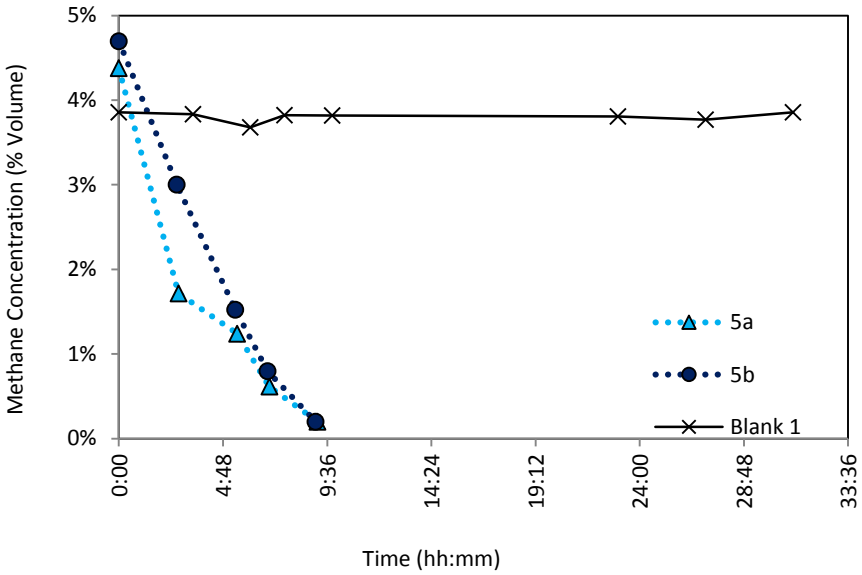


Figure 5.9 E Methane concentrations during the soil incubation tests for soil sample collected from Area B with 5.4% organic content, incubated at 25°C at two moisture content levels of 12.4% (5a) and 16.0% (5b)

Soil sample no.6, with a relatively low organic and moisture content, did not show reasonable results (See Figure 5.10). This sample was taken from an area which appeared to be a new layer of impermeable soil recently placed on top of the old soil cover, and was not believed to represent the whole area, hence was excluded from the final analyses.

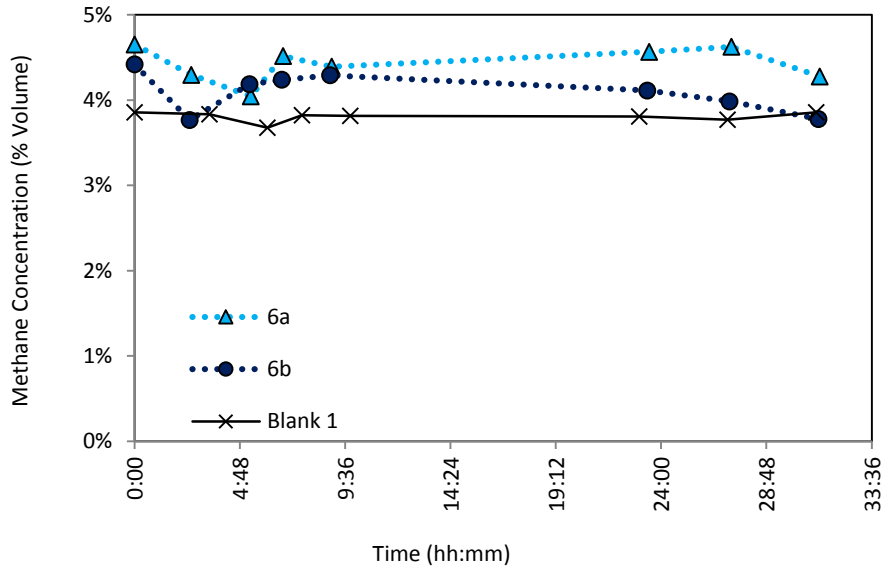


Figure 5.10 Methane concentrations during the soil incubation tests for soil sample collected from Area B with 3.0% organic content, incubated at 25°C at two moisture content levels of 4.2% (6a) and 14.0% (6b). Results from incubation of this sample was excluded from the final analyses as the sample was not believed to represent the whole area.

The isotopic signature values of the soil gas samples, developed during the soil incubation tests, were quantified at the FSU. Figure 5.11 shows two examples of these results. The increase in methane $\delta^{13}C$ over time indicates faster consumption of $^{12}CH_4$ in comparison with $^{13}CH_4$. This degree of preference of bacteria was translated to the oxidation isotopic fractionation factor (α_{ox}) using Equation 5.4.

As shown in Table 5.4, the α_{ox} value was calculated for every soil sample at different moisture levels and, for two samples, at two different temperatures. The averages of results for samples at field conditions (i.e. field moisture content and at 25°C) for Areas A and B were very close at values of 1.0265 ± 0.0010 and 1.0266 ± 0.0052, respectively.

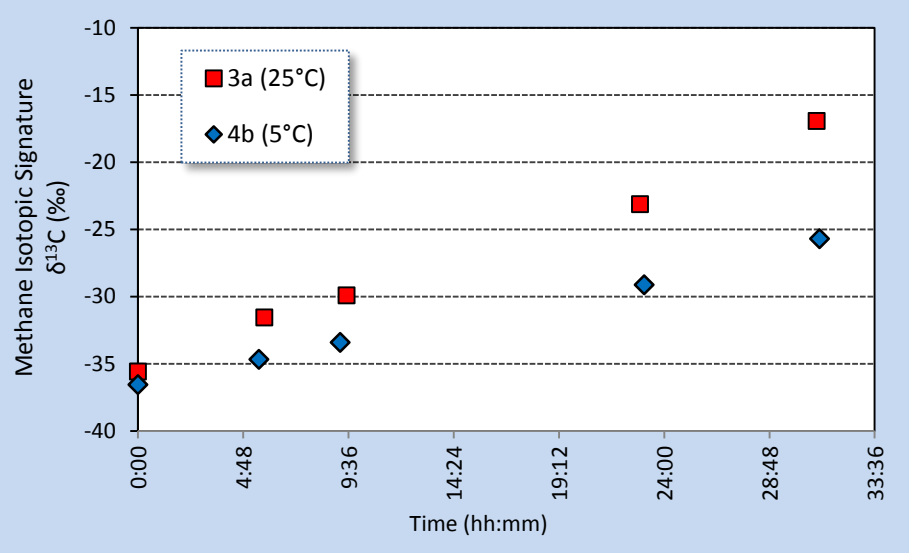


Figure 5.11 Soil gas samples methane isotopic signature

Table 5.4 Oxidation isotopic fractionation factor (α_{ox}) for different cover soil types at VLF

Area	Sample ID	Temperature (°C)	Moisture Content (%)	Organic Content (%)	fractionation factor (α_{ox})
A	1a	25	7.7	1.5	1.0266 ± 0.0012
	1b	25	10.7	1.5	1.0222 ± 0.0034
	2a	25	9.7	2.2	1.0264 ± 0.0008
B	3a	25	7.1	6.8	1.0298 ± 0.0044
	3b	25	11.8	6.8	1.0231 ± 0.0023
	4a	5	7.1	6.8	1.0185 ± 0.0058
	4b	5	11.8	6.8	1.0104 ± 0.0019
	5a	25	12.4	5.4	1.0234 ± 0.0059
	5b	25	16.0	5.4	1.0194 ± 0.0006
	6a	25	4.8	3.0	Excluded from calculations
	6b	25	14.0	3.0	
Average results at actual moisture and ambient temperature					
Area A		25	8.7 ± 1.4	1.9 ± 0.5	**1.0265 ± 0.0010**
Area B		25	9.7 ± 3.7	6.1 ± 1.0	**1.0266 ± 0.0052**

Similarly to the observations of Coleman et al. (1981), King et al. (1989) and Tyler et al. (1994), the present results showed an increase in α_{ox} as a result of increased temperature. As shown in Table 5.5 this increase was 0.00057/°C and 0.00064/°C for the soil samples with moisture contents of 7.1% and 11.8%, respectively.

Table 5.5 Effect of temperature on methane oxidation fractionation factor

Sample ID	Soil Moisture (%)	Temperature (°C)	fractionation factor (α_{ox})	Rate ($\Delta\alpha_{ox}/\Delta T$)
3a	7.1	25	1.0298 ± 0.0044	**+ 0.00057 /°C**
4a	7.1	5	1.0185 ± 0.0058	
3b	11.8	25	1.0231 ± 0.0023	**+ 0.00064 /°C**
4b	11.8	5	1.0104 ± 0.0019	
Mean Value				**+ 0.0006 /°C**

An increase in the moisture content of the soil samples also resulted in decreased values for the isotopic fractionation factor in all cases. As shown in Table 6, for the tests conducted at a temperature of 25°C, this reduction was more significant in soil samples from Area A. However, the largest reduction rate in α_{ox} due to increased moisture content occurred at 5°C for the soil sample from Area B.

Table 5.6 Effect of soil moisture content on methane oxidation fractionation factor

Source of Soil Sample	Sample ID	Temperature (°C)	Soil Moisture (%)	fractionation factor (α_{ox})	Rate ($\Delta\alpha_{ox}/\Delta W$)
Area A	1a	25	7.7	1.0266 ± 0.0012	**- 0.0015**
	1b	25	10.7	1.0222 ± 0.0034	
Area B	5a	25	12.4	1.0234 ± 0.0059	**- 0.0011**
	5b	25	16.0	1.0194 ± 0.0006	
	3a	25	7.1	1.0298 ± 0.0044	**- 0.0014**
	3b	25	11.8	1.0231 ± 0.0023	
	4a	5	7.1	1.0185 ± 0.0058	**- 0.0017**
	4b	5	11.8	1.0104 ± 0.0019	

5.6.4 Fraction of Methane Oxidized (f_{ox})

Finally, the methane oxidation was calculated with Equation 5.3, which quantified the total amount of methane oxidized (O). The methane oxidation is the oxidized fraction (f_{ox}) of methane

that migrated through the cover soil and entered the flux chambers. Obviously, this number could be calculated only when smaller than 100%, or no residual methane would be left in the chamber to be sampled. The values of f_{ox} ranged between 3.4% to 72.7%, with average values of 33.7±21.6% and 27.9±14.9% for cover soil types used in Areas A and B, respectively. These values translate to average methane oxidation rates of 219 g CH_4 m^{-2} d^{-1} and 141 g CH_4 m^{-2} d^{-1} for the cover soil applied at these areas. These results are presented in Table 5.7.

Table 5.7 Fraction of methane oxidized in the Vancouver Landfill cover soil

Areas	Chamber ID	δ_R (‰)	δ_a (‰)	α_{ox}	α_t **	f_{ox} (%)	$f_{ox\ (avg.)}$ (%)	R_{ox} (CH_4) g m^{-2} d^{-1}
Area A	44	-53.07	-53.97	1.0265	1.0000	3.4	**33.7**	**219**
	47	-44.02	-53.97	1.0265	1.0000	37.6		
	48	-46.88	-53.97	1.0265	1.0000	26.8		
	108	-37.52	-53.97	1.0265	1.0000	62.1		
	91A	-50.67	-58.19	1.0265	1.0106	47.3		
	35	-55.55	-58.19	1.0265	1.0106	17.5		
	38	-54.47	-58.19	1.0265	1.0106	23.4		
	300	-55.78	-58.19	1.0265	1.0106	15.1		
	402*	-34.84	-54.12	1.0265	1.0000	72.7		
	406*	-45.75	-54.12	1.0265	1.0000	31.6		
Area B	200	-51.87	-54.33	1.0266	1.0106	15.4	**27.9**	**141**
	205	-52.60	-54.33	1.0266	1.0106	10.8		
	214	-46.38	-54.33	1.0266	1.0106	49.7		
	309	-47.48	-54.33	1.0266	1.0106	42.8		
	114	-46.35	-54.04	1.0266	1.0106	48.1		
	91B	-50.46	-54.04	1.0266	1.0106	22.4		
	71	-50.79	-53.97	1.0266	1.0106	19.9		
	78	-52.36	-53.97	1.0266	1.0106	10.1		
	311	-49.83	-53.97	1.0266	1.0106	25.9		
	62	-48.59	-53.97	1.0266	1.0106	33.7		

* no LFG collection system in this section, therefore, average value of δ_a from other similar phases of the landfill was used in calculation for this Flux Chamber

** α_t =1 was used for areas with no or shut-down active gas collation system

Methane emission rates (MER) measured by the flux chamber tests (see Table 5.2) were plotted against the methane oxidation percentages reported above. For ease of analysis, the rates of emissions were arbitrarily grouped to MER < 550 g CH_4 m^{-2} d^{-1}, and MER > 750 g CH_4 m^{-2} d^{-1} (Figure 5.12(A) and Figure 5.12(B), respectively). For the lower emission rates, the oxidation rates increased with decreasing emission rates. This comparison showed that f_{ox} was an inverse function of MER as shown in Equation 5.5 below. This trend was similar to findings of studies done by Powelson et al. (2006), Huber-Humer et al. (2008), Chanton et al. (2011a), and Chanton et al. (2011b). For the locations with relatively higher emission rates, f_{ox} was found to be in the order of 10 to 25% with no obvious trend.

$$\mathbf{f_{ox}}\,(\%) = \mathbf{51.19 - 0.07 \times MER}(\mathbf{g\ CH_4\ m^{-2}\ d^{-1}}) \qquad \textbf{Equation 5.5}$$

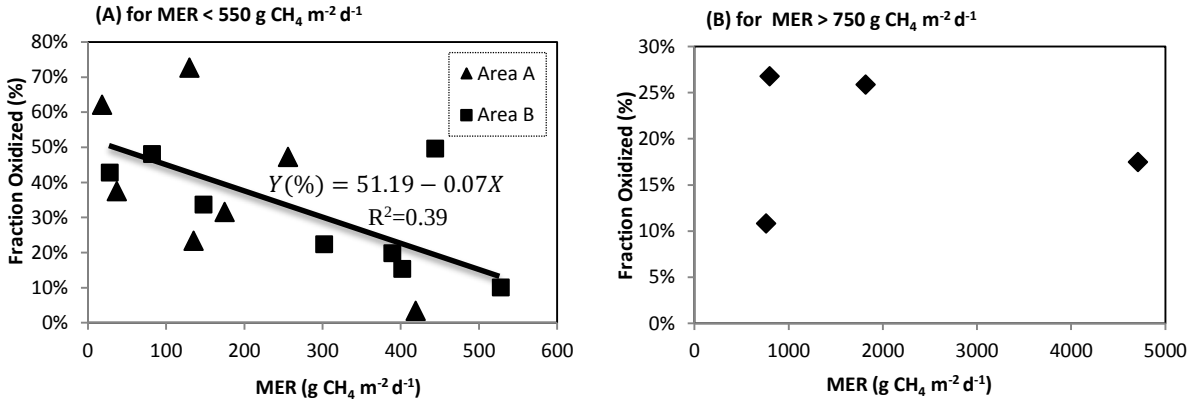


Figure 5.12 Relationship between methane emission rates (MER) and fraction of methane oxidized (f_{ox})

5.7 Total Methane Oxidation at the Vancouver Landfill

The current analyses showed that 10% oxidation would be an appropriate minimum default value. However, the actual oxidation fraction in MSW landfills with active gas collection

systems in place could be much higher depending on methane emission rates (i.e. the methane loading rate applied to the landfill cover soil).

The results showed average methane oxidation rates of 219 g CH_4 m^{-2} d^{-1} and 141 g CH_4 m^{-2} d^{-1} for the cover soil applied at Areas A and B of VLF, respectively. This translates to methane oxidation percentages of 33.7% and 27.9% for these two areas. It is important to note that the methane oxidation rates should only be applied to the fugitive methane emissions from the landfill cover soil. Therefore, the possible methane leaks from cracks, the LFG collection system piping, and other infrastructure flaws, which were previously factored in by the emission correction factor (CF_E), were excluded from calculations of the total methane oxidation (O) at VLF.

It should also be noted that, without the methanotrophic activity and methane oxidations, the measured methane emissions from VLF cover soil would have been higher than the amount determined by the flux chamber tests (i.e. E/CF_E). The total amount of methane oxidized relative to the measured emissions would be:

$$\mathbf{O} = \frac{\mathbf{f_{ox}} \times (\frac{\mathbf{E}}{\mathbf{CF_E}})}{\mathbf{1 - f_{ox}}} \qquad \textbf{Equation 5.6}$$

Where: O = total methane oxidized (tonnes/year)

f_{ox} = methane oxidation rate (%)

E = total methane emissions (tonnes/year)

CF_E = emission correction factor (1.52)

Using Equation 5.6, the total amounts of methane oxidized in different areas of VLF were calculated and summarized in Table 5.8. Results showed that the total average methane oxidized in Area 2W, Area 2E, Area 3, and Phase 1 of the VLF in the year of the study were 119, 64, 94, and 133 tonnes methane year^{-1}, respectively

Table 5.8 Total methane oxidation at each area of VLF

Area/ Phase	Total Avg. Methane Emissions (E) (tonnes year^{-1})	Methane Emissions from Cover Soil (E/CF_E) (tonnes year^{-1})	Methane Oxidation Rate, (f_{ox}) (%)	Total Methane Oxidized ($O \pm \Delta O$) (tonnes year^{-1})
Area 2W	466	307	27.9 ± 14.9	**119 ± 54**
Area 2E	252	167	27.9 ± 14.9	**64 ± 29**
Area 3	367	242	27.9 ± 14.9	**94 ± 42**
Phase 1	396	261	33.7 ± 21.6	**133 ± 72**
Total	**1,481**	**978**		**410 ± 197**

In summary, the results of this portion of the study showed that the effectiveness of methanotrophic bacteria in mitigating fugitive methane emissions from landfills is significantly underestimated when the default value of 10% oxidation is used. The current analyses showed that while a 10% oxidation would be an appropriate minimum default value, the actual oxidation percentage in landfills with active gas collection systems could be much higher and dependent on methane emission rates. Using the correct and region-specific values will change the methane budget in GHG emission inventory reports.

In this chapter of the study, the O values for the four areas of the Vancouver Landfill were calculated. These values would be applied to the simplified METRO equation to calibrate the developed integrated LFG generation model.

Chapter 6: LFG Recovery at the Vancouver Landfill (R)

6.1 VLF Gas Collection System Operational Data

As previously mentioned, the VLF landfill gas management system has been operating since 1991. The system includes (i) an LFG collection system (vertical and horizontal wells and piping network), (ii) a condensate handling system, (iii) an LFG extraction plant (blowers), and (iv) an LFG flare system.

The collection system is the main component of an LFG management system. It includes vertical gas extraction wells and horizontal gas collectors (trenches), as well as wellheads, lateral pipes, sub-header pipes, and a main gas header pipe. Based on the system design, waste depth, well spacing, and the required radius of influence (ROI) of the LFG wells, a minimum amount of vacuum at collection points (wellheads) is required to maintain an acceptable level of LFG collection efficiency, hence, minimal GHG emissions. However, excessive levels of vacuum applied to the system may result in air intrusion into the landfill, which increases the risk of spontaneous combustion and landfill fire (Sperling, 2009). Furthermore, when beneficial use of the collected LFG is intended, it is important to ensure that the quality of the collected gas (i.e. methane, nitrogen and oxygen content) is maintained within an acceptable range, dictated by the gas treatment facility/technology.

Therefore, the operation of an active LFG management system involves an extensive amount of field monitoring, wellfield adjustments, and wellfield data collection. Some of the information recorded as the LFG operational and gas quality data include: gas composition (% CH_4, % CO_2, % O_2, balance gas, H_2S (ppm), CO (ppm), gas temperature), operational data (wellhead's %

opening, system pressure (vacuum), vacuum applied, gas flow rate), and system status (broken wells, leachate levels in the well, upcoming repairs, etc.).

For larger landfills, such as the Vancouver Landfill, with more than 250 data collection points just in the four areas within the study boundaries, the monthly readings would add up to more than 10,000 data points each year. These data were historically stored in various excel spread sheets as weekly and monthly readings. While the available historical LFG data provided an invaluable opportunity to study the VLF historical behavior and operational challenges, a better organization of these data was deemed necessary for data mining.

6.2 The Vancouver Landfill LFG Database

As one of the initial steps of the study, the large amount of existing historical LFG collection system data had to be organized. A site-specific LFG database in Microsoft (MS) Access environment was developed for the VLF. The new data base allowed for the comprehensive and meaningful mining of the existing data. New gas collection data from the work site, including data from new wells generated during the course of the study, were incorporated into the data base. Figure 6.1 through Figure 6.5 below show example snapshots of the developed LFG database. As shown in the following examples, the database was designed to develop graphical and/or tabulated reports for selected parameters and the selected sampling/monitoring point. Data entry can be done line-by-line for each monitoring location and date/time, or could be imported all at once from an MS word table or an excel spread sheet. The stored data could also be exported as excel worksheets, if required.

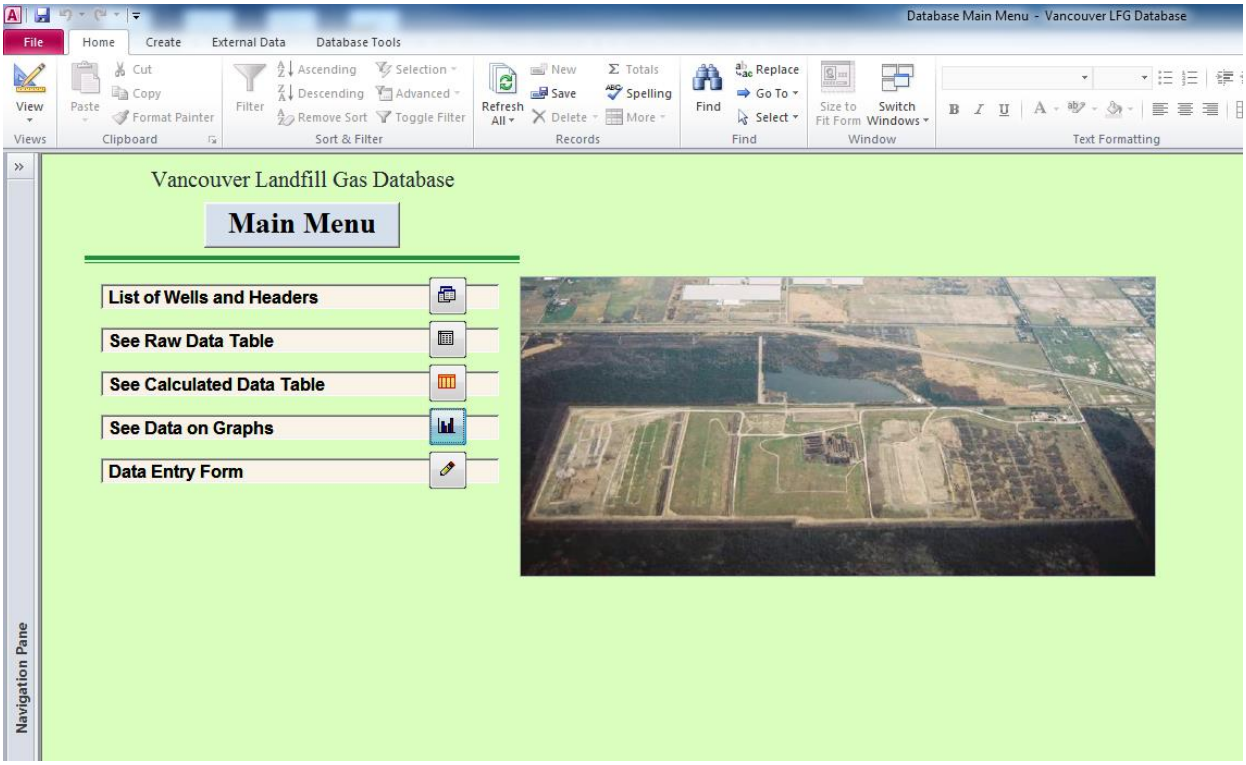


Figure 6.1 The Vancouver Landfill LFG database

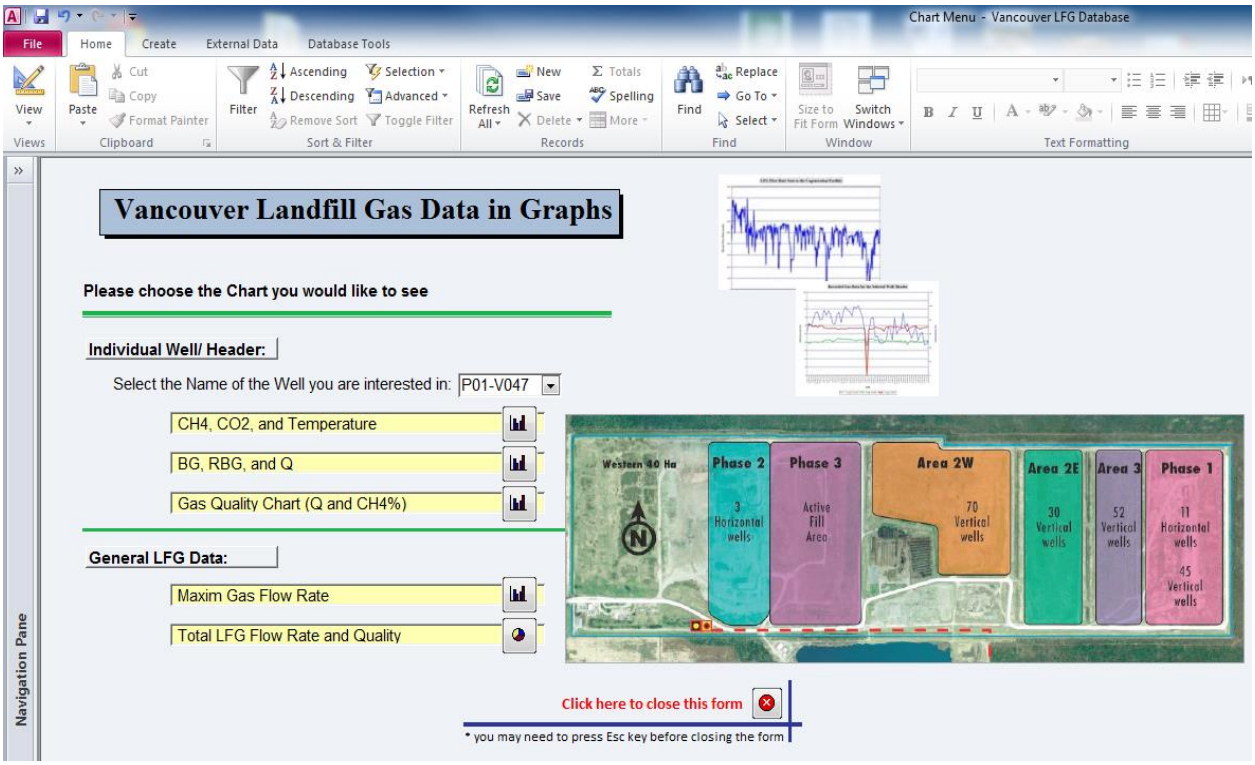


Figure 6.2 Graphical menu of the Vancouver Landfill LFG database

Figure 6.3 Example graphical outputs of the LFG database

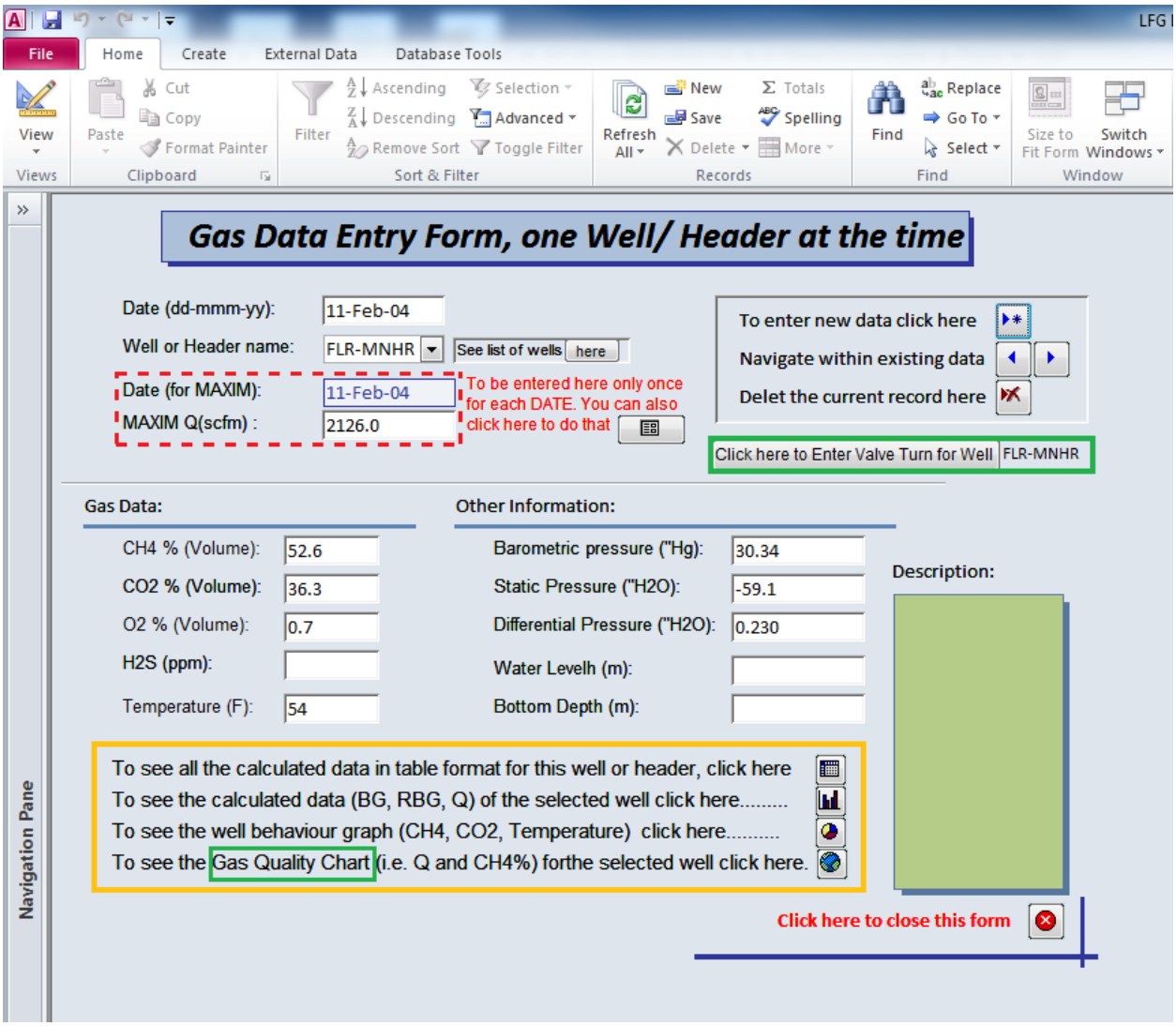
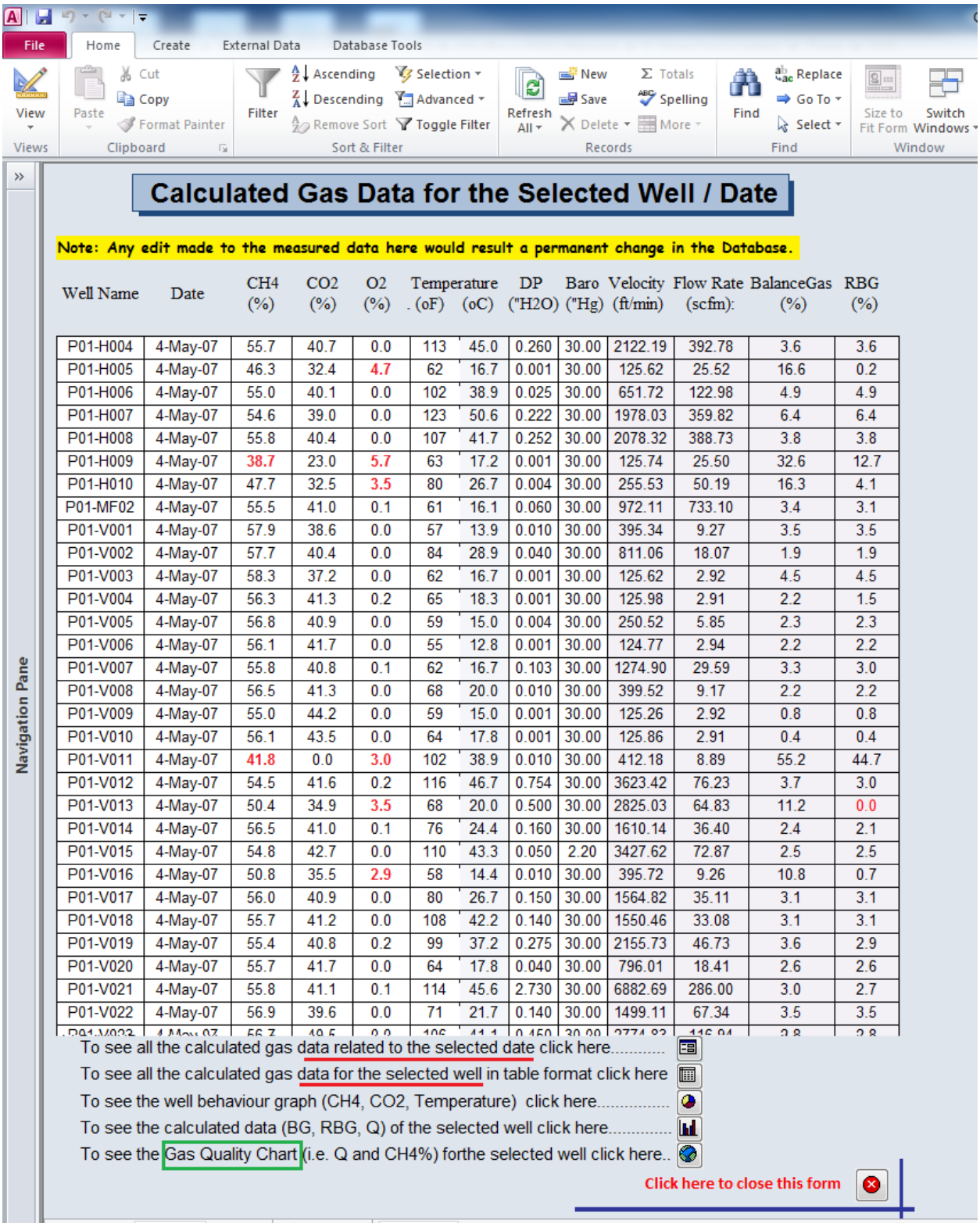


Figure 6.4 LFG database data entry form



Well Name	Date	CH4 (%)	CO2 (%)	O2 (%)	Temperature (oF)	(oC)	DP ("H2O)	Baro ("Hg)	Velocity (ft/min)	Flow Rate (scfm):	BalanceGas (%)	RBG (%)
P01-H004	4-May-07	55.7	40.7	0.0	113	45.0	0.260	30.00	2122.19	392.78	3.6	3.6
P01-H005	4-May-07	46.3	32.4	4.7	62	16.7	0.001	30.00	125.62	25.52	16.6	0.2
P01-H006	4-May-07	55.0	40.1	0.0	102	38.9	0.025	30.00	651.72	122.98	4.9	4.9
P01-H007	4-May-07	54.6	39.0	0.0	123	50.6	0.222	30.00	1978.03	359.82	6.4	6.4
P01-H008	4-May-07	55.8	40.4	0.0	107	41.7	0.252	30.00	2078.32	388.73	3.8	3.8
P01-H009	4-May-07	38.7	23.0	5.7	63	17.2	0.001	30.00	125.74	25.50	32.6	12.7
P01-H010	4-May-07	47.7	32.5	3.5	80	26.7	0.004	30.00	255.53	50.19	16.3	4.1
P01-MF02	4-May-07	55.5	41.0	0.1	61	16.1	0.060	30.00	972.11	733.10	3.4	3.1
P01-V001	4-May-07	57.9	38.6	0.0	57	13.9	0.010	30.00	395.34	9.27	3.5	3.5
P01-V002	4-May-07	57.7	40.4	0.0	84	28.9	0.040	30.00	811.06	18.07	1.9	1.9
P01-V003	4-May-07	58.3	37.2	0.0	62	16.7	0.001	30.00	125.62	2.92	4.5	4.5
P01-V004	4-May-07	56.3	41.3	0.2	65	18.3	0.001	30.00	125.98	2.91	2.2	1.5
P01-V005	4-May-07	56.8	40.9	0.0	59	15.0	0.004	30.00	250.52	5.85	2.3	2.3
P01-V006	4-May-07	56.1	41.7	0.0	55	12.8	0.001	30.00	124.77	2.94	2.2	2.2
P01-V007	4-May-07	55.8	40.8	0.1	62	16.7	0.103	30.00	1274.90	29.59	3.3	3.0
P01-V008	4-May-07	56.5	41.3	0.0	68	20.0	0.010	30.00	399.52	9.17	2.2	2.2
P01-V009	4-May-07	55.0	44.2	0.0	59	15.0	0.001	30.00	125.26	2.92	0.8	0.8
P01-V010	4-May-07	56.1	43.5	0.0	64	17.8	0.001	30.00	125.86	2.91	0.4	0.4
P01-V011	4-May-07	41.8	0.0	3.0	102	38.9	0.010	30.00	412.18	8.89	55.2	44.7
P01-V012	4-May-07	54.5	41.6	0.2	116	46.7	0.754	30.00	3623.42	76.23	3.7	3.0
P01-V013	4-May-07	50.4	34.9	3.5	68	20.0	0.500	30.00	2825.03	64.83	11.2	0.0
P01-V014	4-May-07	56.5	41.0	0.1	76	24.4	0.160	30.00	1610.14	36.40	2.4	2.1
P01-V015	4-May-07	54.8	42.7	0.0	110	43.3	0.050	2.20	3427.62	72.87	2.5	2.5
P01-V016	4-May-07	50.8	35.5	2.9	58	14.4	0.010	30.00	395.72	9.26	10.8	0.7
P01-V017	4-May-07	56.0	40.9	0.0	80	26.7	0.150	30.00	1564.82	35.11	3.1	3.1
P01-V018	4-May-07	55.7	41.2	0.0	108	42.2	0.140	30.00	1550.46	33.08	3.1	3.1
P01-V019	4-May-07	55.4	40.8	0.2	99	37.2	0.275	30.00	2155.73	46.73	3.6	2.9
P01-V020	4-May-07	55.7	41.7	0.0	64	17.8	0.040	30.00	796.01	18.41	2.6	2.6
P01-V021	4-May-07	55.8	41.1	0.1	114	45.6	2.730	30.00	6882.69	286.00	3.0	2.7
P01-V022	4-May-07	56.9	39.6	0.0	71	21.7	0.140	30.00	1499.11	67.34	3.5	3.5

Figure 6.5 LFG database, an example tabulated output

6.3 Methane Recover Rate at the Vancouver Landfill (R)

In order to calibrate the iModel-110© methane generation results with the simplified METRO equation, the amount of recovered methane (R) during the course of the field study was required. The data for 2012 were used for this purpose. Weekly data were collected from the sub-header sampling/flow meter stations of each area using a GEM™ 2000+. The recorded LFG flow rate, as well as the volumetric percentage of methane, was used to calculate the total tonnage of methane. Table 6.1 shows a few examples of the conducted wellfield readings where gas flow rate, methane, carbon dioxide, and oxygen content, along with other parameters such as CO and H_2S levels, temperature, system pressure, etc. are indicated. Due to the type of flow metering device used at the VLF gas collection system, reliable gas flow read out was not possible at all operational conditions. Therefore, out of 65 attempts for each of the four study areas, 40, 35, 40, 49 valid R readings were achieved for Area 2W, Area 2E, Area 3, and Phase 1, respectively. Invalid flow rate readings were considered to be the recorded data at significant fluctuation (surging) of the system, and flow rates recorded in extreme operational conditions (system freeze-up, etc.). The valid recorded data are illustrated in Figure 6.6 and Figure 6.7 (a) through (d), and also are presented in Appendix F.1.

Table 6.1 Wellfield manifolds (sub-headers) reading examples

Area	Date	CH_4 (%v)	CO_2 (%v)	O_2 (%v)	Measured Flow Q (cfm)	Adjusted Q for 50% CH_4 (scfm)	Recovered Methane (R) (tonnes)
Area 2W	30/06/2011	51.0	32.9	1.1	192	196	987
Area 2E	30/06/2011	50.1	32.6	0.7	214	214	1081
Area 3	30/06/2011	40.9	27.5	4.4	211	173	870
Phase 1	29/06/2011	53.1	38.1	0.3	1,086	1153	5815
Area 2W	21/07/2011	51.7	32.9	0.7	134	139	699
Area 2E	21/07/2011	53.5	31.1	0.6	--	--	No Data
Area 3	21/07/2011	65.2	34.4	0.3	146	190	960
Phase 1	22/07/2011	54.0	37.9	0.4	1,139	1230	6202
Area 2W	28/07/2011	51.1	32.8	0.6	--	--	No Data
Area 2E	28/07/2011	53.0	32.1	0.6	--	--	No Data
Area 3	28/07/2011	65.2	34.4	0.3	--	--	960
Phase 1	29/07/2011	53.3	37.9	0.5	1,249	1331	6713
Area 2W	05/08/2011	47.1	32.4	0.7	115	108	546
Area 2E	05/08/2011	49.9	31.2	0.6	117	117	589
Area 3	05/08/2011	47.3	29.2	3.1	113	107	539
Phase 1	05/08/2011	50.6	37.4	0.4	1,415	1432	7220
Area 2W	02/09/2011	48.5	33.0	0.6	162	157	792
Area 2E	02/09/2011	44.3	32.3	1.0	150	133	670
Area 3	02/09/2011	52.0	29.0	3.9	74	77	388
Phase 1	02/09/2011	48.8	37.5	0.5	1,459	1424	7179

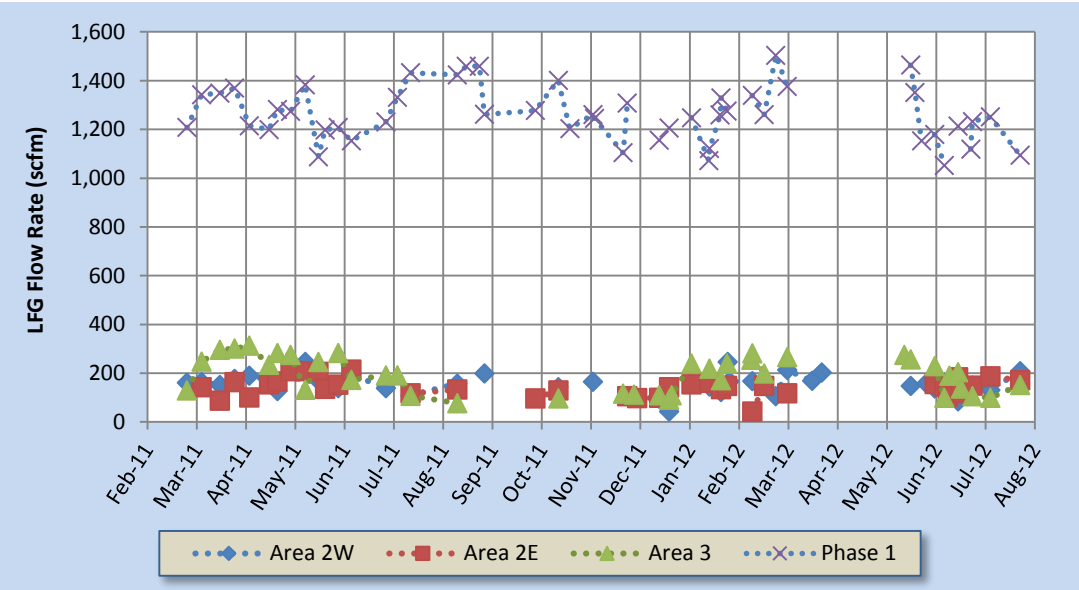


Figure 6.6 Collected LFG flow rates from the four areas of VLF (adjusted for 50% CH_4 content)

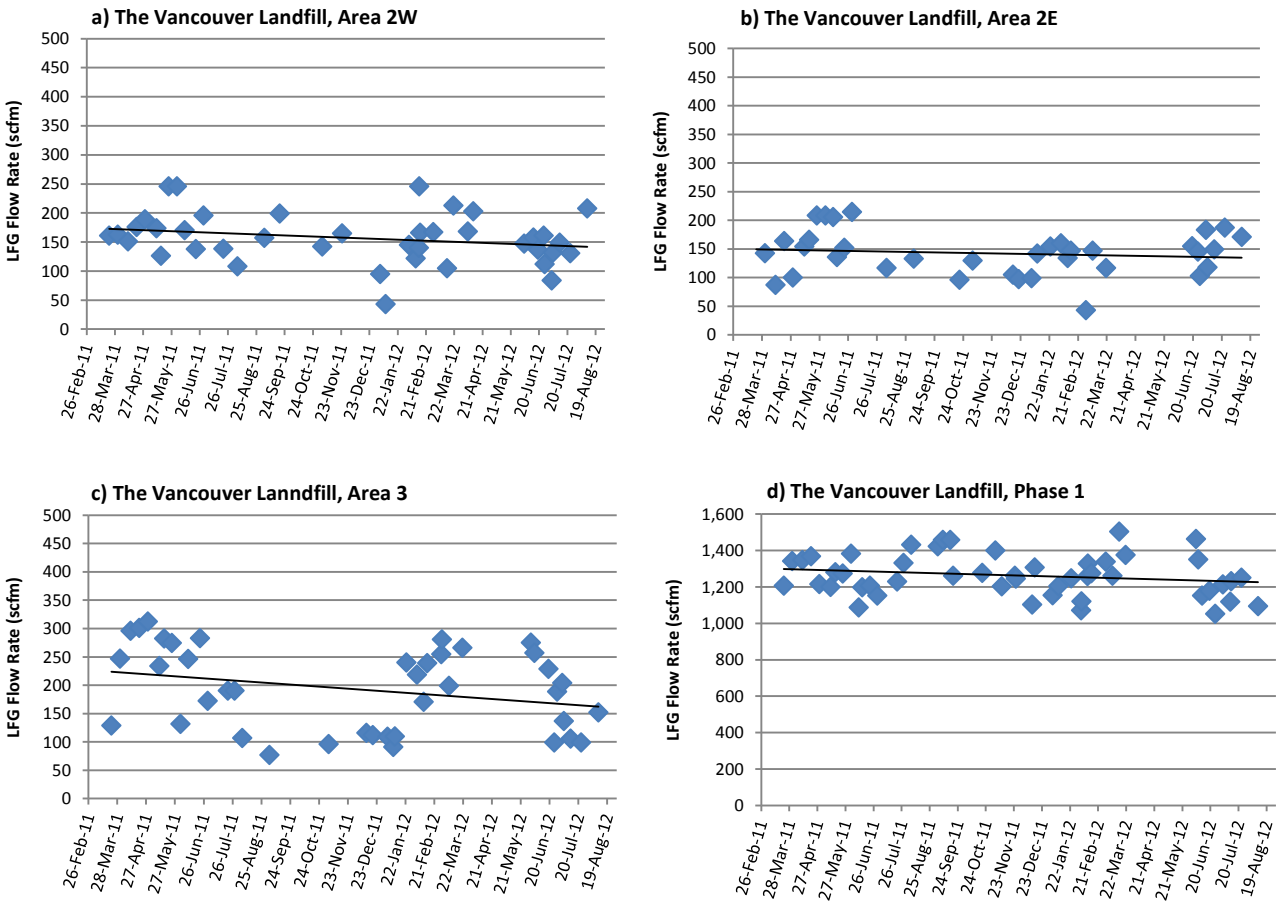


Figure 6.7 Captured LFG flow rates at VLF (flow rated are adjusted for 50% methane content)

As shown in the Appendix F.1. from the 65 attempts during the course of the field work to measure the collected LFG flow rates from the metering stations of each area/phase, only 35 to 49 valid flow readings were achieved, with only 27 events generating flow reading data for all four metering stations. The main reason for failing to read the gas flow rates in some of the events was the type of the flow meter that was installed on manifolds at VLF in the past. The COV is currently replacing all of these metering devices with a new type of flow meter. The fluctuation in the recorded flow rate values is due to the inaccuracy of the flow metering technique, operational field adjustments made to the manifolds, as well as a result of the

barometric pressure changes and its effect on the amount of methane being stored within the landfill's pore spaces. These effects are temporary and are cancelled out over a long period of time. Therefore, averaging the values over a long period would result in a good and representative flow rate data recorded for each area.

Based on the collected data, the total LFG recovery within the study boundaries in 2012 was approximately 1,758 ± 151 scfm, which is equivalent to nearly 9,000 tonnes of methane captured annually. Most of the captured methane was from Phase 1 with relatively newer waste, as well as greater amount of waste in place. Table 6.2 below presents the breakdown of the recovered methane for the four areas.

Table 6.2 Summary of methane recovery data for different areas of the work site

Area	**Footprint** (m^2)	**Waste in Place** (tonnes)	**Closure Year**	**Average LFG Flow Rate** (scfm)	**Annual CH_4 Recovery (R ± ΔR)** (tonnes $year^{-1}$)
Area 2W	259,700	2,010,492	1994	157 ± 43	792 ± 217
Area 2E	189,010	946,200	1996	142 ± 38	716 ± 207
Area 3	140,550	1,366,288	1999	193 ± 73	973 ± 378
Phase 1	242,261	4,470,903	2009	1264 ± 112	6,373 ± 565
Total	**831,521**	**8,793,883**		**1756 ± 151**	**8,853 ±761**

Chapter 7: LFG Generation Modeling Calibration and Verification

7.1 Initial iModel-110© Verification

The advanced LFG generation modeling verification was completed by conducting a methane mass balance under the simplified METRO equation. This would also allow for model calibration, which is described in the next section. The results of the initial methane generation assessment (see Table 3.17), fugitive methane emissions (see Table 4.6), methane oxidation (see Table 5.8), and methane recovery data (see Table 6.2), were used in this analysis. A summary of the methane mass balance analyses, for the entire study boundary is presented in Table 7.1.

Table 7.1 Summary of filed data for the study boundary

Source		Field Data (tonnes CH_4 year $^{-1}$)	
		Average	Std. Dev.
Emissions	E	1,481	± 431
Recovered	R	8,853	± 761
Oxidized	O	410	± 197
Total	**METRO**	**10,744**	**± 1,390**

According to the field data and based on the uncertainties associated with the measurement techniques, the total methane budget at the VLF in the year of the study was between 9,355 tonnes year^{-1} and 12,134 tonne year^{-1} of methane. Comparison of the results of the new model for the year of the study with this filed data was conducted based on the Equation 7.1 below:

$$\mathbf{G_i} = \sum_{i=1}^{n}\sum_{j=1}^{5}(\mathbf{983.2842} \times \boldsymbol{k_j} \times \boldsymbol{M_{ij}} \times \boldsymbol{w_j} \times \boldsymbol{DOC_{a_j}} \times \boldsymbol{e^{-k_j \times t_i}}) = E + R + O \pm (\Delta ERO)$$

Equation 7.1

Where the ΔERO is the sum of uncertainties associated with the three different field works described in Chapter 4, 5, and 6.

Figure 7.1 illustrates the initial methane generation modeling results for the entire work site lifespan, as well as the collected field data for the year of the study (2012). As shown in this figure, the initial methane generation estimate (G_i) is slightly higher than actual field data (ERO). However, the modeling results lies within the range of the field data taking into account the uncertainties associated with these field work experiments (i.e. ERO ± ΔERO).

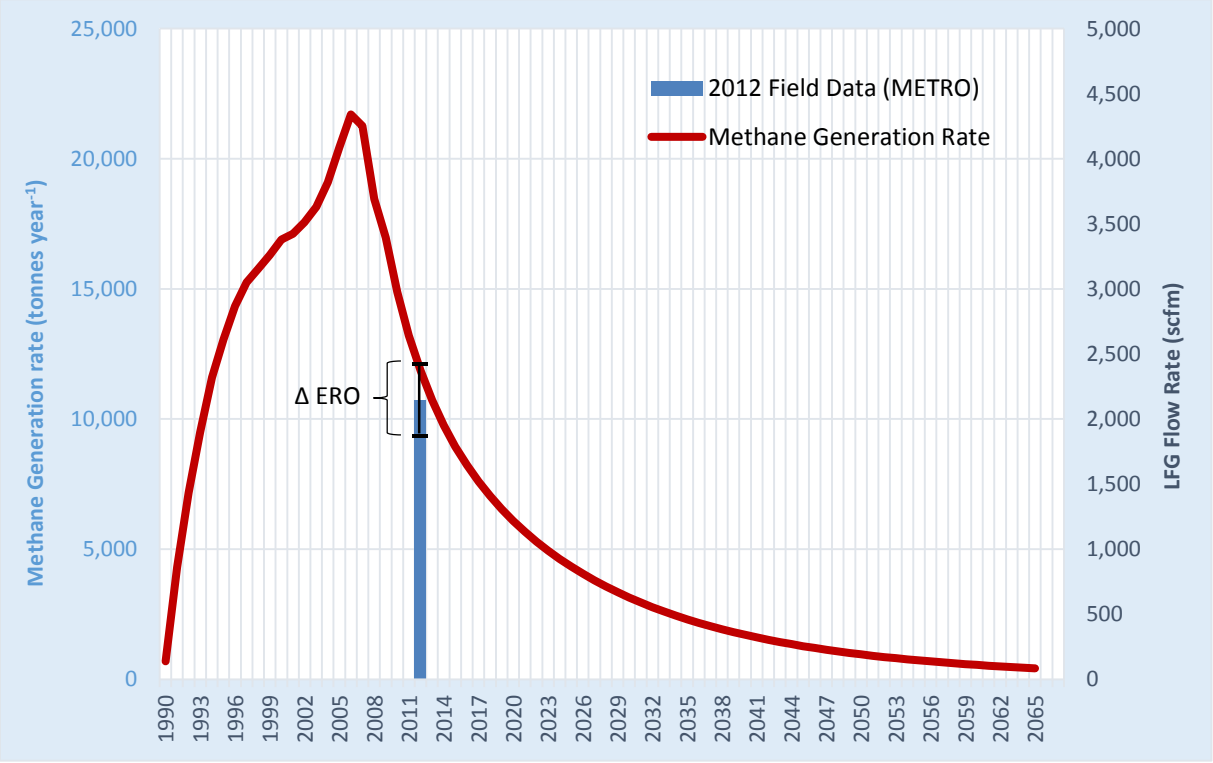


Figure 7.1 Comparison of initial modeling results and field data (G_i vs METRO)

Furthermore, this comparison for the four individual sites within the study boundary showed that the initial modelled methane generation rates (G_i) had approximately between -10% and +15% lack of fit with the field data. The average results for the study boundary showed an overestimation of 10.3% ± 11.8%. This suggested generation calibration factors (CF_G) of between 0.87 and 1.12 for these sites, with an average value of $CF_G = 0.91 \pm 0.12$. A summary of the methane mass balance analyses for the four individual sites, as well as the associated calibration factors, are presented in Table 7.2.

Table 7.2 Initial methane generation modeling lack of fit and suggested generation calibration factors

Area/ Phase	Methane Emissions	Methane Recovery	Oxidized Methane	initial Generation Assessment	Initial Assessment Overestimation	Correction Factors
	E	R	O	G_i	(Gi-∑ERO)/∑ERO	CF_G
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(%)	
Area 2W	466	792	119	1,585	15.2%	0.87
Area 2E	252	716	64	922	-10.7%	1.12
Area 3	367	973	94	1,547	7.9%	0.93
Phase 1	396	6,373	133	7,798	13.0%	0.89
				Average	10.3%	0.91
				StDev.	11.8%	0.12

7.2 Uncertainties in the New Modeling Predictions

A 10% lack of fit of the new model results with the average field data is relatively small and acceptable in the LFG industry. Nevertheless, it was tried to increase the accuracy of the predictions made by iModel-110 through calibration of the model based on the field data. Looking at Equation 3.5 and all the variables involved in development of the model's

predictions, the values for DOC_{dry} and k are the ones with a known range of uncertainties from which the default average values were selected and applied to the model. Based on the sensitivity analyses presented in the next Chapter, the extreme gas generation estimates (Upper Limit and Lower Limit) were identified. Sensitivity analyses showed that the maximum gas generation prediction in 2012 is achieved when the higher DOC_{dryH} values (See Table 8.3) are used along with the lower ranges of k_L values (See Table 8.5). Similarly, the lower gas generation prediction limit occurs when the lower DOC_{dryL} with higher k_H ranges are utilized.

Figure 7.2 illustrates these "extreme" Gi predictions for the work site, along with the initial gas generation estimates (Gi), as well as the field data (METRO) for 2012.

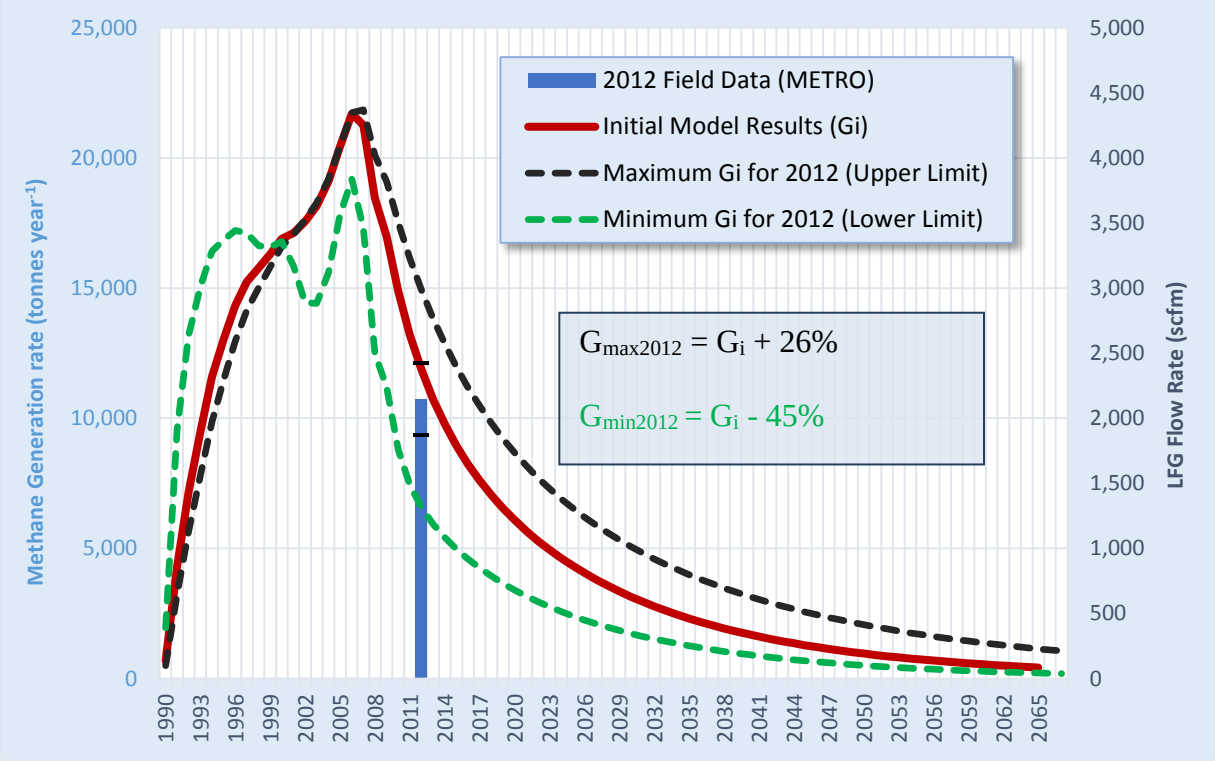


Figure 7.2 Upper limit and lower limit methane generation predictions for the study boundary

7.3 iModel-110© Calibration

There are two methods discussed here to calibrate the new model. Both of these methods involve fine tuning of the modeling parameters, more specifically, the DOC_{dry} and k values. The default values for these parameters are selected from a range for each organic waste type. Fine-tuning the value of these parameters based on the field data is believed to further increase the accuracy of the new model methane generation predictions.

7.3.1 LFG Generation Calibration Factor (CF_G)

As discussed before, the CF_G is a multiplier to the values of the DOC_{dry} which have a direct relation with the final value of methane generation potential (methane yield). Therefore, application of CF_G shifts the entire gas generation curve to fit the 2012 generation estimate to the 2012 field data. As shown in Section 7.1, the average resulting generation correction factor from the field work was $CF_G = 0.91 \pm 0.12$. This average correction factor, and the deviation range, was incorporated into the model to develop lower range and higher range methane generation estimates for the work site. The results of the calibrated model, using the average CF_G, showed that the methane yield for Areas 2W, 2E, 3, and Phase 1 was respectively, 83, 83, 79, and 70 m^3 CH_4 per tonne of waste. Furthermore, the collection efficiencies of the active LFG collection systems in these areas were 55%, 86%, 69%, and 90%, respectively, with an overall collection efficiency of 82% within the study boundaries.

The calibrated methane generation estimates for each area, using the average calibration factor, as well as the lower range and the higher range of the methane generation estimates for the entire study boundaries, are illustrated in Figure 7.3. These results are also summarized in Table 7.3.

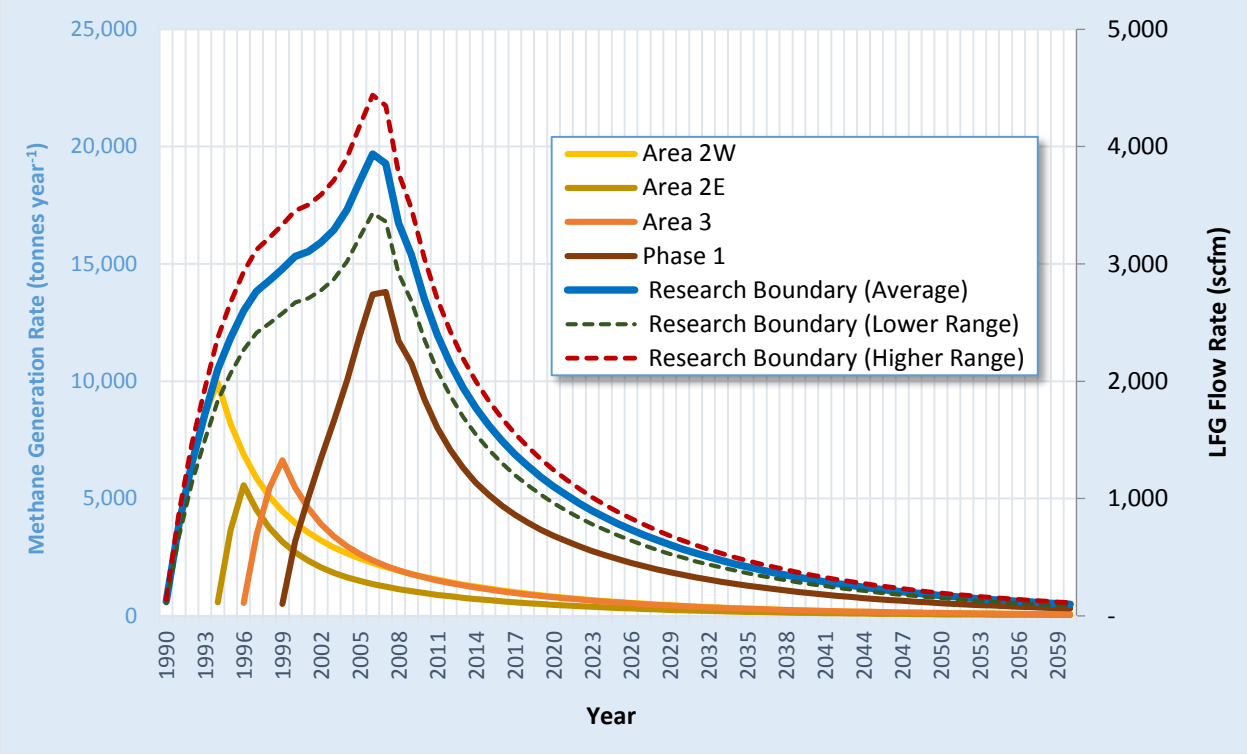


Figure 7.3 Methane generation modeling results with calibrated generation potential (CF_G)

Table 7.3 Summary of the calibrated modeling results (using CF_G) and the corresponding methane capture efficiency

Area/ Phase	Cover System	Waste in Place (tonnes)	Average Methane Yield (m^3 $tonne^{-1}$)	2012 Methane Generation Estimate (tonnes $year^{-1}$)	Methane Capture Efficiency (%)	
Area 2W	Intermediate	2,010,492	83	1,437	55	70 ± 15
Area 2E	Intermediate	946,200	83	836	86	
Area 3	Intermediate	1,366,288	79	1,402	69	
Phase 1	Final Cover	4,470,903	70	7,069	90	
Total		8,793,883	76	10,744	82	

Based on the calibrated model using the generation calibration factor (CF_G) the average methane collection efficiency for areas with an intermediate cover system (i.e. Areas 2W, 2E, and 3) was

70% ± 15%. The modeling results and the historical methane recovery data for Phase 1 showed that the methane capture efficiency in this phase, before installation of the geomembrane cap, was approximately 65% to 70%. However, this capture efficiency has increased to approximately 80% to 90% since 2009, due to the installation of the geomembrane cap and the modifications made to the LFG collection system. These capture efficiency values are in good agreement with what Spokas et al. (2006) and SCS Engineers (2009), reported for the capture efficiencies for active LFG collection systems. Results of the comprehensive study by Spokas et al. (2006), which are used as the default values for the guidelines by the French environment agency (ADEME), showed collection efficiencies of: 35% for an active (operating) phase, 65% for phases covered with a temporary cap, 85% for phases covered with an impermeable (clay) cover soil, and 90% for phases covered with a geomembrane final cover. SCS Engineers (2009), in a study conducted at the national level in the U.S. for the *Solid Waste Industry for Climate Solutions* (SWICS), concluded that the methane collection efficiency at regulated sites in the US landfills, where the best LFG management practices were applied, were between 75% and 95%. Accordingly, for landfills with an active LFG collection system, the SWICS has adopted its GHG reporting rule based on the methane capture efficiencies of: 95% for areas with final cover, 75% for areas with intermediate cover, and 60% for areas that have a daily cover system in place.

7.3.2 Revised iModel-110© Verification

In order to verify the results of the calibrated model, methane generation rates from the Phase 2 of the Vancouver Landfill were estimated using the iModel-110© over the defined range for the generation calibration factor. As shown in Table 2.3, this phase has received approximately 3.5

million tonnes of waste within the two operational periods of 1982-1985 and 2006-2009. Based on the available data, three different waste compositions were applicable to these periods. These data were applied to the model to estimate the methane yield value for this phase. Furthermore, the available SMC data for this phase were expressed in terms of the total amount of methane emission (E) from the area. A conservative oxidation efficiency of 28% was used to estimate the total methane oxidation. Also, the average collected LFG flow rate, adjusted for 50% methane content, was used to estimate the methane recovery (R).

The modeling results for the Phase 2 of the VLF showed a methane generation rate between 6,509 tonnes $year^{-1}$ and 8,419 tonnes $year^{-1}$, with an average value of 7,464 tonnes $year^{-1}$. These values show the lower range and higher range for the generation estimate, which results from using the CF_G range, which was previously developed over the areas within the study boundaries. Furthermore, the total methane emission, the total amount of recovered methane, and the total amount of oxidized methane for this phase was, 3,123 tonnes $year^{-1}$, 3,529 tonnes $year^{-1}$, and 798 tonnes $year^{-1}$, respectively. Therefore, the total mass of methane calculated from the simplified METRO was approximately 7,450 tonnes $year^{-1}$, which was very close to the field data and within ±13% of the higher range and the lower range of the model predictions. The results suggested that the methane capture efficiency for this phase of the VLF ranged between 42% and 54%. Phase 2 had an intermediate cover system and horizontal LFG collectors at the time of the analyses.

7.3.3 LFG Generation Rates Calibration Factor (CF_k)

In this method, the value of the decay rates for different organic waste types were calibrated based on the results of the field work as well as the sensitivity analyses presented in the next chapter. This approach is somewhat similar to what is achieved through conducting a LFG pump test. The LFG pump test is a standard approach developed by the US EPA (EPA – Method 2e) to define site specific LFG modeling parameters. In this method the methane generation potential is selected based on the best knowledge about the site, and a site specific k value is calculated based on the volume of methane extracted from a known volume of organic waste.

This approach was followed to calibrate the value of the decay rates for the work site based on the comprehensive field investigations data and considering that methane generation potential was estimated based on good quality data available for the VLF. The initial decay rate values were initially selected from literature and based on the average of the suggest half-lives range for each organic waste type (See Table 3.15). Calibration of the values was conducted based on the results of the sensitivity analysis illustrated in Figure 8.2. Table 7.4 presents the range, default, and calibrated decay rate values for different types of organic waste at the VLF.

Table 7.4 Calibrated decay rate values for different organic wastes at the VLF

Waste Components	Decay Rate Values (k, $year^{-1}$)			
	Range		Default	**Calibrated**
Food waste	0.23	0.69	0.35	**0.455**
Garden	0.10	0.23	0.14	**0.182**
Paper	0.05	0.14	0.07	**0.063**
Wood and straw	0.03	0.05	0.04	**0.032**
Textiles	0.05	0.14	0.07	**0.063**
Disposable nappies	0.05	0.14	0.07	**0.063**

The calibrated model, using the calibrated decay rates, showed a slightly higher methane generation results in comparison to the initial generation estimates (G_i). Comparing the results of the calibrated model with the results derived from application of the lower range and the higher range CF_G to Gi, showed that the calibrated predictions lies within the previous methane generation estimation range. The calibrated methane generation estimates for each area and the entire work site as well as the values based on the lower range and the higher range CF_G are illustrated in Figure 7.4Figure 7.3

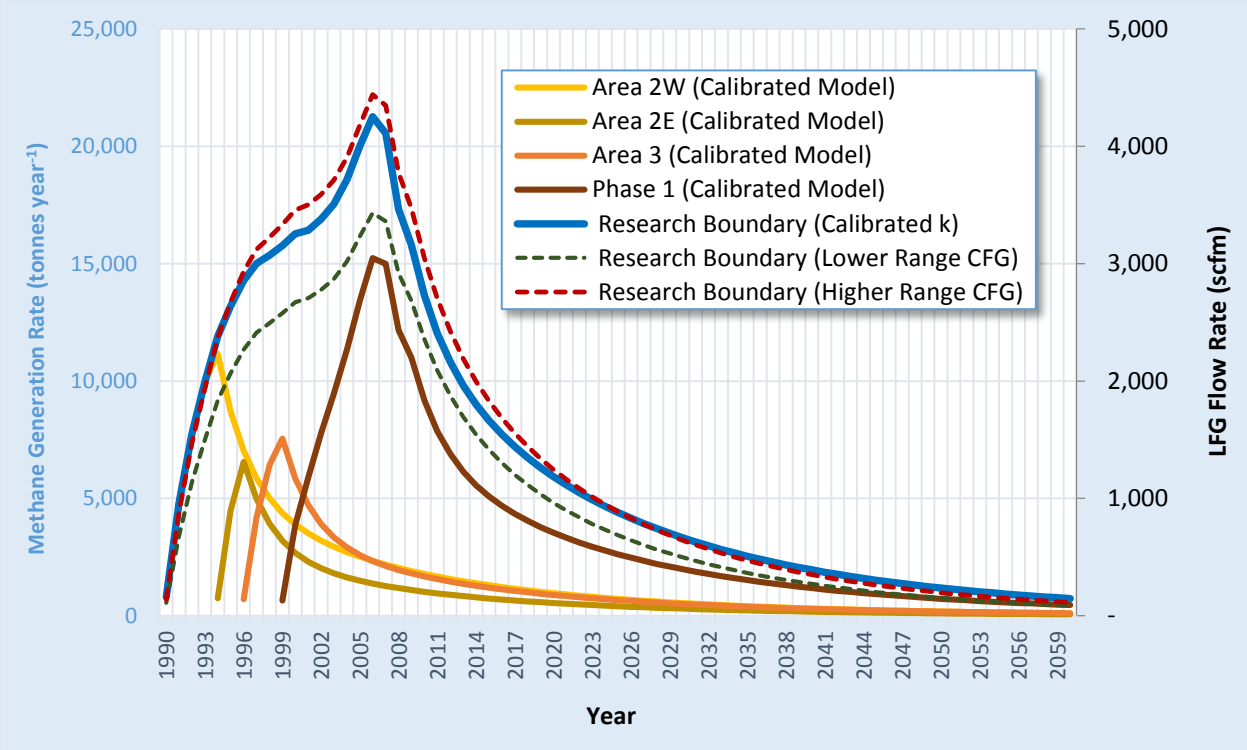


Figure 7.4 Modeling results with calibrated k values in comparison to the results with lower and higher CF_G

As expected, calibrating the decay rate had no effect on the methane generation potential values. Therefore, according to the calibrated model, the methane yield values for Areas 2W, 2E, 3, and Phase 1 of the VLF was respectively, 91, 91, 87, and 77 m^3 CH_4 per tonne of waste. Furthermore, the collection efficiencies of the active LFG collection systems in these areas were 50%, 80%, 67%, and 93%, respectively, with an overall collection efficiency of 82% within the study boundaries. These results are also summarized in Table 7.5.

Table 7.5 Summary of the calibrated modeling results (using CF_k) and the corresponding methane capture efficiency

Area/ Phase	Cover System	Waste in Place (tonnes)	Average Methane Yield (m^3 $tonne^{-1}$)	2012 Methane Generation Estimate (tonnes $year^{-1}$)	Methane Capture Efficiency (%)	
Area 2W	Intermediate	2,010,492	91	1,568	50	66 ± 15
Area 2E	Intermediate	946,200	91	890	80	
Area 3	Intermediate	1,366,288	87	1,455	67	
Phase 1	Final Cover	4,470,903	77	6,886	93	
Total		8,793,883	83	10,798	82	

Based on the calibrated model using the decay rate calibration factor (CF_k) the average methane collection efficiency for areas with an intermediate cover system (i.e. Areas 2W, 2E, and 3) was 66% ± 15%. The calibrated model also showed that the methane capture efficiency in Phase 1 of the VLF was 93% in the year of the study. This value for the entire study boundary was 82% in 2012.

7.4 Methane Generation Estimates for the Entire Vancouver Landfill

The new model was run for the entire Vancouver Landfill site, including the MSW and DLC waste disposal activities between 1967 and 2011. Furthermore, the methane generation assessment was conducted using the BC MOE Tool, where the refined waste composition information was used for both models. The iModel-110© was run for three scenarios: Scenarios A1 and A2, respectively using the lower range and the higher range CF_G (i.e. $CF_{G.L}$ = 0.7906, and $CF_{G.H}$ = 1.0226), and Scenario A3 based on the CF_G = 1 and utilization of the calibrated values of the decay rates. The BC MOE Tool was also run for two scenarios: Scenario B1, based on the entire amount of waste that was historically deposited at the site, and Scenario B2, based on the MOE recommendation, considering the waste mass that has deposited during only the past 30 years.

Based on the results achieved from the calibrated iModel-110©, the average methane yield for the entire VLF ranged between 68 and 89 m^3 CH_4 per tonne of waste, while the MOE Tool used a higher value of 102 m^3 CH_4 per tonne of waste. This translates to 15% to 49% overestimation of the BC MOE Model in comparison to the methane generation prediction range achieved by the new model. Consequently, the resulting methane capture efficiency for the entire VLF in 2012, based on the new model lower range and the higher range estimates, was between 79% and 61%. Whereas, the MOE Tool concluded collection efficiencies of 53% and 55%, based on the Scenarios B1 and B2, respectively.

The modeling results for the entire VLF site based on the five scenarios are illustrated in Figure 7.5. Results are also summarized Table 7.6.

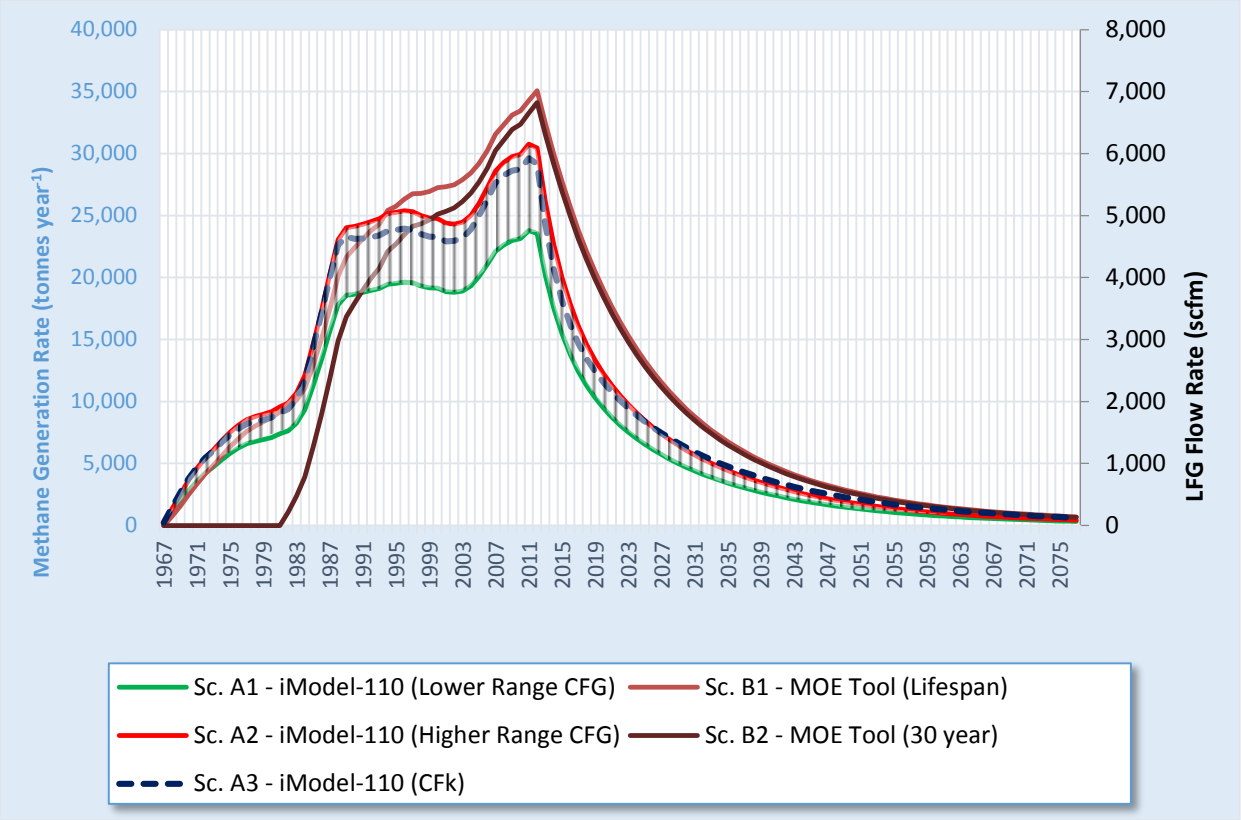


Figure 7.5 Methane generation and LFG flow rate estimates for the entire Vancouver Landfill site (for the disposal activities until end of 2011)

Table 7.6 Methane generation modeling results for the VLF using the iModel-110© and the MOE Tool

Scenarios	Average Methane Yield* L_o (m^3 $tonne^{-1}$)	2012 Generation Estimates		2012 Capture Efficiency**
		CH4 (tonnes $year^{-1}$)	LFG (scfm)	
Sc. A1 - iModel-110 (Lower Range CF_G)	68	23,546	4,670	79%
Sc. A2 - iModel-110 (Higher Range CF_G)	89	30,456	6,041	61%
Sc. A3 - iModel-110 (Calibrated k)	86	29,159	5,784	64%
Sc. B1 - MOE Tool (Lifespan)	102	35,064	6,955	53%
Sc. B2 - MOE Tool (30 year disposal)	102	34,107	6,765	55%

* Calculated based on the lifespan methane generation and the tonnage of waste in place

** Based on ~3,700 scfm collected LFG flow rate during spring 2012, adjusted for 50% methane content

Furthermore, in order to compare the new model predictions to the popular models previously discussed in Chapter 1, the iModel-110© was run for the VLF Phase 1. The modeling was conducted using the lower limit and higher limit CF_G, as well as using the calibrated decay rates. The methane generation estimates obtained from the six different methodologies previously discussed in Chapter 1, along with the new model predictions are illustrated in Figure 7.6.

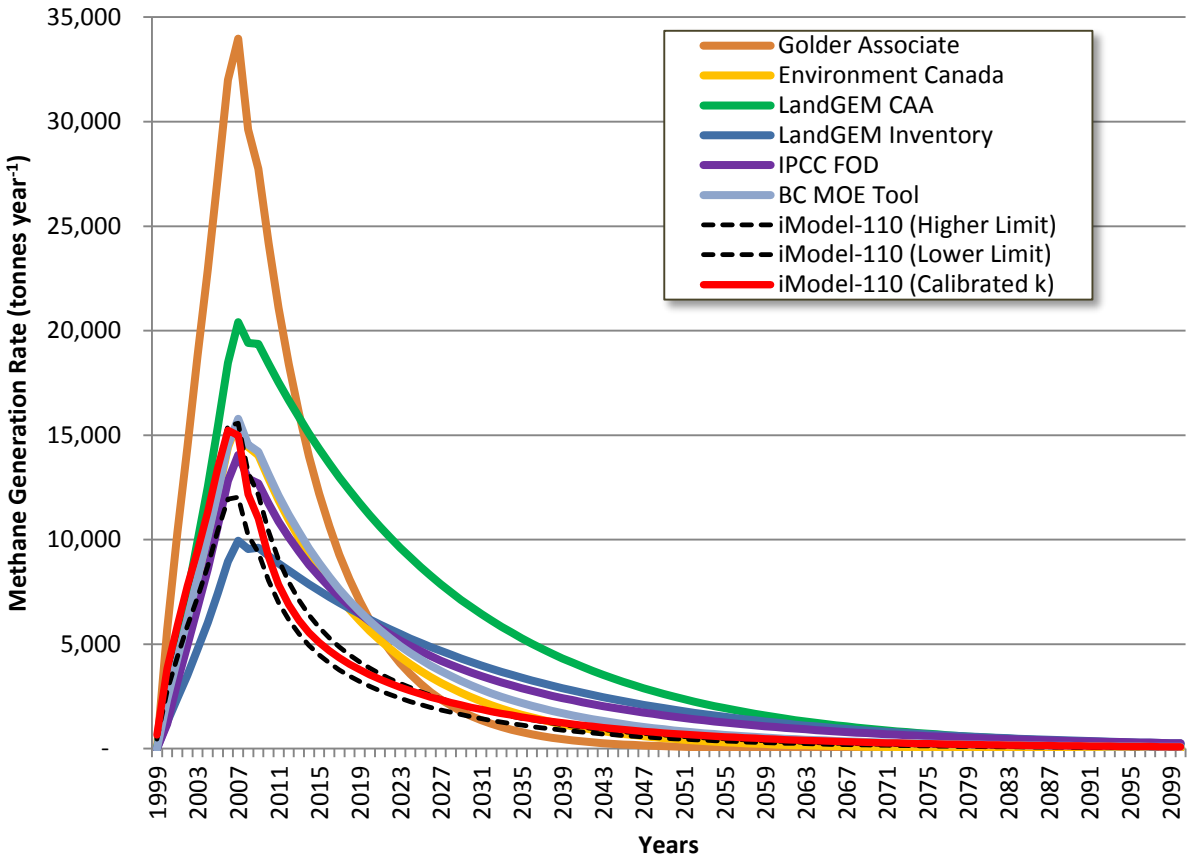


Figure 7.6 Comparison of the new model predictions with other six popular LFG generation models

Chapter 8: Landfill Gas Modeling Uncertainties and Sensitivity Analysis

8.1 Introduction

Given the heterogeneity of landfills, field measurement inaccuracies, discrepancies between the "selected" values for some parameters vs. their "true" values, and the variety of design and operational conditions between landfills, uncertainty in a LFG generation assessment is unavoidable. These "modeling errors" are mainly associated with a lack of reliable historical records regarding disposal tonnages, measurement inaccuracies, as well as lack of an advanced procedure for selection of site-specific modeling parameters, methane yield (L_o, m^3 CH_4 $tonne^{-1}$), and methane generation rate (k, $year^{-1}$). Many studies have compared limited site-specific field data with modeled results, concluding an overestimation of the theoretical assessments (Vogt and Augenstein, 1997; Spokas et al., 2006). Nevertheless, the magnitude of modeling errors has rarely been quantified in large scale for any of the existing models.

One of the main objectives of the present study was to use the results of many well-established research studies as fundamental grounds for the purpose of reducing modeling uncertainties through the selection of more meaningful and site-specific modeling parameters. Furthermore, several field investigations were carried out to conduct a full scale methane mass balance in four separate areas of the Vancouver landfill, based on the concept of the METRO equation, and the field data with regard to methane recovery and all other possible pathways. Therefore, the modeling error was further reduced by application of the developed calibration factors, CF_G and CF_k, to the site-specific L_o and k values, respectively. However, two main sources of uncertainty remain, which may create discrepancies between the model predictions and the field data.

These two uncertainty groups are: (i) modeling errors and (ii) calibration errors, which are discussed in this chapter.

8.2 LFG Modeling Errors Due to Input Parameters Uncertainties (G_i-Err)

The modeling errors are sourced from the input data and the modeling parameters. Reported waste disposal tonnages, composition, and as-received moisture content are the main sources of uncertainty in this category. These values are translated to the available DOC in the landfill and ultimately to methane yield ($L_\circ$) and uncertainty in these parameters will eventually result in modeling errors and uncertainties in the estimation of the total methane generation throughout the landfill's lifespan. Error in the decay rate, however, only affects the distribution of the generated methane throughout the landfill's lifespan.

In general, variables contributing to the uncertainty in methane yield or the total amount of methane generation include:

(i) waste disposal rate,

(ii) waste composition,

(iii) waste moisture content,

(iv) DOC content, and

(v) degradability of DOC.

As discussed in Section 1.4, the suggested methane yield in different LFG generation models for VLF varied between 88 and 170 m^3 methane per tonne of waste. The IPCC FOD, as the most sophisticated methodology amongst them, calculates the $L_\circ$ value based on the DOC content of

wet components of the waste, as well as a constant decomposable fraction of 0.5 for all the waste components.

As described in Section 3.2, development of a variable value for L_o, suggested in iModel-110©, minimized the modeling errors to some extent. The variable L_o values were developed based on the weighed data at VLF, moisture content of the waste component as received at the disposal facility, DOC_{dry} content associated with each organic material, and the actual waste composition physical analysis data, generated by Metro Vancouver since 1991 (See Table 2.4). Furthermore, instead of using the constant decomposable fraction of 0.5, suggested by IPCC (2006), various values for different types of organic material were introduced based on degradability and bio-availability of the materials in the landfill. Nevertheless, one of the major uncertainty sources for L_o relates to the uncertainty range given for values of DOC_{dry} for different waste components (see Table 3.1). These uncertainty ranges, suggested based on the maximum and minimum values developed by well-established and widely accepted research studies, result in an uncertainty in methane generation estimates ($(G_i\text{-}Err)_{DOC}$).

Table 8.1 Low and high DOC_{dry} values for different organic wastes deposited at VLF

Organic Wastes	DOC_{dry} (%)	
	Lower Range	Higher Range
Paper and Cardboard	40	50
Textiles and Nappies	25	50
Food waste	20	50
Wood waste	46	54
Yard waste	45	55

As shown in Table 8.1, the values for most of the organics have a narrow range (mean±10%). Food waste and textiles have the highest variability with lower range and higher range within

±40% of the default value. Nevertheless, to conduct a sensitivity analysis, effect of up to 50% variation in the default DOC_{dry} values on the model predictions was studied. As illustrated in Figure 8.1, variations in DOC_{dry} value of paper waste had the highest effect in model predictions for 2012. However, considering the range of this value (DOC_{dry} paper = 0.45 ± 11%), the actual effect of variation of this value within the range was about 5% of the 2012 methane generation prediction. This effect was similar for textile and food waste respectively with maximum of 42% and 39% variation in the DOC value, resulting in approximately 5% variation in the 2012 methane generation predictions.

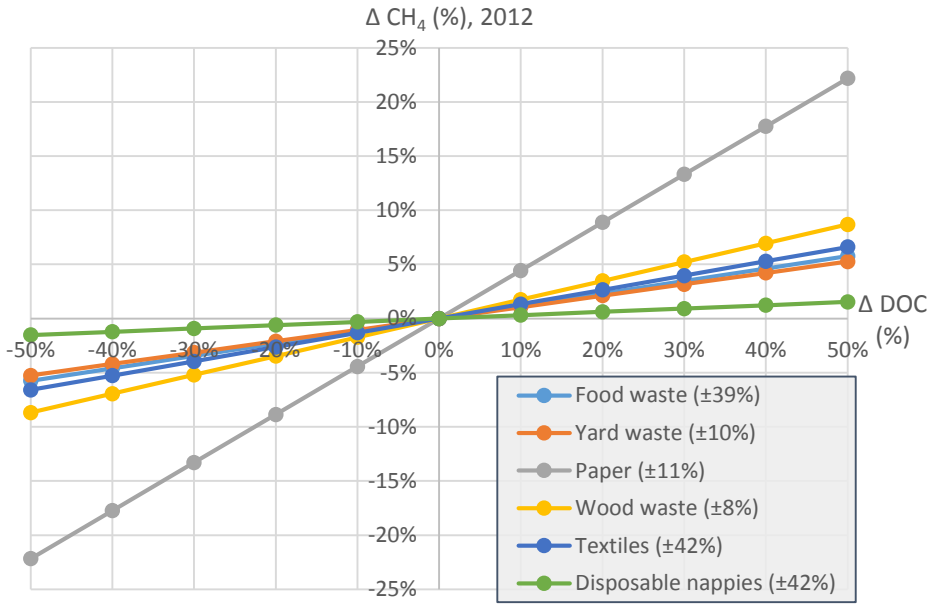


Figure 8.1 Sensitivity analysis, ΔDOC vs. ΔCH_4 (methane generation estimate for 2012)

The DOC bio-availability discount factors are also parameters related to possible uncertainty in methane generation estimates $(G_i\text{-}Err)_{\sum d}$. These parameters are considered to account for operational, climatic, and design conditions which cause the landfill environment to drift from

one that is optimal for anaerobic biodegradation. $(G_i\text{-}Err)_{DOC}$ and $(G_i\text{-}Err)_{\sum d}$ are further discussed in Section 8.2.1 below.

Furthermore, to increase the modeling accuracy, given the actual environmental conditions provided for the anaerobic bacterial activity within VLF, the use of different decay rates for six different types of organic materials were suggested. The field investigations, previously discussed in Section 3.3.1, showed that the temperate climatic condition of Vancouver does not affect the landfill temperature and the decomposition reaction rates. Therefore, the half-lives of organic materials suggested by well-established research studies were used to define more accurate values for decay rates. These values were the average values from the suggested ranges for the half-lives of different organic materials. Table 8.2 presents the ranges of half-lives and the associated decay rates selected for VLF, with an explanation that the lower k values correspond to the longer half-lives.

Table 8.2 Low and high ranges of half-lives and decay rates for different organic wastes at VLF

Waste Components	Half-life (year)		decay rates (k, year $^{-1}$)	
	Low	High	Low	High
Food Waste	1	3	0.23	0.69
Yard Waste	3	7	0.10	0.23
Paper and Textile	5	15	0.05	0.14
Wood Waste	15	20	0.03	0.05

With a similar approach explained above, a sensitivity analysis for the decay rates was conducted and the effect of up to 50% variation in the default k values on the model predictions was studied. As illustrated in Figure 8.2, variations in k value of food waste had the highest effect in

model predictions for 2012. The analysis showed that if the k value assigned to food waste is smaller than the "true" value for this parameter, this can result in more than 10% overestimation of the model prediction. Result of this analysis was utilized as a basis to calibrate the decay rate values for the new model based on the field data collected over the four sites within the study boundary.

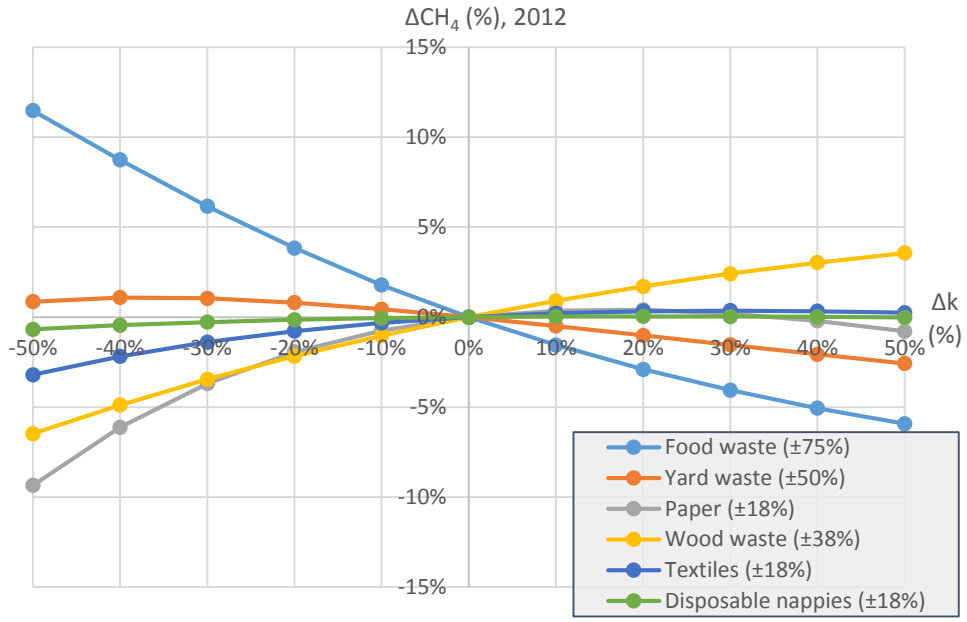


Figure 8.2 Sensitivity analysis, Δk vs. ΔCH_4 (methane generation estimate for 2012)

The uncertainty in methane generation estimates resulting from the uncertainty ranges $((G_i\text{-}Err)_k)$ are further discussed in Section 8.2.2.

8.2.1 LFG Modeling Errors Due to DOC Uncertainty Range $(G_i\text{-}Err)_{DOC}$

A sensitivity analysis was performed on the effect of the uncertainty range for the DOC_{dry} values by re-running the model for the entire work site. The predicted methane generation results from application of the lower range DOC values (Scenario A), and the higher range values (Scenario

B), were compared with the results with the initial and the calibrated methane generation estimates (G_i and G, respectively). This analysis showed that the average methane yield value in the study boundaries could vary between 62 and 93 m^3 CH_4 per tonne of waste, resulting in current methane capture efficiency of 96% to 67% for Scenarios A and B, respectively. As shown in Table 8.3, the deviation in L_o value from the calibrated L_o was between -18% (18% underestimation) and 24% (overestimation).

Figure 8.3 shows that this deviation in methane generation rate, hence methane capture efficiency, varies depending on the year of assessment. For instance, the deviation in the assessed methane generation rate in 2006 was between -22% and 25%, while this value for 2012 was between 14% and 23%.

Table 8.3 Methane generation and capture efficiency deviations in the VLF (within the study boundaries) resulted from application of lower and higher ranges of DOC values

Scenarios	Methane Generation Estimates (tonnes)			Methane Yield, L_o (m^3 $tonne^{-1}$)	Capture Efficiency (CE_{2012})	Deviation from Field Measurements $(G_i\text{-}Err)_{DOC}$
	Life time	Peak	2012			
Initial Assessment (G_i)	496,354	21,706	11,851	83	75%	10.3%
Calibrated Model ($G = G_i \times CF_G$)	449,994	19,678	10,744	76	82%	0.0%
A. Lower Range (DOC_L)	367,820	15,349	9,193	62	96%	-18.3%
B. Higher Range (DOC_H)	556,079	24,614	13,236	93	67%	23.6%

While the developed methane generation calibration factor (CF_G) lies within the resulting uncertainty range in this analysis, the variations of the results for different assessment years may suggest that conducting the field work to develop this number in a different year would have resulted in a different CF_G value.

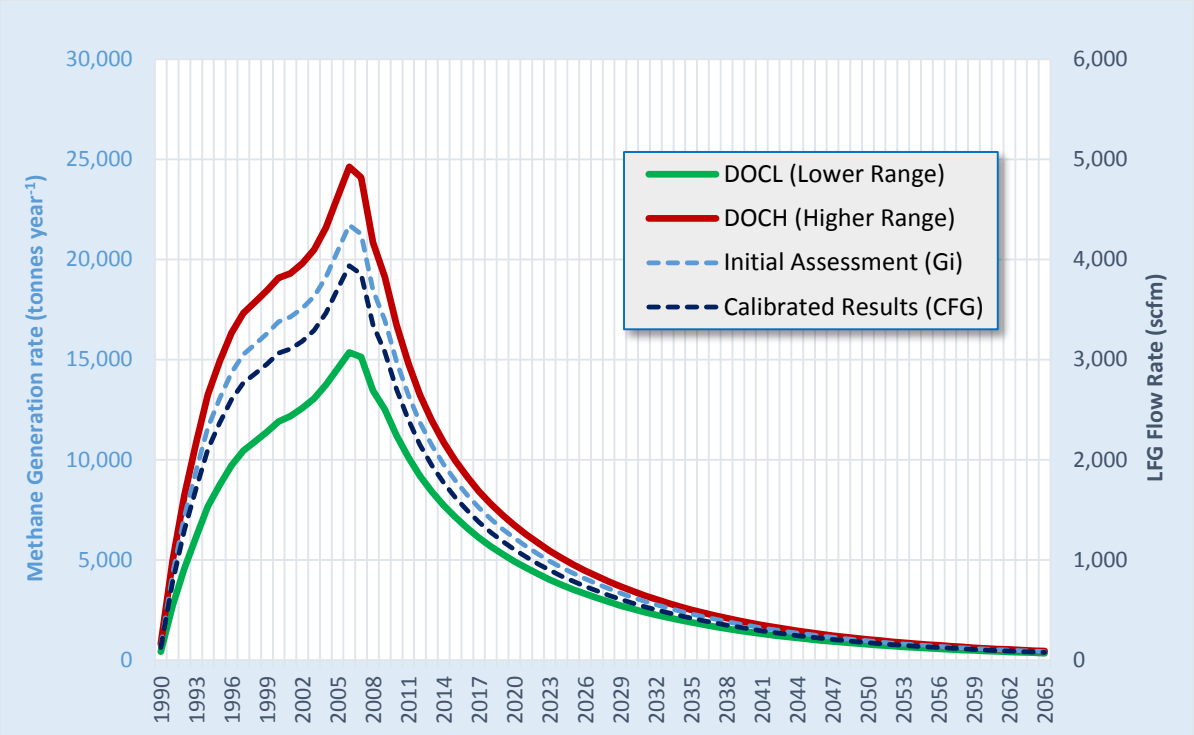


Figure 8.3 Graphical illustration of methane generation with lower and higher DOC ranges in comparison with the initial (Gi) and the calibrated modeling results

Other parameters affecting the final values of the available DOC and L_o include a series of discount factors discussed in Section 3.2. In order to evaluate the impact of these factors on the refined model results, a value of 1 was assigned to all discount factors except for the degradability factor. Methane generation results were compared with the initial and the calibrated results as presented in Table 8.4.

Table 8.4 Effect of DOC discount factors on methane generation estimates

Scenarios	Methane Generation Estimates (tonnes)			Methane Yield, L_o (m^3 $tonne^{-1}$)	Capture Efficiency (CE_{2012})	Deviation from True Value $(G_i\text{-}Err)_{\sum d}$
	Life time	Peak	2012			
Initial Assessment	496,354	21,706	11,851	83	75%	10.3%
Calibrated Model	449,994	19,678	10,744	76	82%	0.0%
∑discount factor = 1	581,869	26,041	13,546	98	65%	29.3%

In this scenario, the value of L_o for VLF between 1990 and 2008 ranged from 88 to 112 m^3 methane per tonne of waste, with an average amount of 97.7 m^3 $tonne^{-1}$. This analysis showed that the elimination of the DOC bio-availability discount factors, which were defined to increase the accuracy of the modeling results, will change the modeling results from the true value (calibrated results) as much as 29%.

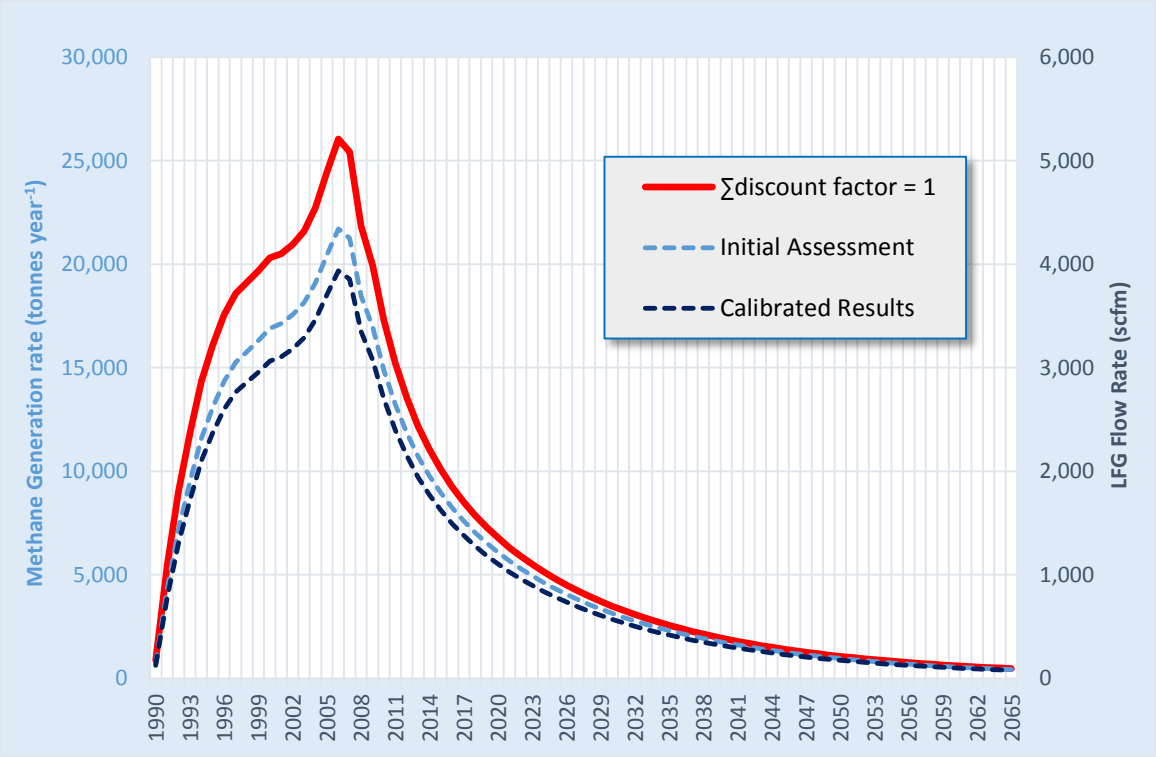


Figure 8.4 Effect of DOC discount factors on methane generation estimates

8.2.2 LFG Modeling Errors Due to Decay Rates Uncertainty Range $(G_i\text{-}Err)_k$

Similarly, a sensitivity analysis was performed on the effect of the uncertainty range for the decay values by re-running the model for the entire work site. The methane generation results from application of the lower range decay values (k_L), and the higher range values (k_H), were

compared with the results of the methane generation assessment. The uncertainties related to the decay rates only affect the distribution of the methane generation levels over the landfill's lifespan and would not change the total lifespan methane generation or the methane yield values. Therefore, in order to conduct a valid comparison, results of the initial methane generation assessment (G_i) were used as the basis, where the $CF_G = 1$ allowing similar L_o values for the three model re-runs.

As shown in Table 8.5, the maximum deviations in the current methane generation rates, in comparison with the initial methane generation assessment results, were 0.2% and -16.5% for the lower and the higher range k values, respectively.

Table 8.5 Methane generation uncertainties due to the decay rates uncertainty range

Scenarios	Methane Generation Estimates (tonnes)			Methane Yield, L_o (m^3 $tonne^{-1}$)	Capture Efficiency (CE)	Deviation from the Initial Assessment $(G_i\text{-}Err)_k$
	Life time	Peak	2012			
Initial Assessment	496,354	21,706	11,851	83	75%	n/a
Lower Range (k_L)	495,685	18,571	11,877	83	75%	0.2%
Higher Range (k_H)	496,537	25,790	9,890	83	90%	-16.5%

The resulting deviations due to the decay rates' uncertainty range seemed to be relatively small. However, depending on the year of assessment, this deviation can increase to more than 100% of the modeling results. As shown in Table 8.6, for the period of 1991 to 2038, when approximately 95% of the lifespan methane generation from the work site would occur, the decay rates uncertainty range resulted in 103% deviation from the estimated methane generation (i.e. $(G_i\text{-}Err)_k = \pm 103\%$). Similarly, for the period of 2001 to 2016, with approximately 50% of the

total methane estimated to be generated within this timeframe, the $(G_i\text{-Err})_k$ value was about 37%, as illustrated in Figure 8.5.

Table 8.6 Maximum deviations in generation estimates due to decay rates for different lifespan periods

Selected Period	Methane Generation within Period	Percent of Total Generation	Deviation from Modeling Results $(G_i\text{-Err})_k$
2001 - 2016	211,521	~50%	37%
1992 - 2032	378,168	~90%	88%
1991 - 2038	393,338	~95%	103%

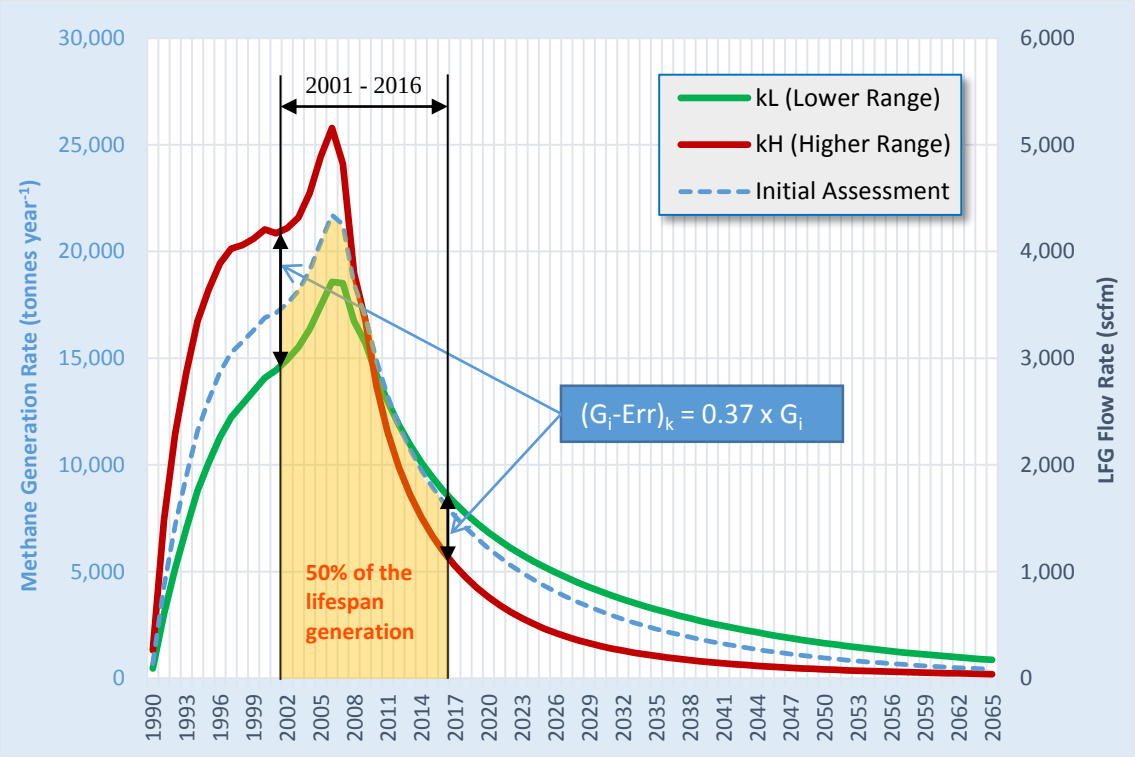


Figure 8.5 Methane generation uncertainties due to the decay rates uncertainty range

8.2.3 MSW Moisture Content and the Associated LFG Modeling Errors $(G_i\text{-}Err)_w$

One of the steps to increase the accuracy of the methane generation estimates was the attempt to consider the moisture content of waste components as they are received at the disposal facility (as-received), instead of basing the DOC value calculations on reported waste moisture content at the sources of waste generation, such as households, schools, etc. (as-generated). Therefore, a sensitivity analysis was performed on the effect of application of the moisture content reported for MSW organic components by Tchobanoglous et al. (1993), in comparison with the moisture content that was initially used to assess the methane generation within the study boundaries. The methane generation results from the application of the as-generated moisture content was relatively close to the initial methane generation assessment, with methane yield of 83 and 82 m^3 methane per tonne of waste, respectively. As shown in Table 8.7, the resulting deviation in the current methane generation estimate and the capture efficiency from the calibrated modeling results was 9%, very close to the generation correction factor (CF_G) which was developed based on the field study at VLF.

Table 8.7 Methane generation uncertainties due to organic material moisture content

Scenarios	Methane Generation Estimates (tonnes)			Methane Yield (m^3 $tonne^{-1}$)	2012 Capture Efficiency	Deviation from Field Measurements
	Life time	Peak	2012	L_o	(CE)	$(G_i\text{-}Err)_w$
Initial Assessment	496,354	21,706	11,851	83	75%	10.2%
Calibrated Model	449,994	19,678	10,744	76	82%	0.0%
Moisture Content at Source	490,481	20,267	12,346	82	72%	9.0%

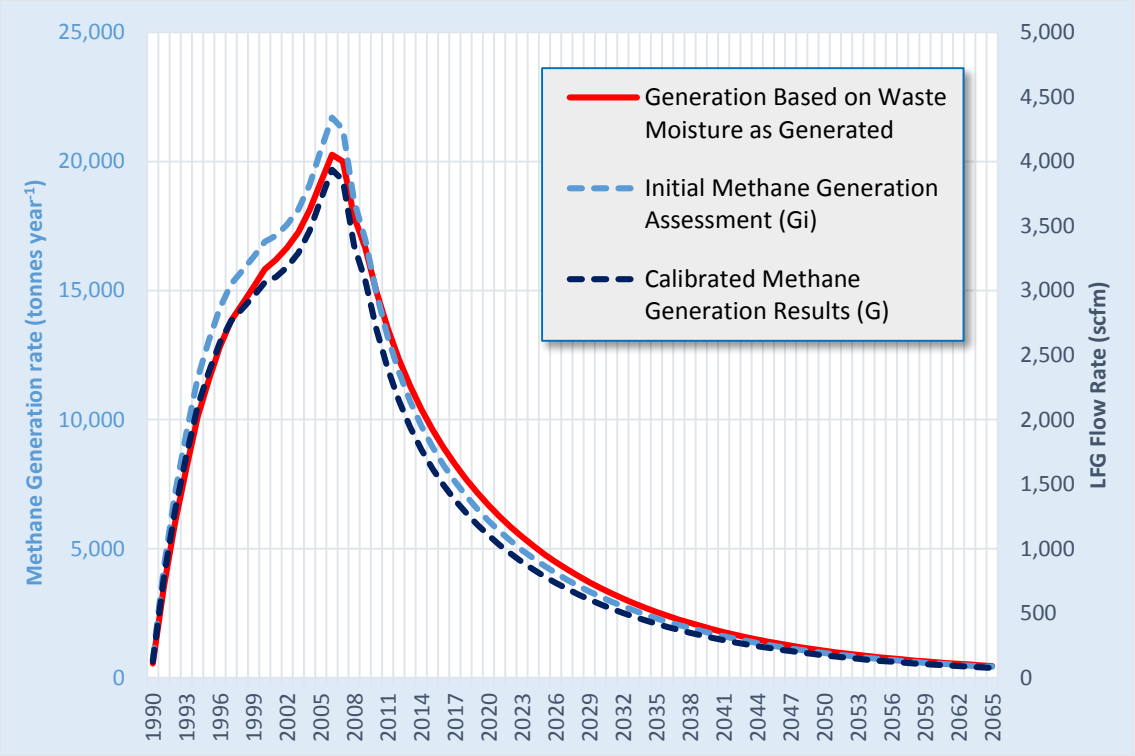


Figure 8.6 Methane generation uncertainties due to organic material moisture content

Even though the effect of the organic material moisture content seems to be relatively insignificant, a proper waste composition analysis, including waste moisture content measurements, at VLF will provide useful information. This information will allow for an even more accurate estimation of L_o, methane generation rate, and methane capture efficiency.

8.3 Calibration Errors Resulted from the Field Study Deviations (CF_G-Err)

As part of the iModel-110©, the methane generation calibration factor (CF_G) was developed based on the field investigations on methane emission, oxidation, and recovery, described in Chapters 4, 5, and 6, respectively. This information was required to integrate the right side of the simplified METRO equitation, allowing for the quantification of a necessary methane generation calibration factor (CF_G) to be applied to the initial generation estimates on the left side of the

equation. However, field measurements themselves bear uncertainty associated with measurement techniques, instrumentation limitations, and sampling errors. These uncertainties created a range of error in the calibration factor (CF_G-Err), which results in a deviation in the final modeling results from the true value.

The CF_G-Err values corresponding to different field work were recognized through three different distinct values: (i) errors due to emission measurement uncertainties ($(CF_G\text{-Err})_E$), (ii) errors due to the uncertainties in the methane oxidation quantification ($(CF_G\text{-Err})_O$), and (iii) errors resulted by the uncertainties in the methane recovery data ($(CF_G\text{-Err})_R$). A collective overlook of these uncertainties and errors resulted from these field investigations was previously discussed in Section 7.1. These errors are individually assessed and described in Sections 8.3.1, 8.3.2, and 8.3.3, respectively.

8.3.1 Errors Due to the Methane Emission Measurement Uncertainties $(CF_G\text{-Err})_E$

As described in Chapter 4, the total methane emission (E) from the study boundaries within VLF was quantified using the surface methane concentration (SMC) data from the entire work site (approximately 83 hectares), and a correlation that was developed between these data and the methane emission rate (MER) data (see Equation 4.9). The MER values were measured through the flux chamber technique conducted for approximately 20% of the total footprint, and the total E was estimated using the regression equation with coefficient of determination of $R^2 = 0.90$. This value is a function of: (i) the deviation of the MER values from their mean (SSy) and (ii) the deviation of the MER values from their predicted values (SSE). In principle, the R^2 is a number between 0 and 1, where lower numbers mean that X values (SMC in this case) provide

no information about Y values (MER in this case) (SSy and SSE are almost identical). However, R^2 values closer to 1 suggests that X contributes lots of information about Y (SSE is very small).

The resulting number for R^2 for the developed regression equation between the SMC and the MER data confirmed that 90% of the variability observed in the MER values (measured in the selected areas of the work site) could be explained by the assessed SMC values in those areas. As presented in Figure 4.13, showing the suggested correlation between SMC and MER, there are bigger uncertainties at grids with lower levels of methane emission recorded. Therefore, in the worst case scenario, 10% of the MER values estimated by the developed regression equation, hence estimated total E, could be defined as the max error in methane emission measurements. Furthermore, the statistical analysis of the developed linear regression in Chapter 4 showed a standard deviation of approximately 28% with 95% confidence limit (see Table 4.6). Nevertheless, even 28% error in the quantified emission levels translates to approximately 400 tonnes of methane which is very insignificant in comparison with the total methane generation estimate of more than 10,000 tonnes $year^{-1}$.

It should be noted that the error discussed above does not include the possible errors and uncertainties associated with the sampling procedure and instrumentation used for the surface methane concentration scan and the flux chamber measurements. However, these instrument were calibrated based on the manufacturer's recommendations and believed to have an insignificant errors.

8.3.2 Errors Due to the Methane Oxidation Measurement Uncertainties (CF_G-Err)$_O$

The total amount of methane oxidation (O) at VLF was calculated based on the total methane emission through landfill cover soil, as well as the f_{ox} value, the fraction of methane oxidized. The f_{ox} value, as described in Chapter 5, was estimated for two different types of cover soil on site using the stable isotope technique. As shown in Equation 5.3, f_{ox} depends on four different parameters: (i) anaerobic methane $\delta^{13}C$ value (δ_a), (ii) residual methane $\delta^{13}C$ value (δ_R), (iii) oxidation fractionation factor (α_{ox}), and (iv) fractionation factor due to transport (α_t). In order to increase the accuracy of the f_{ox} results, grid-specific δ values were generated and used in the calculations. However, the mean values of α_{ox} and α_t, respectively from the soil incubation lab works and literature, were used to calculate the f_{ox} value for each grid, and ultimately for the entirety of Area A (average f_{ox} of 34%) and Area B (average f_{ox} of 28%), each covered with one of the two soil types.

As previously shown in Table 5.4 of Chapter 5, the average α_{ox} value for Areas A and B were 1.0265 ± 0.0010 and 1.0266 ± 0.0052, respectively. The average α_t value of 1.0106 ± 0.007 was adopted from the literature (Chanton et al., 2011a). The average values of fractionation factors resulted in the mean oxidation rates of 33.7% and 27.9%, for Areas A and B, respectively. However, there could be eight other scenarios for each area based on the deviations in the α_{ox} and α_t, values. Therefore, a 9 × 9 matrix was created for each area to calculate the f_{ox} value for all possible combinations of low range, high range, and average value of α_{ox} and α_t. Table 8.8 and Table 8.9 show the resulting deviations in f_{ox} values for Areas A and B due to uncertainties in fractionation factor values. It should be noted that these uncertainties in f_{ox} values do not

include the possible errors and uncertainties associated with the field and lab work sampling procedures and instrumentation errors.

Table 8.8 Deviation in methane oxidation rate due to fractionation factors uncertainties in Area A

f_{ox} Area-A		α_t				
		low	high	average	Mean	StDev
α_{ox}	low	31.8	45.1	35.3	37.4	6.9
	high	29.4	39.1	32.3	33.6	5.0
	average	30.6	41.8	**33.7**	35.4	5.8
	Mean	30.6	42.0	33.8	**35.5 ± 5.4**	
	StDev	1.2	3.0	1.5		

Table 8.9 Deviation in methane oxidation rate due to fractionation factors uncertainties in Area A

f_{ox} Area-B		α_t				
		low	high	average	Mean	StDev
α_{ox}	low	25.0	83.1	41.3	49.8	30.0
	high	15.8	31.4	21.0	22.7	7.9
	average	19.4	49.5	**27.9**	32.3	15.5
	Mean	20.1	54.7	30.1	**34.9 ± 21.0**	
	StDev	4.7	26.2	10.3		

In order to evaluate the effects of uncertainty levels of the methane oxidation rates on the methane generation modeling results, a sensitivity analysis of these deviations on the CF_G value was conducted. The METRO equation was re-run using the lower range and the higher range oxidation rates and the results were compared with the initial assessment where the average values have been used. Results showed that the applicable calibration factor would range from 1.09 to 1.18, in comparison with the initial calibration factor of 1.10. Furthermore, the analysis showed that the overall oxidation rate at VLF ranged between 26% to 63% for Scenarios 1 and 2, respectively. Summary of these results are presented in Table 8.10.

Table 8.10 Generation calibration factor uncertainties due to the oxidation rate uncertainty range

Scenarios	Fraction of Methane Oxidized (f_{ox}, %)		Oxidized Methane (O)			Methane Emissions (E)		Methane Recovery (R)		Total Methane within Boundaries (∑ METRO)	Initial Modeling Results (G_i)	Methane Generation Correction Factors
	Area A	Area B	(tonnes)	(%)*	(%)**	(tonnes)	(%)	(tonnes)	(%) CE	(tonnes)	(tonnes)	CF_G
Initial Assessment (Mean Values)	**33.7**	**27.9**	268	4.1%	30%	1,481	14.7%	8,853	87.7%	10,744	11,852	**1.103**
Scenario 1. Lower Range Oxidation	**30.1**	**13.9**	228	2.3%	26%	972	9.7%	8,853	88.8%	10,053	11,852	**1.179**
Scenario 2. Higher Range Oxidation	**40.9**	**56.0**	1,093	10.4%	63%	972	9.2%	8,853	83.9%	10,919	11,852	**1.085**

* percent of total generated methane (G)

** percent of emitted methane through cover soil (E_s)

8.3.3 Errors Due to the Methane Recovery Data Deviations $(CF_G\text{-}Err)_R$

As previously reported in Chapter 6, the amount of recovered methane (R) was calculated based on the collected LFG flow rate and composition. A GEM™ 2000+ LFG analyzer was used to measure these parameters in 65 events during the course of the field study. A full list of the sampling events and recorded values is presented in Appendix F.1.

The recorded LFG flow rates showed an average result of 1,758 ± 151 standard cubic feet per minute (scfm), which translates to total recovered methane of R = 8,863 ± 761 tonnes per year. A sensitivity analysis on the effect of this deviation in R value on the CF_G value ($(CF_G\text{-}Err)_R$), and eventually on the modeling results, was conducted by re-running the METRO equation for two scenarios of: (i) R_1 = 8,092 tonnes CH_4 $year^{-1}$ and (ii) R_2 = 9,614 tonnes CH_4 $year^{-1}$. The average values for the total amount of methane oxidation (O) and methane emission (E) were applied in both scenarios. The results of this analysis are presented in Table 8.11.

Table 8.11 Deviation in CF_G due to uncertainty range in methane recovery data

Scenarios	Methane Recovery	Methane Emissions	Methane Oxidation	Total Methane within Boundaries	Initial Methane Generation Estimate	Resulted Calibration Factor
	R	E	O	∑ METRO	G_i	CF_G
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	
Average Value	8,853	1,481	410	10,744	11,852	1.103
Scenario 1. Lower Range Methane Recovery	8,092	1,481	410	9,983	11,852	1.187
Scenario 2. Higher Range Methane Recovery	9,614	1,481	410	11,505	11,852	1.030

The calibration factors resulting from these two scenarios were 1.19 and 1.03, respectively corresponding to the lower and the higher range of the amount of captured methane. This resulting deviation in CF_G was higher than what was concluded for $(CF_G\text{-}Err)_O$, which is mainly due to the relatively larger R values in comparison with the O values. It is worth noting that the deviation reported for R values, hence the calculated $(CF_G\text{-}Err)_R$, result from wellfield operational adjustments, LFG flow surging in the manifolds, and the inaccuracies associated with the type of the gas flow meter used at VLF. The reported errors do not include uncertainties due to the LFG analyzer instrument.

8.4 Error Analyses Conclusion

The error analysis was conducted to evaluate the effects of uncertainties in various parameters on (i) methane generation modeling (G_i-Err), and (ii) modeling calibration factor (CF_G-Err).

As expected, uncertainty in k values did not have any effect on L_o or on the total methane generation. However, the effect of this value was the most substantial on the methane capture efficiency. This effect depends on the year of assessment with respect to the landfill closure year. When the assessment was conducted within approximately 10-15 years of the landfill/phase closure year, during which about 50% of the lifespan methane was generated, the effect of the k value became the second most substantial after the effects of the uncertainties in the DOC values. The analysis also showed the importance of the DOC discount factors, where the ignorance of these parameters could increase the overestimation of the initial methane generation assessment from 10% to 29%.

Furthermore, a sensitivity analysis on the effect of uncertainties on methane oxidation and recovery was performed by re-running the entire analyses under the simplified METRO equation and developing a new calibration factor. The developed values for the minimum and maximum values of O and R within their deviation range showed that the effect of R deviations was more substantial, suggesting a methane generation overestimation within range of 3% to 18%.

Chapter 9: Summary and Conclusions

Landfill gas generation modeling results are in general relied upon as a basis for both design of LFG recovery and utilization systems, as well as for GHG legislative emission concerns. These data are also used by the authorities to modify and fine-tune the existing GHG emission policies, regulations, and inventory reports. However, given the number of variables affecting the degradation process within landfills, exact quantification of LFG generation and fugitive methane emissions is very difficult such that serious uncertainties and doubts are reported about the validity of the existing LFG generation models. Many researchers have reported model "errors". These errors are in most cases significant overestimation of the gas generation relative to field measurements, thus resulting in oversized LFG management systems. In larger scales, errors aggregate and create much larger overestimations of the waste management sector methane budget registered in national and international GHG emission inventory reports.

9.1 Common LFG Generation Modeling Methodologies and Shortfalls

The first order reaction is the basis of many of the existing LFG generation models. The main differences between these models lie in both the formulation of gas mass balances and the values assumed for the key influencing "modeling parameters". These modeling parameters define how much (L_o, m^3 CH_4 per tonne of waste) and how fast (k, $year^{-1}$) the methane gas is produced in a landfill as a result of anaerobic decomposition of the organic material deposited in the landfill. Some models, such as the US EPA LandGEM model, make simplified assumptions in selection of the modeling parameters, disregarding many factors including the waste composition and the fact that composition can significantly change throughout the landfill's lifespan. Similarly, the degradability of the organic material deposited at landfills under given conditions is an important

parameter affecting the methane yield. Even though these data are very well researched and known, they are not properly reflected in the modeling parameters.

There are some models which do consider the waste composition to calculate the L_o value, however, some other factors such as the actual moisture and/or carbon content, as well as the ultimate degradability of waste components are selected based on flat assumptions. In some cases the k values also are almost arbitrarily selected. For example, the IPCC model suggests a flat 50% degradability rate for all the materials deposited in landfills. This model also assumes warm region landfills decompose more rapidly than cold region landfills with suggested k values for those affected by the low temperature. Nevertheless, there are many studies that suggest independency of landfill temperature from the ambient temperature due to the exothermic nature of anaerobic degradation process.

A quick modeling exercise presented in Chapter 1 of the present research, involving five popular LFG generation models, including the most popular models used in the North America and BC, showed up to a 340% variation in the results for a single site, arguably demonstrating the need for an enhanced model which offers more realistic and consistent results that could be used by landfill owners, engineers, and regulatory agencies.

With more LFG collection systems installed, superior quality data are being collected by many people. However, this information is not reflected back into the models. A unique opportunity was provided at the Vancouver Landfill (VLF) through the course of this research, making it possible to refine current LFG generation models aiming at reducing uncertainties. Historical

landfill operation and LFG collection data along with very well recorded data with regard to waste generation, composition, and diversion, was integrated into a refined LFG generation model. The latest technological advances in lab and field measurement techniques were also employed to enhance data quality. The iModel-110© was developed based on the widely accepted multiphase first order decay reaction, supported by METRO equation concept which was developed as a quality control basis for this research. Based on the METRO equation, a comprehensive methane mass balance was conducted considering all possible pathways for the generated methane from the four sites within the study boundary and to calibrate and verify the integrated model.

9.2 Vancouver Landfill, the Unique Opportunity

This research was conducted at the Vancouver Landfill (VLF), owned and operated by the City of Vancouver (COV). Working on this site provided a unique opportunity to incorporate results and findings of various research studies into practice, which in turn resulted in more accurate LFG generation estimations. This was achieved through fine tuning the new model for more accurate and educated projection of current and future methane generation, methane capture efficiency, and methane emissions within VLF.

The availability of historical data and information on design and operational phasing of VLF was amongst the key advantages of conducting research on this site. Historically, this site was divided into seven distinct operational phases filled from west to east between 1967 and 2008 (see Figure 2.2). Since 2009, the waste disposal activities were switched back to Phase 2 and Phase 3 with an anticipation that no waste filling would occur in the four eastern phases (areas)

between 2009 and 2015. Therefore, these four phases (Area 2W, Area 2E, Area 3, and Phase 1) were selected as the study boundary. These areas were completed respectively in 1993, 1995, 1998, and 2008, with clear geometric boundaries, each equipped with a distinct active LFG collection system, dedicated LFG manifolds and gas quality and quantity metering stations. Therefore, each of these four areas could be treated as an individual site that has received a known tonnage of MSW and DLC (scaled at the entrance of the landfill) and matching known waste composition which was regularly studied by Metro Vancouver at transfer stations or the Burnaby WTEF.

9.3 Main Contributions to the LFG Industry

9.3.1 The New Model

The METRO© equation concept was developed as a basis for this research to calibrate and verify the integrated model. The iModel-110© was developed based on the widely accepted multiphase first order decay reaction. Variable methane generation potential (L_o) was developed based on the actual decomposable organic carbon (DOC_{dry}) historically deposited in each phase and reflecting the historical changes in waste consumption, recycling, and disposal strategies. Degradability extents as well as the moisture content of each waste component were also included in the calculation of the L_o values. Several other factors defining bioavailability of the total deposited DOC were also identified through literature and incorporated into development of the historical and future projection of L_o value for each year throughout the landfill's lifespan. Through application of the METRO© equation to the four individual sites and conducting a series of full scale investigations, all possible methane pathways were quantified. Accordingly, results of the new model were compared against actual field data for the modeling year and a range of

correction factors for gas generation (CF_G) were obtained which were used to further refine the L_o values. This provided a narrow range for the LFG generation prediction developed by the new model, with the true value believed to sit within the lower and the higher prediction values.

The decay rate (k) for each organic component of the waste was defined based on the biodegradation half-life of that component. Major variables reported as primary factors defining the decay rate for each component are moisture content and temperature. However, this research showed that in optimum moisture content conditions (such as at the VLF) the rates of decay are independent from the ambient temperature fluctuations and/or annual mean temperature. While the decay rates would not affect the lifespan methane generation from a landfill, this finding specifically is of importance for evaluation of methane capture efficiency at some point in time depending on the year of the evaluation related to the site closure year.

Whether the course of the application is in smaller scales, such as evaluating LFG collection efficiency or designing LFG collection and treatment systems for a particular landfill, or in larger scales, such as national or international GHG emissions surveys, it is very important to use reliable data generated by an accurate model, allowing knowledgeable decisions. Even though a very exact quantification of LFG generation is impossible, the gas generation estimates generated by iModel-110© are much closer to the true value in comparison with estimations by other existing models. This model was developed based on nothing more than putting together the available data and knowledge and taking advantage of the unique opportunity at the VLF to test and calibrate the model.

In order to verify the results of the developed model, methane generation rates from the Phase 2 of the Vancouver Landfill, located outside of the research boundary, were estimated using the iModel-110 with the defined range for the generation calibration factor. Similar to the calibration process approach and use of the METRO equation, the actual field data were compared against the predicted values of LFG generation rates. Results indicated reasonably low deviation from actual data at the year of the study ranging from 1.5% to a maximum value of 19.3%.

9.3.2 Other Outcomes of the Study

A crucial component of model calibration process was quantification of fugitive methane emissions. As described in Chapter 4, through the technique developed in this research, total fugitive methane emission from the work site was quantified in a very efficient and cost effective manner. In this technique, surface methane concentrations were translated to methane emission rates from the landfill surface. Another equally important part of the study was quantification of the effectiveness of methanotrophic bacteria in mitigating fugitive methane emissions from landfills, using the stable isotope technique. These analyses, presented in Chapter 5, showed that while the default 10% oxidation rate would be an appropriate minimum value, this could be a significant underestimation for the actual methane oxidation rate in landfills with active gas collection systems. Therefore, using appropriate and region-specific oxidation rate values based on estimated methane emission rates may modify methane budget in GHG emission inventory reports.

9.3.3 Specific Results

Through the calibration and verification process of the new model over the four sites at the VLF, a number of conclusions were made which offer useful information for the LFG industry stakeholders. These results and findings are listed below.

- For landfills located in wet climates, the landfill temperature is governed by the self-warming anaerobic decomposition reactions and is not influenced by ambient temperature fluctuations. Therefore, the decay rates of the organic materials deposited at these landfills are constant throughout the year and independent of ambient temperature (see Section 3.3.1).
- The rate of methane emission from a landfill surface is affected by the rate of change in barometric pressure. This relationship was quantified such that a measured emission rate at a given time can be translated to the actual values in stable weather conditions (see Equation 4.8)
- Total methane fugitive emissions from a landfill are directly related to the landfill surface methane concentration. This relationship was developed for the VLF and the total emissions were quantified (see Equation 4.10).
- Approximately 30% of the non-collected methane at the VLF is oxidized by the methanotrophic bacteria naturally existing in the landfill's cover soil. This oxidation rate is significantly higher than the default value historically used by the regulatory agencies.

9.4 Significance of the Results from Regulatory Perspective

According to the new BC MOE landfill gas regulation, the VLF is a regulated site and is required to capture and flare at least 75% of the generated methane. Many other jurisdictions require that the best LFG management practices be applied at the regulated sites and GHG emissions be monitored on a regular basis. While the author believes that quantification of fugitive emissions from landfills should be used by regulatory bodies to evaluate LFG management system performance, the use of more accurate and site specific or (at a minimum) region specific models could be another option for these agencies. The overestimation of the gas generation tools used by a regulatory agency can simply lead to spending millions of dollars for unnecessary expansion and improvement of a gas collection system to collect gas which does not exist.

Based on the results achieved in this research, the average methane generation potential for the VLF ranged between 68 and 89 m^3 CH_4 per tonne of waste, while the BC MOE Tool used a higher value of 102 m^3 CH_4 per tonne of waste. Consequently, the resulting methane capture efficiency for the entire VLF in 2012, based on the new model's lower range and the higher range estimates, ranged between 61% and 79%. This result based on the calibrated (site-specific) decay rates was 64%. The MOE Tool concluded collection efficiency of 55%. Furthermore, the average methane collection efficiency at the areas within the study boundaries with an intermediate cover system (i.e. Areas 2W, 2E, and 3) was 75% ± 15%. The modeling results and the historical methane recovery data for Phase 1 showed that the methane capture efficiency in this phase, before installation of the geomembrane cap, was approximately 65% to 70%. However, this capture efficiency was increased to approximately 80% to 90% since 2009, due to the installation of the geomembrane cap and the modifications made to the LFG collection

system. These capture efficiency values are in good agreement with what (Spokas et al., 2006) and (SCS Engineers, 2009) reported for the capture efficiencies for active LFG collection systems with similar landfill cover types.

Taking into account the determined methane oxidation in the landfill cover soil, the total atmospheric methane emissions within the study boundaries in 2012 ranged from 6% to 34%. A summary of the field investigation results is presented in Table 9.1.

Table 9.1 Summary of 2012 methane budget within the work site

Area/ Phase	Waste in Place	Closure year	2012 Methane Budget within the Study Boundaries								
			Generation (G)		Recovered (R)		Oxidized (O)			Emissions (E)**	
	tonnes		(tonnes)	(scfm)*	(tonnes)	(%)	(tonnes)	(% of G)	(% of E_s)	(tonnes)	(%)
Area 2W	2,010,492	1994	1,376	273	792	58%	119	8.6%	28%	466	34%
Area 2E	946,200	1996	1,033	205	716	69%	64	6.2%	28%	252	24%
Area 3	1,366,288	1999	1,434	284	973	68%	94	6.5%	28%	367	26%
Phase 1	4,470,903	2009	6,901	1,369	6,373	92%	133	1.9%	34%	396	6%
Total	**8,793,883**		**10,744**	2,131	**8,853**	**82%**	**410**	**3.8%**	**30%**	**1,481**	**14%**

* LFG flow calculated based on 50% methane content

** Emission includes emissions from cover soil (E_s) and emission from pipe and leaks (E_l), $E = E_s+E_l$

9.5 Applicability and Use of the New Model

The iModel-110© is developed in an excel workbook with a user-friendly interface. The model consists of five major interlinked spread sheets, as well as six calculation sheets hidden in the workbook. The major interface spread sheets include Parameters, MSW Tonnage, Dry Tonnages, LFG Results, and Graphics. In the "Parameters" sheet the site-specific information such as the landfill's name, opening year, site's design, operational and climate factors, as well as waste components' parameters such as moisture content, DOC_{dry} and decay factors are to be entered

and or updated by the user. Also in this sheet, based on the precipitation levels, assigned half-lives of different type of organic materials are translated to six different decay rates with much longer half-lives suggested for dryer sites. Landfill activity data, including tonnages and composition of the MSW historically deposited at the landfill or expected to be landfilled in the future, are entered in the "MSW Tonnage" sheet. The total amount of carbon annually deposited at the site is calculated based on the DOC and moisture content values in the "Dry Tonnage" sheet. The "LFG Results" sheet presents the calculated methane generation yield for each year based on the waste data, estimated annual methane generation from each waste component in tonnes per year, and the expected LFG flow rates in standard cubic feet per minute (scfm). These results, along with average waste tonnage and composition data, are graphically illustrated in the "Graphics" sheet.

Any landfill with records of tonnage and composition of deposited waste can benefit from the accuracy of this new enhanced model. The principal advantage of this model over other models is that this model incorporates waste composition and moisture data, when available, along with reasonably good k values which are selected from the literature and calibrated based on the field data. The accuracy of the new model was verified though comparison of the predictions with the filed data. The model predictions was within the narrow uncertainty range associated with the field data. Nevertheless, it was attempted to further calibrate the new model through two different methodologies; (i) calibrating the $L_{\circ}$ by application of generation calibration factor (CF_G), and (ii) through fine-tuning the decay rates which was selected from a suggested range for each organic waste (CF_k). During the calibration phase of the study, the lower and upper range CF_G, as well as the calibrated decay rates were generated for landfills situated in wet climates

similar to that of the Vancouver landfill (i.e. annually receiving close to 1,000 mm or more precipitation). Therefore, owners and operators of such landfills will be able to utilize the new model simply by completing the data entry sheets (i.e. Parameters and MSW Tonnage). For drier sites, the CF_G multiplier and/or site specific decay rates have to be regenerated as recommended in the following section. To benefit from the new model, landfill owners and operators need to know what is being put into the landfill. Keeping good records of the waste composition, as well as moisture content of the materials as received at the landfill, is a key factor that enables users to accurately assess the LFG generation from the landfill. When site specific historical waste composition data are not available, it would be beneficial to use default values or the waste composition data from the region or cities and communities with similar socio economic properties.

9.6 Recommendations

Appropriate Record Keeping at landfills is essential: As noted above, keeping good records of the waste composition, as well as moisture content of the materials as received at the landfill, is a key factor that enables users to accurately assess the LFG generation from the landfill. Incorporation of these data into modeling practice, as well as utilizing very well researched fundamental facts about anaerobic decomposition of organic material in landfills, are the principal advantage of the new model over other models.

Calibration Factors for other climatic conditions: The integrated methane mass balance conducted at the four sites within the study boundaries showed the accuracy of the iModel-110© with a range of generation calibration factors developed to further refine the model's predictions.

However, all of the sites, as well as the VLF Phase 2, on which the model was verified, are located in the same climatic conditions. Therefore, it is necessary that a range of CF_G and/ or calibrated site-specific decay rates be generated for other sites with different climatic and operational conditions. This has to be done through conducting a similar practice (i.e. application of METRO equation) to these sites, where good quality information from the LFG collection, as well as the historical waste composition exist. It should be mentioned that the initial generation estimate before application of any calibration factor was only 10% off from the field data. This was within the uncertainty range associated with the field data.

Decay Rate Calibration (CF_k): It is important to note that the calibration of the new model was conducted over a single point (year) of the Vancouver Landfill's lifespan gas generation curve. Personal observations of the author on the six years of field operational LFG data of the VLF Phase 1 confirms suitability of the calibrated decay rates for this site. However, it is recommended similar methane mass balance calculations be conducted over a long period of time (e.g. 10 years) in which case the decay rate calibration factor can be further validated and verified. Similar recommendations apply to generation of CF_k for dryer sites.

Landfill Temperature in Dryer Regions: While this research showed that landfill temperature in wet climate is not influenced by the ambient temperature fluctuations, the author believes that in a dry climate this may not be the case. Therefore, it is recommended that a similar landfill temperature investigation be conducted at landfills located in different climates with various precipitation levels.

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Appendices

Appendix A Landfill Gas Generation Modeling Full Results

A.1 LFG Generation Modeling for VLF-Phase 1: LandGEM Model

A.1.1 CAA Modeling Parameters

USER INPUTS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1

Clear ALL Non-Parameter Inputs/Selections

1: PROVIDE LANDFILL CHARACTERISTICS

Landfill Open Year	1999
Landfill Closure Year	2008
Have Model Calculate Closure Year?	○ Yes ◉ No
Waste Design Capacity	megagrams

Restore Default Model Parameters

2: DETERMINE MODEL PARAMETERS

Methane Generation Rate, k (*year*$^{-1}$)
CAA Conventional - 0.05

Potential Methane Generation Capacity, L_o (*m*^{3}/*Mg*)
CAA Conventional - 170

NMOC Concentration (*ppmv as hexane*)
CAA - 4,000

Methane Content (*% by volume*)
CAA - 50% by volume

3: SELECT GASES/POLLUTANTS

Gas / Pollutant #1 Default pollutant parameters are currently being used by model.
Total landfill gas

Gas / Pollutant #2
Methane

Gas / Pollutant #3
Carbon dioxide

Gas / Pollutant #4
NMOC

Edit Existing or Add New Pollutant Parameters

Restore Default Pollutant Parameters

Description/Comments:
Waste Composition for the these three years was C, D, and E (as per GVRD waste composition studies in 2001, 2004, and 2007 and corrected for DLC). DLC received at VLF are included in the the reported tonnages

4: ENTER WASTE ACCEPTANCE RATES

Input Units: *Mg/year*

Year	Input Units (*Mg/year*)	Calculated Units (*short tons/year*)
1999	483,572	531,929
2000	456,666	502,332
2001	454,381	499,819
2002	530,775	583,852
2003	553,951	609,346
2004	623,019	685,321
2005	691,847	761,032
2006	514,692	566,162
2007		0
2008	162,000	178,200
2009		
2010		
2011		
2012		
2013		
2014		
2015		
2016		
2017		
2018		
2019		
2020		
2021		
2022		
2023		
2024		
2025		
2026		
2027		
2028		
2029		
2030		

RESULTS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1

Closure Year (with 80-year limit) = 2008

Methane = 50 *% by volume*

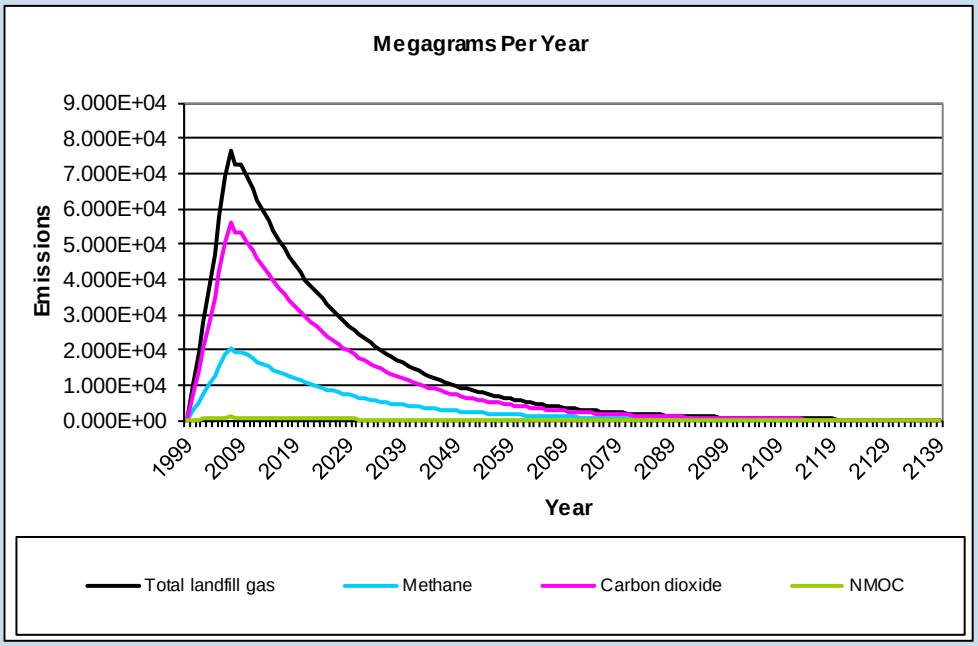
Please choose a third unit of measure to represent all of the emission rates below.

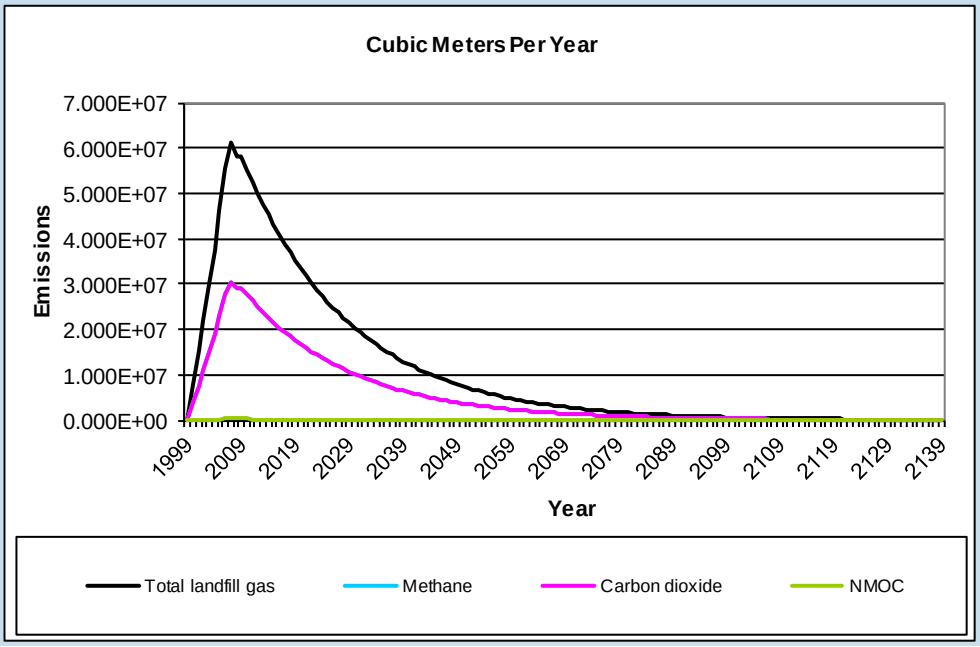
User-specified Unit: *av ft^3/min*

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg/year)	*(short tons/year)*	*(Mg)*	*(short tons)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*
1999	483,572	531,929	0	0	0	0	0	0	0	0
2000	456,666	502,332	483,572	531,929	1.004E+04	8.039E+06	5.401E+02	2.681E+03	4.019E+06	2.701E+02
2001	454,381	499,819	940,237	1,034,261	1.903E+04	1.524E+07	1.024E+03	5.083E+03	7.619E+06	5.119E+02
2002	530,775	583,852	1,394,618	1,534,080	2.753E+04	2.205E+07	1.481E+03	7.355E+03	1.102E+07	7.407E+02
2003	553,951	609,346	1,925,393	2,117,932	3.721E+04	2.980E+07	2.002E+03	9.939E+03	1.490E+07	1.001E+03
2004	623,019	685,321	2,479,344	2,727,278	4.690E+04	3.755E+07	2.523E+03	1.253E+04	1.878E+07	1.262E+03
2005	691,847	761,032	3,102,363	3,412,600	5.754E+04	4.608E+07	3.096E+03	1.537E+04	2.304E+07	1.548E+03
2006	514,692	566,162	3,794,211	4,173,632	6.910E+04	5.533E+07	3.718E+03	1.846E+04	2.767E+07	1.859E+03
2007	0	0	4,308,903	4,739,793	7.641E+04	6.119E+07	4.111E+03	2.041E+04	3.059E+07	2.056E+03
2008	162,000	178,200	4,308,903	4,739,793	7.269E+04	5.820E+07	3.911E+03	1.942E+04	2.910E+07	1.955E+03
2009	0	0	4,470,903	4,917,993	7.250E+04	5.806E+07	3.901E+03	1.937E+04	2.903E+07	1.950E+03
2010	0	0	4,470,903	4,917,993	6.897E+04	5.523E+07	3.711E+03	1.842E+04	2.761E+07	1.855E+03
2011	0	0	4,470,903	4,917,993	6.560E+04	5.253E+07	3.530E+03	1.752E+04	2.627E+07	1.765E+03
2012	0	0	4,470,903	4,917,993	6.241E+04	4.997E+07	3.358E+03	1.667E+04	2.499E+07	1.679E+03
2013	0	0	4,470,903	4,917,993	5.936E+04	4.753E+07	3.194E+03	1.586E+04	2.377E+07	1.597E+03
2014	0	0	4,470,903	4,917,993	5.647E+04	4.522E+07	3.038E+03	1.508E+04	2.261E+07	1.519E+03
2015	0	0	4,470,903	4,917,993	5.371E+04	4.301E+07	2.890E+03	1.435E+04	2.151E+07	1.445E+03
2016	0	0	4,470,903	4,917,993	5.109E+04	4.091E+07	2.749E+03	1.365E+04	2.046E+07	1.374E+03
2017	0	0	4,470,903	4,917,993	4.860E+04	3.892E+07	2.615E+03	1.298E+04	1.946E+07	1.307E+03
2018	0	0	4,470,903	4,917,993	4.623E+04	3.702E+07	2.487E+03	1.235E+04	1.851E+07	1.244E+03
2019	0	0	4,470,903	4,917,993	4.398E+04	3.521E+07	2.366E+03	1.175E+04	1.761E+07	1.183E+03
2020	0	0	4,470,903	4,917,993	4.183E+04	3.350E+07	2.251E+03	1.117E+04	1.675E+07	1.125E+03
2021	0	0	4,470,903	4,917,993	3.979E+04	3.186E+07	2.141E+03	1.063E+04	1.593E+07	1.070E+03
2022	0	0	4,470,903	4,917,993	3.785E+04	3.031E+07	2.036E+03	1.011E+04	1.515E+07	1.018E+03
2023	0	0	4,470,903	4,917,993	3.600E+04	2.883E+07	1.937E+03	9.617E+03	1.442E+07	9.686E+02
2024	0	0	4,470,903	4,917,993	3.425E+04	2.742E+07	1.843E+03	9.148E+03	1.371E+07	9.213E+02
2025	0	0	4,470,903	4,917,993	3.258E+04	2.609E+07	1.753E+03	8.702E+03	1.304E+07	8.764E+02
2026	0	0	4,470,903	4,917,993	3.099E+04	2.482E+07	1.667E+03	8.278E+03	1.241E+07	8.337E+02
2027	0	0	4,470,903	4,917,993	2.948E+04	2.360E+07	1.586E+03	7.874E+03	1.180E+07	7.930E+02
2028	0	0	4,470,903	4,917,993	2.804E+04	2.245E+07	1.509E+03	7.490E+03	1.123E+07	7.543E+02
2029	0	0	4,470,903	4,917,993	2.667E+04	2.136E+07	1.435E+03	7.125E+03	1.068E+07	7.175E+02
2030	0	0	4,470,903	4,917,993	2.537E+04	2.032E+07	1.365E+03	6.777E+03	1.016E+07	6.825E+02
2031	0	0	4,470,903	4,917,993	2.413E+04	1.933E+07	1.299E+03	6.447E+03	9.663E+06	6.493E+02
2032	0	0	4,470,903	4,917,993	2.296E+04	1.838E+07	1.235E+03	6.132E+03	9.192E+06	6.176E+02
2033	0	0	4,470,903	4,917,993	2.184E+04	1.749E+07	1.175E+03	5.833E+03	8.743E+06	5.875E+02
2034	0	0	4,470,903	4,917,993	2.077E+04	1.663E+07	1.118E+03	5.549E+03	8.317E+06	5.588E+02
2035	0	0	4,470,903	4,917,993	1.976E+04	1.582E+07	1.063E+03	5.278E+03	7.911E+06	5.316E+02
2036	0	0	4,470,903	4,917,993	1.880E+04	1.505E+07	1.011E+03	5.021E+03	7.526E+06	5.056E+02
2037	0	0	4,470,903	4,917,993	1.788E+04	1.432E+07	9.620E+02	4.776E+03	7.159E+06	4.810E+02
2038	0	0	4,470,903	4,917,993	1.701E+04	1.362E+07	9.150E+02	4.543E+03	6.809E+06	4.575E+02
2039	0	0	4,470,903	4,917,993	1.618E+04	1.295E+07	8.704E+02	4.321E+03	6.477E+06	4.352E+02
2040	0	0	4,470,903	4,917,993	1.539E+04	1.232E+07	8.280E+02	4.111E+03	6.161E+06	4.140E+02
2041	0	0	4,470,903	4,917,993	1.464E+04	1.172E+07	7.876E+02	3.910E+03	5.861E+06	3.938E+02
2042	0	0	4,470,903	4,917,993	1.392E+04	1.115E+07	7.492E+02	3.719E+03	5.575E+06	3.746E+02
2043	0	0	4,470,903	4,917,993	1.325E+04	1.061E+07	7.126E+02	3.538E+03	5.303E+06	3.563E+02
2044	0	0	4,470,903	4,917,993	1.260E+04	1.009E+07	6.779E+02	3.365E+03	5.045E+06	3.389E+02
2045	0	0	4,470,903	4,917,993	1.198E+04	9.597E+06	6.448E+02	3.201E+03	4.798E+06	3.224E+02
2046	0	0	4,470,903	4,917,993	1.140E+04	9.129E+06	6.134E+02	3.045E+03	4.564E+06	3.067E+02
2047	0	0	4,470,903	4,917,993	1.084E+04	8.684E+06	5.835E+02	2.897E+03	4.342E+06	2.917E+02
2048	0	0	4,470,903	4,917,993	1.032E+04	8.260E+06	5.550E+02	2.755E+03	4.130E+06	2.775E+02
2049	0	0	4,470,903	4,917,993	9.812E+03	7.857E+06	5.279E+02	2.621E+03	3.929E+06	2.640E+02
2050	0	0	4,470,903	4,917,993	9.334E+03	7.474E+06	5.022E+02	2.493E+03	3.737E+06	2.511E+02
2051	0	0	4,470,903	4,917,993	8.879E+03	7.110E+06	4.777E+02	2.372E+03	3.555E+06	2.388E+02
2052	0	0	4,470,903	4,917,993	8.446E+03	6.763E+06	4.544E+02	2.256E+03	3.381E+06	2.272E+02
2053	0	0	4,470,903	4,917,993	8.034E+03	6.433E+06	4.322E+02	2.146E+03	3.217E+06	2.161E+02
2054	0	0	4,470,903	4,917,993	7.642E+03	6.119E+06	4.112E+02	2.041E+03	3.060E+06	2.056E+02
2055	0	0	4,470,903	4,917,993	7.269E+03	5.821E+06	3.911E+02	1.942E+03	2.910E+06	1.956E+02
2056	0	0	4,470,903	4,917,993	6.915E+03	5.537E+06	3.720E+02	1.847E+03	2.768E+06	1.860E+02
2057	0	0	4,470,903	4,917,993	6.577E+03	5.267E+06	3.539E+02	1.757E+03	2.633E+06	1.769E+02
2058	0	0	4,470,903	4,917,993	6.257E+03	5.010E+06	3.366E+02	1.671E+03	2.505E+06	1.683E+02
2059	0	0	4,470,903	4,917,993	5.952E+03	4.766E+06	3.202E+02	1.590E+03	2.383E+06	1.601E+02
2060	0	0	4,470,903	4,917,993	5.661E+03	4.533E+06	3.046E+02	1.512E+03	2.267E+06	1.523E+02
2061	0	0	4,470,903	4,917,993	5.385E+03	4.312E+06	2.897E+02	1.438E+03	2.156E+06	1.449E+02
2062	0	0	4,470,903	4,917,993	5.123E+03	4.102E+06	2.756E+02	1.368E+03	2.051E+06	1.378E+02
2063	0	0	4,470,903	4,917,993	4.873E+03	3.902E+06	2.622E+02	1.302E+03	1.951E+06	1.311E+02
2064	0	0	4,470,903	4,917,993	4.635E+03	3.712E+06	2.494E+02	1.238E+03	1.856E+06	1.247E+02
2065	0	0	4,470,903	4,917,993	4.409E+03	3.531E+06	2.372E+02	1.178E+03	1.765E+06	1.186E+02

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg/year)	(short tons/year)	(Mg)	(short tons)	(Mg/year)	(m^3/year)	(av ft^3/min)	(Mg/year)	(m^3/year)	(av ft^3/min)
2066	0	0	4,470,903	4,917,993	4.194E+03	3.358E+06	2.256E+02	1.120E+03	1.679E+06	1.128E+02
2067	0	0	4,470,903	4,917,993	3.989E+03	3.195E+06	2.146E+02	1.066E+03	1.597E+06	1.073E+02
2068	0	0	4,470,903	4,917,993	3.795E+03	3.039E+06	2.042E+02	1.014E+03	1.519E+06	1.021E+02
2069	0	0	4,470,903	4,917,993	3.610E+03	2.891E+06	1.942E+02	9.642E+02	1.445E+06	9.711E+01
2070	0	0	4,470,903	4,917,993	3.434E+03	2.750E+06	1.847E+02	9.172E+02	1.375E+06	9.237E+01
2071	0	0	4,470,903	4,917,993	3.266E+03	2.615E+06	1.757E+02	8.725E+02	1.308E+06	8.787E+01
2072	0	0	4,470,903	4,917,993	3.107E+03	2.488E+06	1.672E+02	8.299E+02	1.244E+06	8.358E+01
2073	0	0	4,470,903	4,917,993	2.955E+03	2.367E+06	1.590E+02	7.894E+02	1.183E+06	7.951E+01
2074	0	0	4,470,903	4,917,993	2.811E+03	2.251E+06	1.513E+02	7.509E+02	1.126E+06	7.563E+01
2075	0	0	4,470,903	4,917,993	2.674E+03	2.141E+06	1.439E+02	7.143E+02	1.071E+06	7.194E+01
2076	0	0	4,470,903	4,917,993	2.544E+03	2.037E+06	1.369E+02	6.795E+02	1.018E+06	6.843E+01
2077	0	0	4,470,903	4,917,993	2.420E+03	1.938E+06	1.302E+02	6.463E+02	9.688E+05	6.509E+01
2078	0	0	4,470,903	4,917,993	2.302E+03	1.843E+06	1.238E+02	6.148E+02	9.215E+05	6.192E+01
2079	0	0	4,470,903	4,917,993	2.189E+03	1.753E+06	1.178E+02	5.848E+02	8.766E+05	5.890E+01
2080	0	0	4,470,903	4,917,993	2.083E+03	1.668E+06	1.121E+02	5.563E+02	8.339E+05	5.603E+01
2081	0	0	4,470,903	4,917,993	1.981E+03	1.586E+06	1.066E+02	5.292E+02	7.932E+05	5.329E+01
2082	0	0	4,470,903	4,917,993	1.884E+03	1.509E+06	1.014E+02	5.034E+02	7.545E+05	5.069E+01
2083	0	0	4,470,903	4,917,993	1.793E+03	1.435E+06	9.644E+01	4.788E+02	7.177E+05	4.822E+01
2084	0	0	4,470,903	4,917,993	1.705E+03	1.365E+06	9.174E+01	4.555E+02	6.827E+05	4.587E+01
2085	0	0	4,470,903	4,917,993	1.622E+03	1.299E+06	8.727E+01	4.332E+02	6.494E+05	4.363E+01
2086	0	0	4,470,903	4,917,993	1.543E+03	1.235E+06	8.301E+01	4.121E+02	6.177E+05	4.151E+01
2087	0	0	4,470,903	4,917,993	1.468E+03	1.175E+06	7.896E+01	3.920E+02	5.876E+05	3.948E+01
2088	0	0	4,470,903	4,917,993	1.396E+03	1.118E+06	7.511E+01	3.729E+02	5.589E+05	3.756E+01
2089	0	0	4,470,903	4,917,993	1.328E+03	1.063E+06	7.145E+01	3.547E+02	5.317E+05	3.572E+01
2090	0	0	4,470,903	4,917,993	1.263E+03	1.012E+06	6.796E+01	3.374E+02	5.058E+05	3.398E+01
2091	0	0	4,470,903	4,917,993	1.202E+03	9.622E+05	6.465E+01	3.210E+02	4.811E+05	3.232E+01
2092	0	0	4,470,903	4,917,993	1.143E+03	9.153E+05	6.150E+01	3.053E+02	4.576E+05	3.075E+01
2093	0	0	4,470,903	4,917,993	1.087E+03	8.706E+05	5.850E+01	2.904E+02	4.353E+05	2.925E+01
2094	0	0	4,470,903	4,917,993	1.034E+03	8.282E+05	5.564E+01	2.763E+02	4.141E+05	2.782E+01
2095	0	0	4,470,903	4,917,993	9.838E+02	7.878E+05	5.293E+01	2.628E+02	3.939E+05	2.647E+01
2096	0	0	4,470,903	4,917,993	9.358E+02	7.493E+05	5.035E+01	2.500E+02	3.747E+05	2.517E+01
2097	0	0	4,470,903	4,917,993	8.902E+02	7.128E+05	4.789E+01	2.378E+02	3.564E+05	2.395E+01
2098	0	0	4,470,903	4,917,993	8.468E+02	6.780E+05	4.556E+01	2.262E+02	3.390E+05	2.278E+01
2099	0	0	4,470,903	4,917,993	8.055E+02	6.450E+05	4.334E+01	2.151E+02	3.225E+05	2.167E+01
2100	0	0	4,470,903	4,917,993	7.662E+02	6.135E+05	4.122E+01	2.047E+02	3.068E+05	2.061E+01
2101	0	0	4,470,903	4,917,993	7.288E+02	5.836E+05	3.921E+01	1.947E+02	2.918E+05	1.961E+01
2102	0	0	4,470,903	4,917,993	6.933E+02	5.551E+05	3.730E+01	1.852E+02	2.776E+05	1.865E+01
2103	0	0	4,470,903	4,917,993	6.594E+02	5.281E+05	3.548E+01	1.761E+02	2.640E+05	1.774E+01
2104	0	0	4,470,903	4,917,993	6.273E+02	5.023E+05	3.375E+01	1.676E+02	2.512E+05	1.687E+01
2105	0	0	4,470,903	4,917,993	5.967E+02	4.778E+05	3.210E+01	1.594E+02	2.389E+05	1.605E+01
2106	0	0	4,470,903	4,917,993	5.676E+02	4.545E+05	3.054E+01	1.516E+02	2.273E+05	1.527E+01
2107	0	0	4,470,903	4,917,993	5.399E+02	4.323E+05	2.905E+01	1.442E+02	2.162E+05	1.452E+01
2108	0	0	4,470,903	4,917,993	5.136E+02	4.113E+05	2.763E+01	1.372E+02	2.056E+05	1.382E+01
2109	0	0	4,470,903	4,917,993	4.885E+02	3.912E+05	2.628E+01	1.305E+02	1.956E+05	1.314E+01
2110	0	0	4,470,903	4,917,993	4.647E+02	3.721E+05	2.500E+01	1.241E+02	1.861E+05	1.250E+01
2111	0	0	4,470,903	4,917,993	4.420E+02	3.540E+05	2.378E+01	1.181E+02	1.770E+05	1.189E+01
2112	0	0	4,470,903	4,917,993	4.205E+02	3.367E+05	2.262E+01	1.123E+02	1.684E+05	1.131E+01
2113	0	0	4,470,903	4,917,993	4.000E+02	3.203E+05	2.152E+01	1.068E+02	1.601E+05	1.076E+01
2114	0	0	4,470,903	4,917,993	3.805E+02	3.047E+05	2.047E+01	1.016E+02	1.523E+05	1.024E+01
2115	0	0	4,470,903	4,917,993	3.619E+02	2.898E+05	1.947E+01	9.667E+01	1.449E+05	9.736E+00
2116	0	0	4,470,903	4,917,993	3.443E+02	2.757E+05	1.852E+01	9.196E+01	1.378E+05	9.261E+00
2117	0	0	4,470,903	4,917,993	3.275E+02	2.622E+05	1.762E+01	8.747E+01	1.311E+05	8.809E+00
2118	0	0	4,470,903	4,917,993	3.115E+02	2.494E+05	1.676E+01	8.321E+01	1.247E+05	8.380E+00
2119	0	0	4,470,903	4,917,993	2.963E+02	2.373E+05	1.594E+01	7.915E+01	1.186E+05	7.971E+00
2120	0	0	4,470,903	4,917,993	2.819E+02	2.257E+05	1.516E+01	7.529E+01	1.128E+05	7.582E+00
2121	0	0	4,470,903	4,917,993	2.681E+02	2.147E+05	1.443E+01	7.162E+01	1.073E+05	7.213E+00
2122	0	0	4,470,903	4,917,993	2.550E+02	2.042E+05	1.372E+01	6.812E+01	1.021E+05	6.861E+00
2123	0	0	4,470,903	4,917,993	2.426E+02	1.943E+05	1.305E+01	6.480E+01	9.713E+04	6.526E+00
2124	0	0	4,470,903	4,917,993	2.308E+02	1.848E+05	1.242E+01	6.164E+01	9.239E+04	6.208E+00
2125	0	0	4,470,903	4,917,993	2.195E+02	1.758E+05	1.181E+01	5.863E+01	8.789E+04	5.905E+00
2126	0	0	4,470,903	4,917,993	2.088E+02	1.672E+05	1.123E+01	5.577E+01	8.360E+04	5.617E+00
2127	0	0	4,470,903	4,917,993	1.986E+02	1.590E+05	1.069E+01	5.305E+01	7.952E+04	5.343E+00
2128	0	0	4,470,903	4,917,993	1.889E+02	1.513E+05	1.017E+01	5.047E+01	7.565E+04	5.083E+00
2129	0	0	4,470,903	4,917,993	1.797E+02	1.439E+05	9.669E+00	4.801E+01	7.196E+04	4.835E+00
2130	0	0	4,470,903	4,917,993	1.710E+02	1.369E+05	9.198E+00	4.566E+01	6.845E+04	4.599E+00
2131	0	0	4,470,903	4,917,993	1.626E+02	1.302E+05	8.749E+00	4.344E+01	6.511E+04	4.375E+00
2132	0	0	4,470,903	4,917,993	1.547E+02	1.239E+05	8.323E+00	4.132E+01	6.193E+04	4.161E+00
2133	0	0	4,470,903	4,917,993	1.471E+02	1.178E+05	7.917E+00	3.930E+01	5.891E+04	3.958E+00
2134	0	0	4,470,903	4,917,993	1.400E+02	1.121E+05	7.531E+00	3.739E+01	5.604E+04	3.765E+00
2135	0	0	4,470,903	4,917,993	1.331E+02	1.066E+05	7.163E+00	3.556E+01	5.331E+04	3.582E+00
2136	0	0	4,470,903	4,917,993	1.266E+02	1.014E+05	6.814E+00	3.383E+01	5.071E+04	3.407E+00
2137	0	0	4,470,903	4,917,993	1.205E+02	9.647E+04	6.482E+00	3.218E+01	4.823E+04	3.241E+00
2138	0	0	4,470,903	4,917,993	1.146E+02	9.176E+04	6.166E+00	3.061E+01	4.588E+04	3.083E+00
2139	0	0	4,470,903	4,917,993	1.090E+02	8.729E+04	5.865E+00	2.912E+01	4.364E+04	2.932E+00

GRAPHS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1





A.1.2 Inventory Modeling Parameters

USER INPUTS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1

Clear ALL Non-Parameter Inputs/Selections

1: PROVIDE LANDFILL CHARACTERISTICS

Landfill Open Year	1999
Landfill Closure Year	2008
Have Model Calculate Closure Year?	○ Yes ◉ No
Waste Design Capacity	megagrams

Restore Default Model Parameters

2: DETERMINE MODEL PARAMETERS

Methane Generation Rate, k (*year*$^{-1}$)
Inventory Conventional - 0.04

Potential Methane Generation Capacity, L_o (*m^3/Mg*)
Inventory Conventional - 100

NMOC Concentration (*ppmv as hexane*)
CAA - 4,000

Methane Content (*% by volume*)
CAA - 50% by volume

3: SELECT GASES/POLLUTANTS

Gas / Pollutant #1 Default pollutant parameters are currently being used by model.
Total landfill gas

Gas / Pollutant #2
Methane

Gas / Pollutant #3
Carbon dioxide

Gas / Pollutant #4
NMOC

Edit Existing or Add New Pollutant Parameters

Restore Default Pollutant Parameters

Description/Comments:
Waste Composition for the these three years was C, D, and E (as per GVRD waste composition studies in 2001, 2004, and 2007 and corrected for DLC). DLC received at VLF are included in the the reported tonnages

4: ENTER WASTE ACCEPTANCE RATE

Input Units: *Mg/year*

Year	Input Units *(Mg/year)*	Calculated Units *(short tons/year)*
1999	483,572	531,929
2000	456,666	502,332
2001	454,381	499,819
2002	530,775	583,852
2003	553,951	609,346
2004	623,019	685,321
2005	691,847	761,032
2006	514,692	566,162
2007		0
2008	162,000	178,200
2009		
2010		
2011		
2012		
2013		
2014		
2015		
2016		
2017		
2018		
2019		
2020		
2021		
2022		
2023		
2024		
2025		
2026		
2027		
2028		
2029		
2030		

RESULTS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1

Closure Year (with 80-year limit) = 2008

Methane = 50 *% by volume*

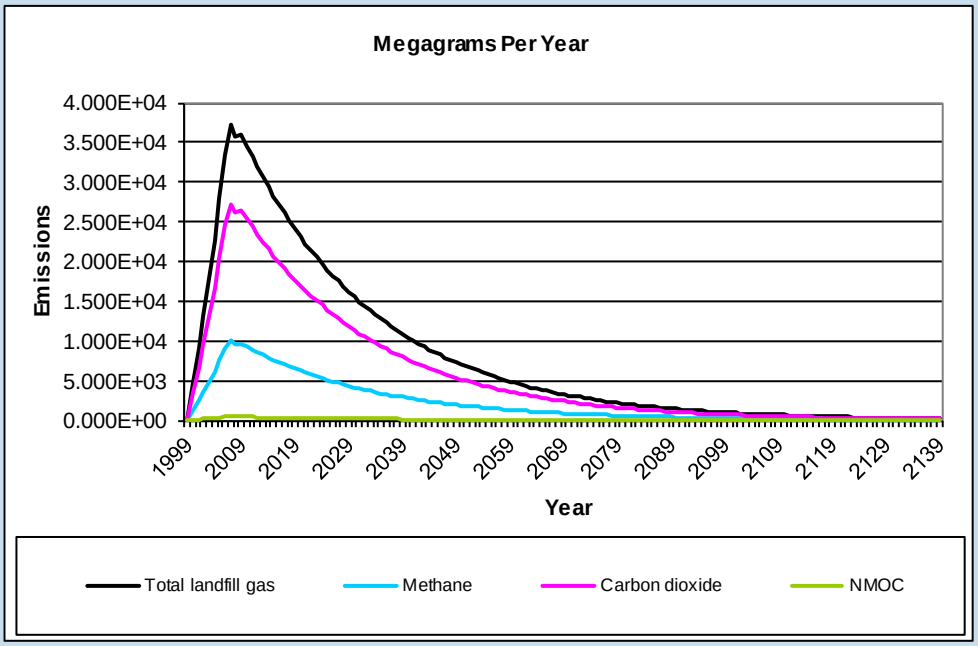
Please choose a third unit of measure to represent all of the emission rates below.

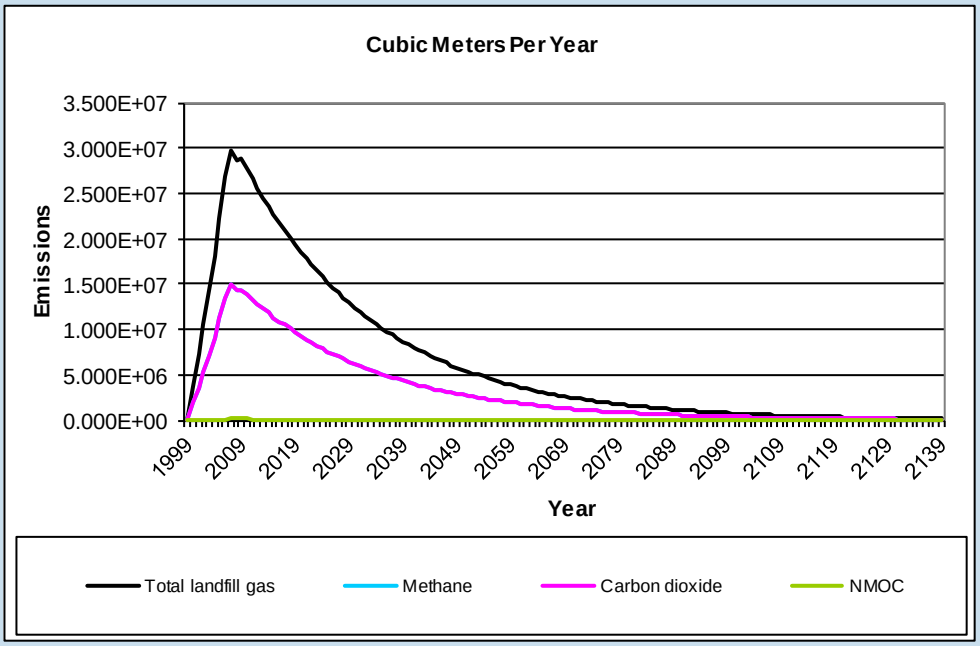
User-specified Unit: *av ft^3/min*

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg/year)	*(short tons/year)*	*(Mg)*	*(short tons)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*	*(Mg/year)*	*(m^3/year)*	*(av ft^3/min)*
1999	483,572	531,929	0	0	0	0	0	0	0	0
2000	456,666	502,332	483,572	531,929	4.745E+03	3.800E+06	2.553E+02	1.268E+03	1.900E+06	1.277E+02
2001	454,381	499,819	940,237	1,034,261	9.040E+03	7.239E+06	4.864E+02	2.415E+03	3.620E+06	2.432E+02
2002	530,775	583,852	1,394,618	1,534,080	1.314E+04	1.053E+07	7.072E+02	3.511E+03	5.263E+06	3.536E+02
2003	553,951	609,346	1,925,393	2,117,932	1.784E+04	1.428E+07	9.597E+02	4.765E+03	7.142E+06	4.799E+02
2004	623,019	685,321	2,479,344	2,727,278	2.257E+04	1.808E+07	1.215E+03	6.030E+03	9.038E+06	6.073E+02
2005	691,847	761,032	3,102,363	3,412,600	2.780E+04	2.226E+07	1.496E+03	7.426E+03	1.113E+07	7.479E+02
2006	514,692	566,162	3,794,211	4,173,632	3.350E+04	2.683E+07	1.802E+03	8.949E+03	1.341E+07	9.012E+02
2007	0	0	4,308,903	4,739,793	3.724E+04	2.982E+07	2.004E+03	9.947E+03	1.491E+07	1.002E+03
2008	162,000	178,200	4,308,903	4,739,793	3.578E+04	2.865E+07	1.925E+03	9.557E+03	1.433E+07	9.625E+02
2009	0	0	4,470,903	4,917,993	3.597E+04	2.880E+07	1.935E+03	9.607E+03	1.440E+07	9.675E+02
2010	0	0	4,470,903	4,917,993	3.456E+04	2.767E+07	1.859E+03	9.230E+03	1.384E+07	9.296E+02
2011	0	0	4,470,903	4,917,993	3.320E+04	2.659E+07	1.786E+03	8.868E+03	1.329E+07	8.931E+02
2012	0	0	4,470,903	4,917,993	3.190E+04	2.554E+07	1.716E+03	8.520E+03	1.277E+07	8.581E+02
2013	0	0	4,470,903	4,917,993	3.065E+04	2.454E+07	1.649E+03	8.186E+03	1.227E+07	8.245E+02
2014	0	0	4,470,903	4,917,993	2.945E+04	2.358E+07	1.584E+03	7.865E+03	1.179E+07	7.921E+02
2015	0	0	4,470,903	4,917,993	2.829E+04	2.265E+07	1.522E+03	7.557E+03	1.133E+07	7.611E+02
2016	0	0	4,470,903	4,917,993	2.718E+04	2.177E+07	1.462E+03	7.261E+03	1.088E+07	7.312E+02
2017	0	0	4,470,903	4,917,993	2.612E+04	2.091E+07	1.405E+03	6.976E+03	1.046E+07	7.026E+02
2018	0	0	4,470,903	4,917,993	2.509E+04	2.009E+07	1.350E+03	6.702E+03	1.005E+07	6.750E+02
2019	0	0	4,470,903	4,917,993	2.411E+04	1.930E+07	1.297E+03	6.440E+03	9.652E+06	6.485E+02
2020	0	0	4,470,903	4,917,993	2.316E+04	1.855E+07	1.246E+03	6.187E+03	9.274E+06	6.231E+02
2021	0	0	4,470,903	4,917,993	2.225E+04	1.782E+07	1.197E+03	5.945E+03	8.910E+06	5.987E+02
2022	0	0	4,470,903	4,917,993	2.138E+04	1.712E+07	1.150E+03	5.711E+03	8.561E+06	5.752E+02
2023	0	0	4,470,903	4,917,993	2.054E+04	1.645E+07	1.105E+03	5.487E+03	8.225E+06	5.527E+02
2024	0	0	4,470,903	4,917,993	1.974E+04	1.581E+07	1.062E+03	5.272E+03	7.903E+06	5.310E+02
2025	0	0	4,470,903	4,917,993	1.896E+04	1.519E+07	1.020E+03	5.066E+03	7.593E+06	5.102E+02
2026	0	0	4,470,903	4,917,993	1.822E+04	1.459E+07	9.803E+02	4.867E+03	7.295E+06	4.902E+02
2027	0	0	4,470,903	4,917,993	1.751E+04	1.402E+07	9.419E+02	4.676E+03	7.009E+06	4.709E+02
2028	0	0	4,470,903	4,917,993	1.682E+04	1.347E+07	9.050E+02	4.493E+03	6.734E+06	4.525E+02
2029	0	0	4,470,903	4,917,993	1.616E+04	1.294E+07	8.695E+02	4.317E+03	6.470E+06	4.347E+02
2030	0	0	4,470,903	4,917,993	1.553E+04	1.243E+07	8.354E+02	4.147E+03	6.217E+06	4.177E+02
2031	0	0	4,470,903	4,917,993	1.492E+04	1.195E+07	8.026E+02	3.985E+03	5.973E+06	4.013E+02
2032	0	0	4,470,903	4,917,993	1.433E+04	1.148E+07	7.712E+02	3.828E+03	5.739E+06	3.856E+02
2033	0	0	4,470,903	4,917,993	1.377E+04	1.103E+07	7.409E+02	3.678E+03	5.514E+06	3.705E+02
2034	0	0	4,470,903	4,917,993	1.323E+04	1.059E+07	7.119E+02	3.534E+03	5.297E+06	3.559E+02
2035	0	0	4,470,903	4,917,993	1.271E+04	1.018E+07	6.839E+02	3.396E+03	5.090E+06	3.420E+02
2036	0	0	4,470,903	4,917,993	1.221E+04	9.780E+06	6.571E+02	3.262E+03	4.890E+06	3.286E+02
2037	0	0	4,470,903	4,917,993	1.173E+04	9.397E+06	6.314E+02	3.135E+03	4.698E+06	3.157E+02
2038	0	0	4,470,903	4,917,993	1.127E+04	9.028E+06	6.066E+02	3.012E+03	4.514E+06	3.033E+02
2039	0	0	4,470,903	4,917,993	1.083E+04	8.674E+06	5.828E+02	2.894E+03	4.337E+06	2.914E+02
2040	0	0	4,470,903	4,917,993	1.041E+04	8.334E+06	5.600E+02	2.780E+03	4.167E+06	2.800E+02
2041	0	0	4,470,903	4,917,993	1.000E+04	8.007E+06	5.380E+02	2.671E+03	4.004E+06	2.690E+02
2042	0	0	4,470,903	4,917,993	9.608E+03	7.693E+06	5.169E+02	2.566E+03	3.847E+06	2.585E+02
2043	0	0	4,470,903	4,917,993	9.231E+03	7.392E+06	4.966E+02	2.466E+03	3.696E+06	2.483E+02
2044	0	0	4,470,903	4,917,993	8.869E+03	7.102E+06	4.772E+02	2.369E+03	3.551E+06	2.386E+02
2045	0	0	4,470,903	4,917,993	8.521E+03	6.823E+06	4.585E+02	2.276E+03	3.412E+06	2.292E+02
2046	0	0	4,470,903	4,917,993	8.187E+03	6.556E+06	4.405E+02	2.187E+03	3.278E+06	2.202E+02
2047	0	0	4,470,903	4,917,993	7.866E+03	6.299E+06	4.232E+02	2.101E+03	3.149E+06	2.116E+02
2048	0	0	4,470,903	4,917,993	7.558E+03	6.052E+06	4.066E+02	2.019E+03	3.026E+06	2.033E+02
2049	0	0	4,470,903	4,917,993	7.261E+03	5.815E+06	3.907E+02	1.940E+03	2.907E+06	1.953E+02
2050	0	0	4,470,903	4,917,993	6.977E+03	5.587E+06	3.754E+02	1.864E+03	2.793E+06	1.877E+02
2051	0	0	4,470,903	4,917,993	6.703E+03	5.367E+06	3.606E+02	1.790E+03	2.684E+06	1.803E+02
2052	0	0	4,470,903	4,917,993	6.440E+03	5.157E+06	3.465E+02	1.720E+03	2.579E+06	1.733E+02
2053	0	0	4,470,903	4,917,993	6.188E+03	4.955E+06	3.329E+02	1.653E+03	2.477E+06	1.665E+02
2054	0	0	4,470,903	4,917,993	5.945E+03	4.761E+06	3.199E+02	1.588E+03	2.380E+06	1.599E+02
2055	0	0	4,470,903	4,917,993	5.712E+03	4.574E+06	3.073E+02	1.526E+03	2.287E+06	1.537E+02
2056	0	0	4,470,903	4,917,993	5.488E+03	4.395E+06	2.953E+02	1.466E+03	2.197E+06	1.476E+02
2057	0	0	4,470,903	4,917,993	5.273E+03	4.222E+06	2.837E+02	1.408E+03	2.111E+06	1.418E+02
2058	0	0	4,470,903	4,917,993	5.066E+03	4.057E+06	2.726E+02	1.353E+03	2.028E+06	1.363E+02
2059	0	0	4,470,903	4,917,993	4.867E+03	3.898E+06	2.619E+02	1.300E+03	1.949E+06	1.309E+02
2060	0	0	4,470,903	4,917,993	4.677E+03	3.745E+06	2.516E+02	1.249E+03	1.872E+06	1.258E+02
2061	0	0	4,470,903	4,917,993	4.493E+03	3.598E+06	2.417E+02	1.200E+03	1.799E+06	1.209E+02
2062	0	0	4,470,903	4,917,993	4.317E+03	3.457E+06	2.323E+02	1.153E+03	1.728E+06	1.161E+02
2063	0	0	4,470,903	4,917,993	4.148E+03	3.321E+06	2.232E+02	1.108E+03	1.661E+06	1.116E+02
2064	0	0	4,470,903	4,917,993	3.985E+03	3.191E+06	2.144E+02	1.064E+03	1.596E+06	1.072E+02
2065	0	0	4,470,903	4,917,993	3.829E+03	3.066E+06	2.060E+02	1.023E+03	1.533E+06	1.030E+02

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg/year)	(short tons/year)	(Mg)	(short tons)	(Mg/year)	(m^3/year)	(av ft^3/min)	(Mg/year)	(m^3/year)	(av ft^3/min)
2066	0	0	4,470,903	4,917,993	3.679E+03	2.946E+06	1.979E+02	9.826E+02	1.473E+06	9.896E+01
2067	0	0	4,470,903	4,917,993	3.534E+03	2.830E+06	1.902E+02	9.441E+02	1.415E+06	9.508E+01
2068	0	0	4,470,903	4,917,993	3.396E+03	2.719E+06	1.827E+02	9.071E+02	1.360E+06	9.135E+01
2069	0	0	4,470,903	4,917,993	3.263E+03	2.613E+06	1.755E+02	8.715E+02	1.306E+06	8.777E+01
2070	0	0	4,470,903	4,917,993	3.135E+03	2.510E+06	1.687E+02	8.373E+02	1.255E+06	8.433E+01
2071	0	0	4,470,903	4,917,993	3.012E+03	2.412E+06	1.620E+02	8.045E+02	1.206E+06	8.102E+01
2072	0	0	4,470,903	4,917,993	2.894E+03	2.317E+06	1.557E+02	7.730E+02	1.159E+06	7.785E+01
2073	0	0	4,470,903	4,917,993	2.780E+03	2.226E+06	1.496E+02	7.427E+02	1.113E+06	7.479E+01
2074	0	0	4,470,903	4,917,993	2.671E+03	2.139E+06	1.437E+02	7.135E+02	1.070E+06	7.186E+01
2075	0	0	4,470,903	4,917,993	2.567E+03	2.055E+06	1.381E+02	6.856E+02	1.028E+06	6.904E+01
2076	0	0	4,470,903	4,917,993	2.466E+03	1.975E+06	1.327E+02	6.587E+02	9.873E+05	6.634E+01
2077	0	0	4,470,903	4,917,993	2.369E+03	1.897E+06	1.275E+02	6.328E+02	9.486E+05	6.374E+01
2078	0	0	4,470,903	4,917,993	2.276E+03	1.823E+06	1.225E+02	6.080E+02	9.114E+05	6.124E+01
2079	0	0	4,470,903	4,917,993	2.187E+03	1.751E+06	1.177E+02	5.842E+02	8.757E+05	5.883E+01
2080	0	0	4,470,903	4,917,993	2.101E+03	1.683E+06	1.131E+02	5.613E+02	8.413E+05	5.653E+01
2081	0	0	4,470,903	4,917,993	2.019E+03	1.617E+06	1.086E+02	5.393E+02	8.083E+05	5.431E+01
2082	0	0	4,470,903	4,917,993	1.940E+03	1.553E+06	1.044E+02	5.181E+02	7.766E+05	5.218E+01
2083	0	0	4,470,903	4,917,993	1.864E+03	1.492E+06	1.003E+02	4.978E+02	7.462E+05	5.014E+01
2084	0	0	4,470,903	4,917,993	1.791E+03	1.434E+06	9.634E+01	4.783E+02	7.169E+05	4.817E+01
2085	0	0	4,470,903	4,917,993	1.720E+03	1.378E+06	9.256E+01	4.595E+02	6.888E+05	4.628E+01
2086	0	0	4,470,903	4,917,993	1.653E+03	1.324E+06	8.893E+01	4.415E+02	6.618E+05	4.447E+01
2087	0	0	4,470,903	4,917,993	1.588E+03	1.272E+06	8.545E+01	4.242E+02	6.359E+05	4.272E+01
2088	0	0	4,470,903	4,917,993	1.526E+03	1.222E+06	8.210E+01	4.076E+02	6.109E+05	4.105E+01
2089	0	0	4,470,903	4,917,993	1.466E+03	1.174E+06	7.888E+01	3.916E+02	5.870E+05	3.944E+01
2090	0	0	4,470,903	4,917,993	1.409E+03	1.128E+06	7.578E+01	3.762E+02	5.640E+05	3.789E+01
2091	0	0	4,470,903	4,917,993	1.353E+03	1.084E+06	7.281E+01	3.615E+02	5.418E+05	3.641E+01
2092	0	0	4,470,903	4,917,993	1.300E+03	1.041E+06	6.996E+01	3.473E+02	5.206E+05	3.498E+01
2093	0	0	4,470,903	4,917,993	1.249E+03	1.000E+06	6.721E+01	3.337E+02	5.002E+05	3.361E+01
2094	0	0	4,470,903	4,917,993	1.200E+03	9.611E+05	6.458E+01	3.206E+02	4.806E+05	3.229E+01
2095	0	0	4,470,903	4,917,993	1.153E+03	9.234E+05	6.205E+01	3.080E+02	4.617E+05	3.102E+01
2096	0	0	4,470,903	4,917,993	1.108E+03	8.872E+05	5.961E+01	2.960E+02	4.436E+05	2.981E+01
2097	0	0	4,470,903	4,917,993	1.065E+03	8.525E+05	5.728E+01	2.844E+02	4.262E+05	2.864E+01
2098	0	0	4,470,903	4,917,993	1.023E+03	8.190E+05	5.503E+01	2.732E+02	4.095E+05	2.752E+01
2099	0	0	4,470,903	4,917,993	9.827E+02	7.869E+05	5.287E+01	2.625E+02	3.935E+05	2.644E+01
2100	0	0	4,470,903	4,917,993	9.442E+02	7.561E+05	5.080E+01	2.522E+02	3.780E+05	2.540E+01
2101	0	0	4,470,903	4,917,993	9.072E+02	7.264E+05	4.881E+01	2.423E+02	3.632E+05	2.440E+01
2102	0	0	4,470,903	4,917,993	8.716E+02	6.979E+05	4.689E+01	2.328E+02	3.490E+05	2.345E+01
2103	0	0	4,470,903	4,917,993	8.374E+02	6.706E+05	4.505E+01	2.237E+02	3.353E+05	2.253E+01
2104	0	0	4,470,903	4,917,993	8.046E+02	6.443E+05	4.329E+01	2.149E+02	3.221E+05	2.164E+01
2105	0	0	4,470,903	4,917,993	7.730E+02	6.190E+05	4.159E+01	2.065E+02	3.095E+05	2.080E+01
2106	0	0	4,470,903	4,917,993	7.427E+02	5.947E+05	3.996E+01	1.984E+02	2.974E+05	1.998E+01
2107	0	0	4,470,903	4,917,993	7.136E+02	5.714E+05	3.839E+01	1.906E+02	2.857E+05	1.920E+01
2108	0	0	4,470,903	4,917,993	6.856E+02	5.490E+05	3.689E+01	1.831E+02	2.745E+05	1.844E+01
2109	0	0	4,470,903	4,917,993	6.587E+02	5.275E+05	3.544E+01	1.760E+02	2.637E+05	1.772E+01
2110	0	0	4,470,903	4,917,993	6.329E+02	5.068E+05	3.405E+01	1.691E+02	2.534E+05	1.703E+01
2111	0	0	4,470,903	4,917,993	6.081E+02	4.869E+05	3.272E+01	1.624E+02	2.435E+05	1.636E+01
2112	0	0	4,470,903	4,917,993	5.842E+02	4.678E+05	3.143E+01	1.561E+02	2.339E+05	1.572E+01
2113	0	0	4,470,903	4,917,993	5.613E+02	4.495E+05	3.020E+01	1.499E+02	2.247E+05	1.510E+01
2114	0	0	4,470,903	4,917,993	5.393E+02	4.319E+05	2.902E+01	1.441E+02	2.159E+05	1.451E+01
2115	0	0	4,470,903	4,917,993	5.182E+02	4.149E+05	2.788E+01	1.384E+02	2.075E+05	1.394E+01
2116	0	0	4,470,903	4,917,993	4.979E+02	3.987E+05	2.679E+01	1.330E+02	1.993E+05	1.339E+01
2117	0	0	4,470,903	4,917,993	4.783E+02	3.830E+05	2.574E+01	1.278E+02	1.915E+05	1.287E+01
2118	0	0	4,470,903	4,917,993	4.596E+02	3.680E+05	2.473E+01	1.228E+02	1.840E+05	1.236E+01
2119	0	0	4,470,903	4,917,993	4.416E+02	3.536E+05	2.376E+01	1.179E+02	1.768E+05	1.188E+01
2120	0	0	4,470,903	4,917,993	4.242E+02	3.397E+05	2.283E+01	1.133E+02	1.699E+05	1.141E+01
2121	0	0	4,470,903	4,917,993	4.076E+02	3.264E+05	2.193E+01	1.089E+02	1.632E+05	1.097E+01
2122	0	0	4,470,903	4,917,993	3.916E+02	3.136E+05	2.107E+01	1.046E+02	1.568E+05	1.054E+01
2123	0	0	4,470,903	4,917,993	3.763E+02	3.013E+05	2.024E+01	1.005E+02	1.507E+05	1.012E+01
2124	0	0	4,470,903	4,917,993	3.615E+02	2.895E+05	1.945E+01	9.657E+01	1.447E+05	9.725E+00
2125	0	0	4,470,903	4,917,993	3.473E+02	2.781E+05	1.869E+01	9.278E+01	1.391E+05	9.344E+00
2126	0	0	4,470,903	4,917,993	3.337E+02	2.672E+05	1.796E+01	8.914E+01	1.336E+05	8.978E+00
2127	0	0	4,470,903	4,917,993	3.206E+02	2.568E+05	1.725E+01	8.565E+01	1.284E+05	8.626E+00
2128	0	0	4,470,903	4,917,993	3.081E+02	2.467E+05	1.657E+01	8.229E+01	1.233E+05	8.287E+00
2129	0	0	4,470,903	4,917,993	2.960E+02	2.370E+05	1.592E+01	7.906E+01	1.185E+05	7.962E+00
2130	0	0	4,470,903	4,917,993	2.844E+02	2.277E+05	1.530E+01	7.596E+01	1.139E+05	7.650E+00
2131	0	0	4,470,903	4,917,993	2.732E+02	2.188E+05	1.470E+01	7.298E+01	1.094E+05	7.350E+00
2132	0	0	4,470,903	4,917,993	2.625E+02	2.102E+05	1.412E+01	7.012E+01	1.051E+05	7.062E+00
2133	0	0	4,470,903	4,917,993	2.522E+02	2.020E+05	1.357E+01	6.737E+01	1.010E+05	6.785E+00
2134	0	0	4,470,903	4,917,993	2.423E+02	1.941E+05	1.304E+01	6.473E+01	9.703E+04	6.519E+00
2135	0	0	4,470,903	4,917,993	2.328E+02	1.864E+05	1.253E+01	6.219E+01	9.322E+04	6.263E+00
2136	0	0	4,470,903	4,917,993	2.237E+02	1.791E+05	1.204E+01	5.975E+01	8.957E+04	6.018E+00
2137	0	0	4,470,903	4,917,993	2.149E+02	1.721E+05	1.156E+01	5.741E+01	8.605E+04	5.782E+00
2138	0	0	4,470,903	4,917,993	2.065E+02	1.654E+05	1.111E+01	5.516E+01	8.268E+04	5.555E+00
2139	0	0	4,470,903	4,917,993	1.984E+02	1.589E+05	1.067E+01	5.300E+01	7.944E+04	5.337E+00

GRAPHS **Landfill Name or Identifier:** Vancouver Landfill_Phase 1





A.2 LFG Generation Modeling for VLF-Phase 1: IPCC Model

Parameters

Country	**Canada_Vancouver Landfill Phase 1**
Region	America: North

Please enter parameters in the yellow cells. If no national data are available, copy the IPCC default value.
Help on parameter selection can be found in the 2006 IPCC guidelines

	IPCC default value		Country-specific parameters	
			Value	Reference and remarks
Starting year		1950	1999	
DOC (Degradable organic carbon)	Waste by composition			
(weight fraction, wet basis)	**Range**	**Default**		
Food waste	0.08-0.20	0.15	0.15	
Garden	0.18-0.22	0.2	0.2	
Paper	0.36-0.45	0.4	0.4	
Wood and straw	0.39-0.46	0.43	0.43	
Textiles	0.20-0.40	0.24	0.24	
Disposable nappies	0.18-0.32	0.24	0.24	
Sewage sludge	0.04-0.05	0.05	0.05	
Industrial waste	0-0.54	0.15	0.15	
DOCf (fraction of DOC dissimilated)		0.5	0.5	
Methane generation rate constant (k)	Wet temperate			
(years^{-1})	**Range**	**Default**		
Food waste	0.1–0.2	0.185	0.185	
Garden	0.06–0.1	0.1	0.1	
Paper	0.05–0.07	0.06	0.06	
Wood and straw	0.02–0.04	0.03	0.03	
Textiles	0.05–0.07	0.06	0.06	
Disposable nappies	0.06–0.1	0.1	0.1	
Sewage sludge	0.1–0.2	0.185	0.185	
Industrial waste	0.08–0.1	0.09	0.09	
Delay time (months)		6	6	
Fraction of methane (F) in developed gas		0.5	0.5	
Conversion factor, C to CH_4		1.33	1.33	
Oxidation factor (OX)		0	0	
Parameters for carbon storage				
% paper in industrial waste		0%	0%	
% wood in industrial waste		0%	0%	

MSW activity data

Enter population, waste per capita and MSW waste composition into the yellow cells.
Help and default regional values are given in the 2006 IPCC Guidelines.
Industrial waste activity data must be entered separately starting in Column Q.

IPCC Regional defaults

	N/A		58%	34%	0%	23%	6%	4%	0%	33%	100%
				Composition of waste going to solid waste disposal sites							
Year	Population	Waste per capita	Total MSW	% to SWDS	Food	Garden	Paper	Wood	Textile	Nappies	Plastics, other inert	Total
	millions	kg/cap/yr	Gg	%	%	%	%	%	%	%	%	(=100%)
1999	0	N/A	483.6	100%	15%	4%	25%	22%	6%	2%	26%	100%
2000	0	N/A	456.7	100%	13%	4%	22%	28%	5%	2%	26%	100%
2001	0	N/A	454.4	100%	14%	9%	17%	21%	7%	2%	31%	100%
2002	0	N/A	530.8	100%	12%	7%	15%	28%	6%	2%	31%	100%
2003	0	N/A	554.0	100%	13%	8%	16%	23%	7%	2%	31%	100%
2004	0	N/A	623.0	100%	17%	3%	18%	22%	6%	1%	32%	100%
2005	0	N/A	691.8	100%	17%	3%	18%	21%	7%	1%	32%	100%
2006	0	N/A	514.7	100%	17%	3%	19%	20%	7%	1%	32%	100%
2007	0	N/A	0.0	100%	20%	3%	22%	20%	3%	2%	30%	100%
2008	0	N/A	162.0	100%	19%	3%	22%	22%	3%	2%	30%	100%
2009	0	N/A	0	0%	34%	0%	23%	6%	4%	0%	33%	100%

Results

Country

Canada_Vancouver Landfill Phase 1

Enter starting year, industrial waste disposal data and methane recovery into the yellow cells.
MSW activity data is entered on MSW sheet

	Methane generated												
Year	Food	Garden	Paper	Wood	Textile	Nappies	Sludge	MSW	Industrial	Total	Methane recovery	Methane emission	Methane emission
	A	B	C	D	E	F	G	H	J	K	L	M = (K-L)*(1-OX)	M = (K-L)*(1-OX)
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Tonne
1999	0	0	0	0	0	0	0		0	0	0	0	0
2000	0	0	0	0	0	0	0		0	1	0	1	1,175
2001	1	0	1	1	0	0	0		0	3	0	3	3,191
2002	1	0	2	1	0	0	0		0	5	0	5	4,923
2003	2	1	2	2	0	0	0		0	7	0	7	6,744
2004	2	1	3	2	1	0	0		0	9	0	9	8,592
2005	2	1	4	3	1	0	0		0	11	0	11	10,626
2006	3	1	4	3	1	0	0		0	13	0	13	12,807
2007	3	1	5	4	1	0	0		0	14	0	14	14,046
2008	3	1	5	4	1	0	0		0	13	0	13	12,922
2009	3	1	5	4	1	0	0		0	13	0	13	12,685
2010	2	1	4	3	1	0	0		0	12	0	12	11,729
2011	2	1	4	3	1	0	0		0	11	0	11	10,876
2012	1	1	4	3	1	0	0		0	10	0	10	10,112
2013	1	1	4	3	1	0	0		0	9	0	9	9,426
2014	1	0	3	3	1	0	0		0	9	0	9	8,807
2015	1	0	3	3	1	0	0		0	8	0	8	8,247
2016	1	0	3	3	1	0	0		0	8	0	8	7,737

	Methane generated												
Year	Food	Garden	Paper	Wood	Textile	Nappies	Sludge	MSW	Industrial	Total	Methane recovery	Methane emission	Methane emission
	A	B	C	D	E	F	G	H	J	K	L	M = (K-L)*(1-OX)	M = (K-L)*(1-OX)
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Tonne
2017	1	0	3	3	1	0	0		0	7	0	7	7,273
2018	0	0	3	3	1	0	0		0	7	0	7	6,848
2019	0	0	2	3	1	0	0		0	6	0	6	6,457
2020	0	0	2	3	0	0	0		0	6	0	6	6,098
2021	0	0	2	2	0	0	0		0	6	0	6	5,766
2022	0	0	2	2	0	0	0		0	5	0	5	5,459
2023	0	0	2	2	0	0	0		0	5	0	5	5,174
2024	0	0	2	2	0	0	0		0	5	0	5	4,909
2025	0	0	2	2	0	0	0		0	5	0	5	4,662
2026	0	0	2	2	0	0	0		0	4	0	4	4,431
2027	0	0	2	2	0	0	0		0	4	0	4	4,215
2028	0	0	1	2	0	0	0		0	4	0	4	4,012
2029	0	0	1	2	0	0	0		0	4	0	4	3,822
2030	0	0	1	2	0	0	0		0	4	0	4	3,643
2031	0	0	1	2	0	0	0		0	3	0	3	3,475
2032	0	0	1	2	0	0	0		0	3	0	3	3,316
2033	0	0	1	2	0	0	0		0	3	0	3	3,166
2034	0	0	1	2	0	0	0		0	3	0	3	3,025
2035	0	0	1	2	0	0	0		0	3	0	3	2,891
2036	0	0	1	2	0	0	0		0	3	0	3	2,764
2037	0	0	1	2	0	0	0		0	3	0	3	2,644
2038	0	0	1	1	0	0	0		0	3	0	3	2,530
2039	0	0	1	1	0	0	0		0	2	0	2	2,422
2040	0	0	1	1	0	0	0		0	2	0	2	2,320
2041	0	0	1	1	0	0	0		0	2	0	2	2,222
2042	0	0	1	1	0	0	0		0	2	0	2	2,129
2043	0	0	1	1	0	0	0		0	2	0	2	2,041
2044	0	0	1	1	0	0	0		0	2	0	2	1,958
2045	0	0	1	1	0	0	0		0	2	0	2	1,878
2046	0	0	0	1	0	0	0		0	2	0	2	1,802
2047	0	0	0	1	0	0	0		0	2	0	2	1,729
2048	0	0	0	1	0	0	0		0	2	0	2	1,660
2049	0	0	0	1	0	0	0		0	2	0	2	1,594
2050	0	0	0	1	0	0	0		0	2	0	2	1,531
2051	0	0	0	1	0	0	0		0	1	0	1	1,471
2052	0	0	0	1	0	0	0		0	1	0	1	1,414
2053	0	0	0	1	0	0	0		0	1	0	1	1,359
2054	0	0	0	1	0	0	0		0	1	0	1	1,307
2055	0	0	0	1	0	0	0		0	1	0	1	1,257
2056	0	0	0	1	0	0	0		0	1	0	1	1,209
2057	0	0	0	1	0	0	0		0	1	0	1	1,163
2058	0	0	0	1	0	0	0		0	1	0	1	1,119
2059	0	0	0	1	0	0	0		0	1	0	1	1,077
2060	0	0	0	1	0	0	0		0	1	0	1	1,037
2061	0	0	0	1	0	0	0		0	1	0	1	999
2062	0	0	0	1	0	0	0		0	1	0	1	962
2063	0	0	0	1	0	0	0		0	1	0	1	926
2064	0	0	0	1	0	0	0		0	1	0	1	893
2065	0	0	0	1	0	0	0		0	1	0	1	860
2066	0	0	0	1	0	0	0		0	1	0	1	829
2067	0	0	0	1	0	0	0		0	1	0	1	799
2068	0	0	0	1	0	0	0		0	1	0	1	770
2069	0	0	0	1	0	0	0		0	1	0	1	743
2070	0	0	0	1	0	0	0		0	1	0	1	716
2071	0	0	0	1	0	0	0		0	1	0	1	691
2072	0	0	0	1	0	0	0		0	1	0	1	667
2073	0	0	0	1	0	0	0		0	1	0	1	643
2074	0	0	0	1	0	0	0		0	1	0	1	621
2075	0	0	0	0	0	0	0		0	1	0	1	599
2076	0	0	0	0	0	0	0		0	1	0	1	578
2077	0	0	0	0	0	0	0		0	1	0	1	558
2078	0	0	0	0	0	0	0		0	1	0	1	539
2079	0	0	0	0	0	0	0		0	1	0	1	521
2080	0	0	0	0	0	0	0		0	1	0	1	503

A.3 LFG Generation Modeling for VLF-Phase 1: BC MOE Tool

	Relatively Inert	Moderately Decomposable	Decomposable	
Gas Production potential, Lo =	20	120	160	m^3 CH4/tonne
lag time before start of gas production, lag =	1	years		
Historical Data Used (years)	13			
1st Year of Historical Data Used	1999			
4 Years after Reporting Year	2140			
methane (by volume)	50%			
carbon dioxide (by volume)	50%			
methane (density) - 1atm, 25C	0.6770	kg/m^3	**(15C,SP)**	
carbon dioxide (density)	1.7988	kg/m^3	(25C,SP)	

Year	Relatively Inert	Moderately Decomposable	Decomposable
1999	25.6%	55.1%	19.2%
2000	26.1%	56.9%	17.0%
2001	30.9%	46.6%	22.5%
2002	30.8%	49.7%	19.5%
2003	30.9%	47.7%	21.5%
2004	32.0%	48.1%	19.9%
2005	32.0%	47.8%	20.2%
2006	32.1%	47.3%	20.6%
2007			
2008	29.6%	48.3%	22.0%

				Waste Tonnage			Methane Generation Rate, k			Annual
		Annual	Cumulative		Moderately			Moderately		Methane
Year	Year	Tonnage	Waste-in-place	Relatively Inert	Decomposable	Decomposable	Relatively Inert	Decomposable	Decomposable	Production
	Number	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	($year^{-1}$)	($year^{-1}$)	($year^{-1}$)	(tonnes/yr)
1999	1	483,572	483,572	123,924	266,562	93,085	0.02	0.06	0.11	0.00
2000	2	456,666	940,237	119,400	259,795	77,471	0.02	0.06	0.11	2354.25
2001	3	454,381	1,394,618	140,382	211,643	102,355	0.02	0.06	0.11	4313.71
2002	4	530,775	1,925,393	163,351	263,795	103,629	0.02	0.06	0.11	6184.39
2003	5	553,951	2,479,344	170,913	264,081	118,957	0.02	0.06	0.11	8171.02
2004	6	623,019	3,102,363	199,293	299,854	123,872	0.02	0.06	0.11	10180.24
2005	7	691,847	3,794,211	221,524	330,625	139,698	0.02	0.06	0.11	12262.85
2006	8	514,692	4,308,903	165,014	243,620	106,059	0.02	0.06	0.11	14515.32
2007	9	0	4,308,903	0	0	0	0.02	0.06	0.11	15782.87
2008	10	162,000	4,470,903	47,994	78,316	35,690	0.02	0.06	0.11	14550.67
2009	11	0	4,470,903	0	0	0	0.02	0.06	0.11	14213.34
2010	12	0	4,470,903	0	0	0	0.02	0.06	0.11	13118.27
2011	13	0	4,470,903	0	0	0	0.02	0.06	0.11	12115.88
2012	14	0	4,470,903	0	0	0	0.02	0.06	0.11	11197.76
2013	15	0	4,470,903	0	0	0	0.02	0.06	0.11	10356.26
2014	16	0	4,470,903	0	0	0	0.02	0.06	0.11	9584.50
2015	17	0	4,470,903	0	0	0	0.02	0.06	0.11	8876.24
2016	18	0	4,470,903	0	0	0	0.02	0.06	0.11	8225.83
2017	19	0	4,470,903	0	0	0	0.02	0.06	0.11	7628.14
2018	20	0	4,470,903	0	0	0	0.02	0.06	0.11	7078.55
2019	21	0	4,470,903	0	0	0	0.02	0.06	0.11	6572.85
2020	22	0	4,470,903	0	0	0	0.02	0.06	0.11	6107.23
2021	23	0	4,470,903	0	0	0	0.02	0.06	0.11	5678.23
2022	24	0	4,470,903	0	0	0	0.02	0.06	0.11	5282.70
2023	25	0	4,470,903	0	0	0	0.02	0.06	0.11	4917.81
2024	26	0	4,470,903	0	0	0	0.02	0.06	0.11	4580.95
2025	27	0	4,470,903	0	0	0	0.02	0.06	0.11	4269.77
2026	28	0	4,470,903	0	0	0	0.02	0.06	0.11	3982.13
2027	29	0	4,470,903	0	0	0	0.02	0.06	0.11	3716.07
2028	30	0	4,470,903	0	0	0	0.02	0.06	0.11	3469.83
2029	31	0	4,470,903	0	0	0	0.02	0.06	0.11	3241.78
2030	32	0	4,470,903	0	0	0	0.02	0.06	0.11	3030.44
2031	33	0	4,470,903	0	0	0	0.02	0.06	0.11	2834.48
2032	34	0	4,470,903	0	0	0	0.02	0.06	0.11	2652.66
2033	35	0	4,470,903	0	0	0	0.02	0.06	0.11	2483.86
2034	36	0	4,470,903	0	0	0	0.02	0.06	0.11	2327.05
2035	37	0	4,470,903	0	0	0	0.02	0.06	0.11	2181.31
2036	38	0	4,470,903	0	0	0	0.02	0.06	0.11	2045.76
2037	39	0	4,470,903	0	0	0	0.02	0.06	0.11	1919.63
2038	40	0	4,470,903	0	0	0	0.02	0.06	0.11	1802.19
2039	41	0	4,470,903	0	0	0	0.02	0.06	0.11	1692.79
2040	42	0	4,470,903	0	0	0	0.02	0.06	0.11	1590.83
2041	43	0	4,470,903	0	0	0	0.02	0.06	0.11	1495.73
2042	44	0	4,470,903	0	0	0	0.02	0.06	0.11	1407.01
2043	45	0	4,470,903	0	0	0	0.02	0.06	0.11	1324.18
2044	46	0	4,470,903	0	0	0	0.02	0.06	0.11	1246.82
2045	47	0	4,470,903	0	0	0	0.02	0.06	0.11	1174.54

				Waste Tonnage			Methane Generation Rate, k			Annual
		Annual	Cumulative		Moderately			Moderately		Methane
Year	Year	Tonnage	Waste-in-place	Relatively Inert	Decomposable	Decomposable	Relatively Inert	Decomposable	Decomposable	Production
	Number	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	($year^{-1}$)	($year^{-1}$)	($year^{-1}$)	(tonnes/yr)
2046	48	0	4,470,903	0	0	0	0.02	0.06	0.11	1106.95
2047	49	0	4,470,903	0	0	0	0.02	0.06	0.11	1043.74
2048	50	0	4,470,903	0	0	0	0.02	0.06	0.11	984.59
2049	51	0	4,470,903	0	0	0	0.02	0.06	0.11	929.21
2050	52	0	4,470,903	0	0	0	0.02	0.06	0.11	877.34
2051	53	0	4,470,903	0	0	0	0.02	0.06	0.11	828.74
2052	54	0	4,470,903	0	0	0	0.02	0.06	0.11	783.18
2053	55	0	4,470,903	0	0	0	0.02	0.06	0.11	740.45
2054	56	0	4,470,903	0	0	0	0.02	0.06	0.11	700.36
2055	57	0	4,470,903	0	0	0	0.02	0.06	0.11	662.73
2056	58	0	4,470,903	0	0	0	0.02	0.06	0.11	627.40
2057	59	0	4,470,903	0	0	0	0.02	0.06	0.11	594.21
2058	60	0	4,470,903	0	0	0	0.02	0.06	0.11	563.02
2059	61	0	4,470,903	0	0	0	0.02	0.06	0.11	533.70
2060	62	0	4,470,903	0	0	0	0.02	0.06	0.11	506.13
2061	63	0	4,470,903	0	0	0	0.02	0.06	0.11	480.19
2062	64	0	4,470,903	0	0	0	0.02	0.06	0.11	455.78
2063	65	0	4,470,903	0	0	0	0.02	0.06	0.11	432.79
2064	66	0	4,470,903	0	0	0	0.02	0.06	0.11	411.15
2065	67	0	4,470,903	0	0	0	0.02	0.06	0.11	390.75
2066	68	0	4,470,903	0	0	0	0.02	0.06	0.11	371.53
2067	69	0	4,470,903	0	0	0	0.02	0.06	0.11	353.41
2068	70	0	4,470,903	0	0	0	0.02	0.06	0.11	336.32
2069	71	0	4,470,903	0	0	0	0.02	0.06	0.11	320.19
2070	72	0	4,470,903	0	0	0	0.02	0.06	0.11	304.98
2071	73	0	4,470,903	0	0	0	0.02	0.06	0.11	290.61
2072	74	0	4,470,903	0	0	0	0.02	0.06	0.11	277.04
2073	75	0	4,470,903	0	0	0	0.02	0.06	0.11	264.22
2074	76	0	4,470,903	0	0	0	0.02	0.06	0.11	252.10
2075	77	0	4,470,903	0	0	0	0.02	0.06	0.11	240.65
2076	78	0	4,470,903	0	0	0	0.02	0.06	0.11	229.81
2077	79	0	4,470,903	0	0	0	0.02	0.06	0.11	219.56
2078	80	0	4,470,903	0	0	0	0.02	0.06	0.11	209.87
2079	81	0	4,470,903	0	0	0	0.02	0.06	0.11	200.68
2080	82	0	4,470,903	0	0	0	0.02	0.06	0.11	191.99
2081	83	0	4,470,903	0	0	0	0.02	0.06	0.11	183.75
2082	84	0	4,470,903	0	0	0	0.02	0.06	0.11	175.94
2083	85	0	4,470,903	0	0	0	0.02	0.06	0.11	168.54
2084	86	0	4,470,903	0	0	0	0.02	0.06	0.11	161.53
2085	87	0	4,470,903	0	0	0	0.02	0.06	0.11	154.87
2086	88	0	4,470,903	0	0	0	0.02	0.06	0.11	148.55
2087	89	0	4,470,903	0	0	0	0.02	0.06	0.11	142.55
2088	90	0	4,470,903	0	0	0	0.02	0.06	0.11	136.85
2089	91	0	4,470,903	0	0	0	0.02	0.06	0.11	131.44
2090	92	0	4,470,903	0	0	0	0.02	0.06	0.11	126.30
2091	93	0	4,470,903	0	0	0	0.02	0.06	0.11	121.41
2092	94	0	4,470,903	0	0	0	0.02	0.06	0.11	116.76
2093	95	0	4,470,903	0	0	0	0.02	0.06	0.11	112.33
2094	96	0	4,470,903	0	0	0	0.02	0.06	0.11	108.12
2095	97	0	4,470,903	0	0	0	0.02	0.06	0.11	104.11
2096	98	0	4,470,903	0	0	0	0.02	0.06	0.11	100.29
2097	99	0	4,470,903	0	0	0	0.02	0.06	0.11	96.65
2098	100	0	4,470,903	0	0	0	0.02	0.06	0.11	93.18
2099	101	0	4,470,903	0	0	0	0.02	0.06	0.11	89.87
2100	102	0	4,470,903	0	0	0	0.02	0.06	0.11	86.71
2101	103	0	4,470,903	0	0	0	0.02	0.06	0.11	83.70
2102	104	0	4,470,903	0	0	0	0.02	0.06	0.11	80.82
2103	105	0	4,470,903	0	0	0	0.02	0.06	0.11	78.07
2104	106	0	4,470,903	0	0	0	0.02	0.06	0.11	75.45
2105	107	0	4,470,903	0	0	0	0.02	0.06	0.11	72.94
2106	108	0	4,470,903	0	0	0	0.02	0.06	0.11	70.54
2107	109	0	4,470,903	0	0	0	0.02	0.06	0.11	68.24
2108	110	0	4,470,903	0	0	0	0.02	0.06	0.11	66.04
2109	111	0	4,470,903	0	0	0	0.02	0.06	0.11	63.93
2110	112	0	4,470,903	0	0	0	0.02	0.06	0.11	61.92

Appendix B iModel-110© Modeling Results – Vancouver Landfill

B.1 iModel-110© Modeling Results – Area 2W

Landfill's Site-Specific Information

Enter Site's Name/ ID: **Vancouver Landfill - Area 2W**

Year Filling Started: **1990** **Date OK!**

Thesis References and Parameters		Food waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies
		%	%	%	%	%	%
Table 3.1 of Thesis	DOC_{dry}	0.38	0.49	0.44	0.5	0.3	0.3
Table 2.8 of Thesis	Moisture	50%	45%	20%	18%	14%	14%
Degradability Factor	f_{dg}	0.84	0.66	0.46	0.2	0.5	0.5
Climate Factor	f_{cl}	1	1	1	1	1	1
Depth Factor	f_{dp}	0.9	0.9	0.9	0.9	0.9	0.9
Storage Factor	f_{st}	0.8	1	1	1	1	1
$f = f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$	∑Discount	**0.60**	**0.59**	**0.41**	**0.18**	**0.45**	**0.45**
Theoretical Methane Yield	L_o	***113***	***158***	***143***	***73***	***114***	***114***

Dry Degradable Organic Carbon Content and Decay Rates for Different Waste Components

Waste Components	DOC_{dry} (kg in 1kg dry)	k $year^{-1}$
Food waste	**0.38**	**0.35**
Garden	**0.49**	**0.14**
Paper	**0.44**	**0.07**
Wood and straw	**0.50**	**0.04**
Textiles	**0.30**	**0.07**
Disposable nappies	**0.30**	**0.07**

Thesis References: Table 3.1 Table 3.15

Methane Characteristics, Generation Calibration Factor & Delay Time

Parameters	Values & Units
CH_4 Density:	**0.6775** kg/m^3
CH_4 Fraction:	**0.5** m^3/m^3
CH_4/C (16/12):	**1.333** kg/kg
Enter (CF_G) here:	**1**
Delay Time (T_d):	**4** Months

Table 3.16

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2W								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
1990	91,901	25,742	150,652	34,604	40,277	11,769	113,939	**468,883**	**468,883**
1991	91,117	25,522	149,366	34,308	39,933	11,669	112,966	**464,881**	**933,764**
1992	88,793	24,871	145,558	33,433	38,915	11,371	110,086	**453,028**	**1,386,792**
1993	90,493	25,347	148,344	147,473	39,660	11,589	160,793	**623,700**	**2,010,492**
1994	-	-	-	-	-	-	-	**-**	**2,010,492**
1995	-	-	-	-	-	-	-	**-**	**2,010,492**
1996	-	-	-	-	-	-	-	**-**	**2,010,492**
1997	-	-	-	-	-	-	-	**-**	**2,010,492**
1998	-	-	-	-	-	-	-	**-**	**2,010,492**
1999	-	-	-	-	-	-	-	**-**	**2,010,492**
2000	-	-	-	-	-	-	-	**-**	**2,010,492**
2001	-	-	-	-	-	-	-	**-**	**2,010,492**
2002	-	-	-	-	-	-	-	**-**	**2,010,492**
2003	-	-	-	-	-	-	-	**-**	**2,010,492**
2004	-	-	-	-	-	-	-	**-**	**2,010,492**
2005	-	-	-	-	-	-	-	**-**	**2,010,492**
2006	-	-	-	-	-	-	-	**-**	**2,010,492**
2007	-	-	-	-	-	-	-	**-**	**2,010,492**
2008	-	-	-	-	-	-	-	**-**	**2,010,492**
2009	-	-	-	-	-	-	-	**-**	**2,010,492**
2010	-	-	-	-	-	-	-	**-**	**2,010,492**
2011	-	-	-	-	-	-	-	**-**	**2,010,492**
2012	-	-	-	-	-	-	-	**-**	**2,010,492**
2013	-	-	-	-	-	-	-	**-**	**2,010,492**
2014	-	-	-	-	-	-	-	**-**	**2,010,492**
2015	-	-	-	-	-	-	-	**-**	**2,010,492**
2016	-	-	-	-	-	-	-	**-**	**2,010,492**
2017	-	-	-	-	-	-	-	**-**	**2,010,492**
2018	-	-	-	-	-	-	-	**-**	**2,010,492**
2019	-	-	-	-	-	-	-	**-**	**2,010,492**
2020	-	-	-	-	-	-	-	**-**	**2,010,492**
2021	-	-	-	-	-	-	-	**-**	**2,010,492**
2022	-	-	-	-	-	-	-	**-**	**2,010,492**
2023	-	-	-	-	-	-	-	**-**	**2,010,492**
2024	-	-	-	-	-	-	-	**-**	**2,010,492**
2025	-	-	-	-	-	-	-	**-**	**2,010,492**
2026	-	-	-	-	-	-	-	**-**	**2,010,492**
2027	-	-	-	-	-	-	-	**-**	**2,010,492**
2028	-	-	-	-	-	-	-	**-**	**2,010,492**
2029	-	-	-	-	-	-	-	**-**	**2,010,492**
2030	-	-	-	-	-	-	-	**-**	**2,010,492**
2031	-	-	-	-	-	-	-	**-**	**2,010,492**
2032	-	-	-	-	-	-	-	**-**	**2,010,492**
2033	-	-	-	-	-	-	-	**-**	**2,010,492**
2034	-	-	-	-	-	-	-	**-**	**2,010,492**
2035	-	-	-	-	-	-	-	**-**	**2,010,492**
2036	-	-	-	-	-	-	-	**-**	**2,010,492**
2037	-	-	-	-	-	-	-	**-**	**2,010,492**
2038	-	-	-	-	-	-	-	**-**	**2,010,492**
2039	-	-	-	-	-	-	-	**-**	**2,010,492**
2040	-	-	-	-	-	-	-	**-**	**2,010,492**
2041	-	-	-	-	-	-	-	**-**	**2,010,492**
2042	-	-	-	-	-	-	-	**-**	**2,010,492**
2043	-	-	-	-	-	-	-	**-**	**2,010,492**
2044	-	-	-	-	-	-	-	**-**	**2,010,492**
2045	-	-	-	-	-	-	-	**-**	**2,010,492**
2046	-	-	-	-	-	-	-	**-**	**2,010,492**

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2W								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2047	-	-	-	-	-	-	-	-	2,010,492
2048	-	-	-	-	-	-	-	-	2,010,492
2049	-	-	-	-	-	-	-	-	2,010,492
2050	-	-	-	-	-	-	-	-	2,010,492
2051	-	-	-	-	-	-	-	-	2,010,492
2052	-	-	-	-	-	-	-	-	2,010,492
2053	-	-	-	-	-	-	-	-	2,010,492
2054	-	-	-	-	-	-	-	-	2,010,492
2055	-	-	-	-	-	-	-	-	2,010,492
2056	-	-	-	-	-	-	-	-	2,010,492
2057	-	-	-	-	-	-	-	-	2,010,492
2058	-	-	-	-	-	-	-	-	2,010,492
2059	-	-	-	-	-	-	-	-	2,010,492
2060	-	-	-	-	-	-	-	-	2,010,492
2061	-	-	-	-	-	-	-	-	2,010,492
2062	-	-	-	-	-	-	-	-	2,010,492
2063	-	-	-	-	-	-	-	-	2,010,492
2064	-	-	-	-	-	-	-	-	2,010,492
2065	-	-	-	-	-	-	-	-	2,010,492
2066	-	-	-	-	-	-	-	-	2,010,492
2067	-	-	-	-	-	-	-	-	2,010,492
2068	-	-	-	-	-	-	-	-	2,010,492
2069	-	-	-	-	-	-	-	-	2,010,492
2070	-	-	-	-	-	-	-	-	2,010,492
2071	-	-	-	-	-	-	-	-	2,010,492
2072	-	-	-	-	-	-	-	-	2,010,492
2073	-	-	-	-	-	-	-	-	2,010,492
2074	-	-	-	-	-	-	-	-	2,010,492
2075	-	-	-	-	-	-	-	-	2,010,492
2076	-	-	-	-	-	-	-	-	2,010,492
2077	-	-	-	-	-	-	-	-	2,010,492
2078	-	-	-	-	-	-	-	-	2,010,492
2079	-	-	-	-	-	-	-	-	2,010,492
2080	-	-	-	-	-	-	-	-	2,010,492
2081	-	-	-	-	-	-	-	-	2,010,492
2082	-	-	-	-	-	-	-	-	2,010,492
2083	-	-	-	-	-	-	-	-	2,010,492
2084	-	-	-	-	-	-	-	-	2,010,492
2085	-	-	-	-	-	-	-	-	2,010,492
2086	-	-	-	-	-	-	-	-	2,010,492
2087	-	-	-	-	-	-	-	-	2,010,492
2088	-	-	-	-	-	-	-	-	2,010,492
2089	-	-	-	-	-	-	-	-	2,010,492
2090	-	-	-	-	-	-	-	-	2,010,492
2091	-	-	-	-	-	-	-	-	2,010,492
2092	-	-	-	-	-	-	-	-	2,010,492
2093	-	-	-	-	-	-	-	-	2,010,492
2094	-	-	-	-	-	-	-	-	2,010,492
2095	-	-	-	-	-	-	-	-	2,010,492
2096	-	-	-	-	-	-	-	-	2,010,492
2097	-	-	-	-	-	-	-	-	2,010,492
2098	-	-	-	-	-	-	-	-	2,010,492
2099	-	-	-	-	-	-	-	-	2,010,492
2100	-	-	-	-	-	-	-	-	2,010,492
2101	-	-	-	-	-	-	-	-	2,010,492
2102	-	-	-	-	-	-	-	-	2,010,492
2103	-	-	-	-	-	-	-	-	2,010,492

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2W								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2104	-	-	-	-	-	-	-	-	2,010,492
2105	-	-	-	-	-	-	-	-	2,010,492
2106	-	-	-	-	-	-	-	-	2,010,492
2107	-	-	-	-	-	-	-	-	2,010,492
2108	-	-	-	-	-	-	-	-	2,010,492
2109	-	-	-	-	-	-	-	-	2,010,492
2110	-	-	-	-	-	-	-	-	2,010,492
2111	-	-	-	-	-	-	-	-	2,010,492
2112	-	-	-	-	-	-	-	-	2,010,492
2113	-	-	-	-	-	-	-	-	2,010,492
2114	-	-	-	-	-	-	-	-	2,010,492
2115	-	-	-	-	-	-	-	-	2,010,492
2116	-	-	-	-	-	-	-	-	2,010,492
2117	-	-	-	-	-	-	-	-	2,010,492
2118	-	-	-	-	-	-	-	-	2,010,492
2119	-	-	-	-	-	-	-	-	2,010,492
2120	-	-	-	-	-	-	-	-	2,010,492
2121	-	-	-	-	-	-	-	-	2,010,492
2122	-	-	-	-	-	-	-	-	2,010,492
2123	-	-	-	-	-	-	-	-	2,010,492
2124	-	-	-	-	-	-	-	-	2,010,492
2125	-	-	-	-	-	-	-	-	2,010,492
2126	-	-	-	-	-	-	-	-	2,010,492
2127	-	-	-	-	-	-	-	-	2,010,492
2128	-	-	-	-	-	-	-	-	2,010,492
2129	-	-	-	-	-	-	-	-	2,010,492
2130	-	-	-	-	-	-	-	-	2,010,492
2131	-	-	-	-	-	-	-	-	2,010,492
2132	-	-	-	-	-	-	-	-	2,010,492
2133	-	-	-	-	-	-	-	-	2,010,492
2134	-	-	-	-	-	-	-	-	2,010,492
2135	-	-	-	-	-	-	-	-	2,010,492
2136	-	-	-	-	-	-	-	-	2,010,492
2137	-	-	-	-	-	-	-	-	2,010,492
2138	-	-	-	-	-	-	-	-	2,010,492
2139	-	-	-	-	-	-	-	-	2,010,492
2140	-	-	-	-	-	-	-	-	2,010,492

Dry Tonnages Deposited at the Vancouver Landfill - Area 2W

	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
Moisture	50%	45%	20%	18%	14%	14%	10%	23%
Solid	50%	55%	80%	82%	86%	86%	90%	77%

Dry Amounts Historically Deposited at the Vancouver Landfill - Area 2W

Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
1990	46	14	121	28	35	10	103	356
1991	46	14	119	28	34	10	102	353
1992	44	14	116	27	33	10	99	344
1993	45	14	119	121	34	10	145	488
1994	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0

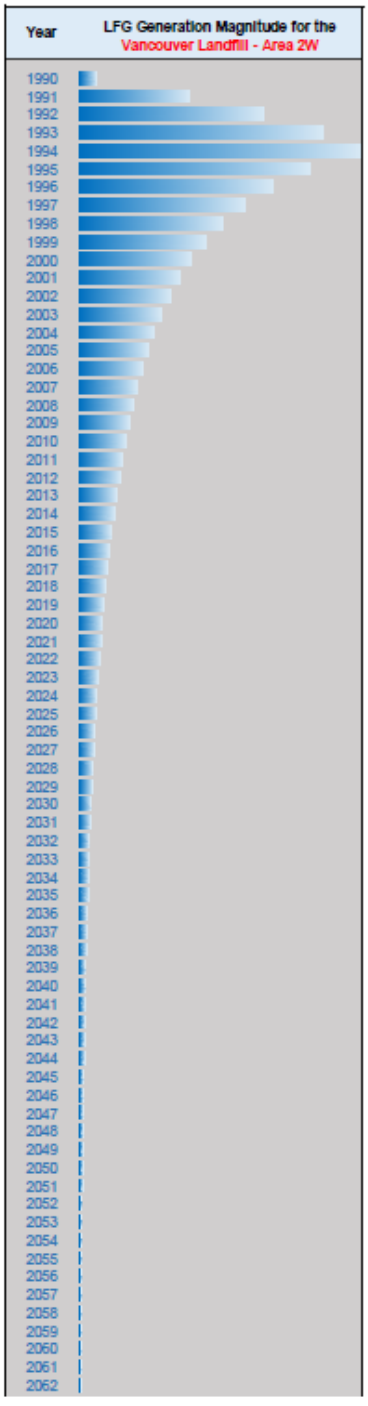
	Dry Amounts Historically Deposited at the Vancouver Landfill - Area 2W							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2037	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0
2051	0	0	0	0	0	0	0	0
2052	0	0	0	0	0	0	0	0
2053	0	0	0	0	0	0	0	0
2054	0	0	0	0	0	0	0	0
2055	0	0	0	0	0	0	0	0
2056	0	0	0	0	0	0	0	0
2057	0	0	0	0	0	0	0	0
2058	0	0	0	0	0	0	0	0
2059	0	0	0	0	0	0	0	0
2060	0	0	0	0	0	0	0	0
2061	0	0	0	0	0	0	0	0
2062	0	0	0	0	0	0	0	0
2063	0	0	0	0	0	0	0	0
2064	0	0	0	0	0	0	0	0
2065	0	0	0	0	0	0	0	0
2066	0	0	0	0	0	0	0	0
2067	0	0	0	0	0	0	0	0
2068	0	0	0	0	0	0	0	0
2069	0	0	0	0	0	0	0	0
2070	0	0	0	0	0	0	0	0
2071	0	0	0	0	0	0	0	0
2072	0	0	0	0	0	0	0	0
2073	0	0	0	0	0	0	0	0
2074	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0
2076	0	0	0	0	0	0	0	0
2077	0	0	0	0	0	0	0	0
2078	0	0	0	0	0	0	0	0
2079	0	0	0	0	0	0	0	0
2080	0	0	0	0	0	0	0	0
2081	0	0	0	0	0	0	0	0
2082	0	0	0	0	0	0	0	0

Methane Generation Estimates from the Vancouver Landfill - Area 2W

Actual CH_4 Yields

L_o (m^3/tonne)	113	157	143	72	114	114	91.3

Year	Methane generation estimates for the Vancouver Landfill - Area 2W							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)
1990	399	63	170	11	36	11	690	94.9	137
1991	2,357	413	1,146	78	244	71	4,310	94.9	855
1992	3,712	714	2,046	140	436	127	7,175	94.9	1,423
1993	4,632	968	2,866	237	611	178	9,492	83.5	1,883
1994	4,919	1,133	3,460	464	741	217	10,953		2,172
1995	3,466	985	3,245	445	691	202	9,034		1,792
1996	2,442	856	3,025	428	644	188	7,585		1,504
1997	1,721	744	2,821	411	601	176	6,474		1,284
1998	1,213	647	2,630	395	560	164	5,609		1,113
1999	855	563	2,452	380	522	153	4,924		977
2000	602	489	2,286	365	487	142	4,372		867
2001	424	425	2,132	350	454	133	3,919		777
2002	299	370	1,988	337	423	124	3,540		702
2003	211	321	1,853	323	395	115	3,219		638
2004	149	279	1,728	311	368	108	2,942		584
2005	105	243	1,611	299	343	100	2,701		536
2006	74	211	1,502	287	320	93	2,488		493
2007	52	184	1,401	276	298	87	2,297		456
2008	37	160	1,306	265	278	81	2,127		422
2009	26	139	1,218	254	259	76	1,972		391
2010	18	121	1,135	244	242	71	1,831		363
2011	13	105	1,059	235	225	66	1,703		338
2012	9	91	987	226	210	61	1,585		314
2013	6	79	920	217	196	57	1,476		293
2014	4	69	858	208	183	53	1,376		273
2015	3	60	800	200	170	50	1,284		255
2016	2	52	746	192	159	46	1,198		238
2017	2	45	696	185	148	43	1,119		222
2018	1	39	649	178	138	40	1,045		207
2019	1	34	605	171	129	38	977		194
2020	1	30	564	164	120	35	913		181
2021	0	26	526	157	112	33	854		169
2022	0	22	490	151	104	31	799		158
2023	0	20	457	145	97	28	748		148
2024	0	17	426	140	91	27	700		139
2025	0	15	397	134	85	25	656		130
2026	0	13	370	129	79	23	614		122
2027	0	11	345	124	74	21	576		114
2028	0	10	322	119	69	20	539		107
2029	0	8	300	114	64	19	506		100
2030	0	7	280	110	60	17	474		94
2031	0	6	261	106	56	16	445		88
2032	0	6	243	101	52	15	417		83
2033	0	5	227	97	48	14	392		78
2034	0	4	212	94	45	13	368		73
2035	0	4	197	90	42	12	345		68
2036	0	3	184	86	39	11	324		64
2037	0	3	172	83	37	11	305		60
2038	0	2	160	80	34	10	286		57
2039	0	2	149	77	32	9	269		53
2040	0	2	139	74	30	9	253		50
2041	0	2	130	71	28	8	238		47
2042	0	1	121	68	26	8	223		44
2043	0	1	113	65	24	7	210		42
2044	0	1	105	63	22	7	198		39
2045	0	1	98	60	21	6	186		37
2046	0	1	91	58	19	6	175		35
2047	0	1	85	56	18	5	165		33
2048	0	1	79	53	17	5	155		31
2049	0	1	74	51	16	5	146		29
2050	0	0	69	49	15	4	138		27
2051	0	0	64	47	14	4	130		26
2052	0	0	60	46	13	4	122		24
2053	0	0	56	44	12	3	115		23
2054	0	0	52	42	11	3	109		22
2055	0	0	49	40	10	3	103		20
2056	0	0	45	39	10	3	97		19
2057	0	0	42	37	9	3	91		18
2058	0	0	39	36	8	2	86		17
2059	0	0	37	34	8	2	81		16
2060	0	0	34	33	7	2	77		15
2061	0	0	32	32	7	2	73		14
2062	0	0	30	31	6	2	69		14



Year	Methane generation estimates for the Vancouver Landfill - Area 2W							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)
2063	0	0	28	29	6	2	65		13
2064	0	0	26	28	6	2	61		12
2065	0	0	24	27	5	2	58		11
2066	0	0	23	26	5	1	55		11
2067	0	0	21	25	4	1	52		10
2068	0	0	20	24	4	1	49		10
2069	0	0	18	23	4	1	46		9
2070	0	0	17	22	4	1	44		9
2071	0	0	16	21	3	1	42		8
2072	0	0	15	20	3	1	39		8
2073	0	0	14	20	3	1	37		7
2074	0	0	13	19	3	1	35		7
2075	0	0	12	18	3	1	33		7
2076	0	0	11	17	2	1	32		6
2077	0	0	10	17	2	1	30		6
2078	0	0	10	16	2	1	29		6
2079	0	0	9	15	2	1	27		5
2080	0	0	8	15	2	1	26		5
2081	0	0	8	14	2	0	24		5
2082	0	0	7	14	2	0	23		5
2083	0	0	7	13	1	0	22		4
2084	0	0	6	13	1	0	21		4
2085	0	0	6	12	1	0	20		4
2086	0	0	6	12	1	0	19		4
2087	0	0	5	11	1	0	18		4
2088	0	0	5	11	1	0	17		3
2089	0	0	5	10	1	0	16		3
2090	0	0	4	10	1	0	15		3
2091	0	0	4	10	1	0	15		3
2092	0	0	4	9	1	0	14		3
2093	0	0	3	9	1	0	13		3
2094	0	0	3	8	1	0	13		2
2095	0	0	3	8	1	0	12		2
2096	0	0	3	8	1	0	11		2
2097	0	0	3	8	1	0	11		2
2098	0	0	2	7	1	0	10		2
2099	0	0	2	7	0	0	10		2
2100	0	0	2	7	0	0	9		2
2101	0	0	2	6	0	0	9		2
2102	0	0	2	6	0	0	8		2
2103	0	0	2	6	0	0	8		2
2104	0	0	2	6	0	0	8		2
2105	0	0	1	5	0	0	7		1
2106	0	0	1	5	0	0	7		1
2107	0	0	1	5	0	0	7		1
2108	0	0	1	5	0	0	6		1
2109	0	0	1	5	0	0	6		1
2110	0	0	1	4	0	0	6		1
2111	0	0	1	4	0	0	6		1
2112	0	0	1	4	0	0	5		1
2113	0	0	1	4	0	0	5		1
2114	0	0	1	4	0	0	5		1
2115	0	0	1	4	0	0	5		1
2116	0	0	1	4	0	0	4		1
2117	0	0	1	3	0	0	4		1
2118	0	0	1	3	0	0	4		1
2119	0	0	1	3	0	0	4		1
2120	0	0	1	3	0	0	4		1
2121	0	0	0	3	0	0	3		1
2122	0	0	0	3	0	0	3		1
2123	0	0	0	3	0	0	3		1
2124	0	0	0	3	0	0	3		1
2125	0	0	0	2	0	0	3		1
2126	0	0	0	2	0	0	3		1
2127	0	0	0	2	0	0	3		1
2128	0	0	0	2	0	0	3		1
2129	0	0	0	2	0	0	2		0
2130	0	0	0	2	0	0	2		0
2131	0	0	0	2	0	0	2		0
2132	0	0	0	2	0	0	2		0
2133	0	0	0	2	0	0	2		0
2134	0	0	0	2	0	0	2		0
2135	0	0	0	2	0	0	2		0
2136	0	0	0	2	0	0	2		0
2137	0	0	0	2	0	0	2		0
2138	0	0	0	1	0	0	2		0
2139	0	0	0	1	0	0	2		0
2140	0	0	0	1	0	0	2		0

Year	LFG Generation Magnitude for the Vancouver Landfill - Area 2W
2063	
2064	
2065	
2066	
2067	
2068	
2069	
2070	
2071	
2072	
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2075	
2076	
2077	
2078	
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2081	
2082	
2083	
2084	
2085	
2086	
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2089	
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2091	
2092	
2093	
2094	
2095	
2096	
2097	
2098	
2099	
2100	
2101	
2102	
2103	
2104	
2105	
2106	
2107	
2108	
2109	
2110	
2111	
2112	
2113	
2114	
2115	
2116	
2117	
2118	
2119	
2120	
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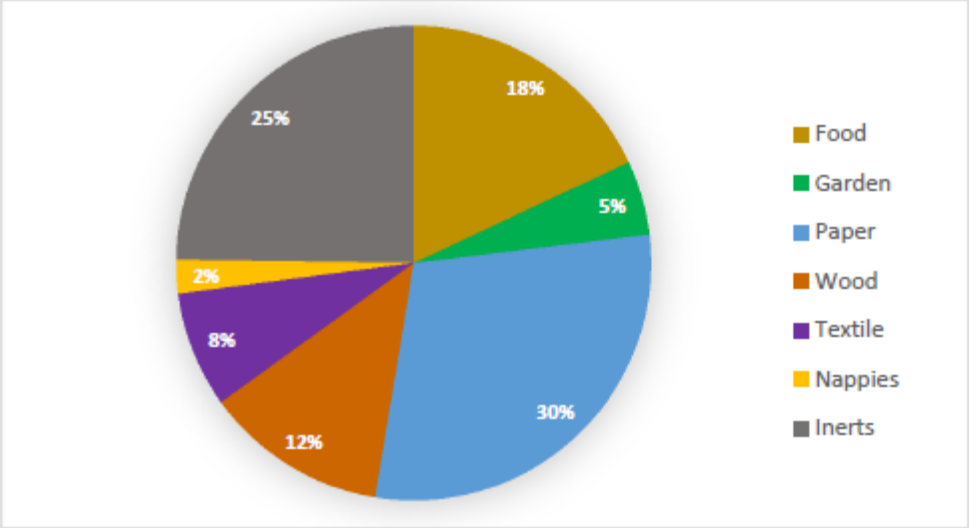
2137	
2138	
2139	
2140	

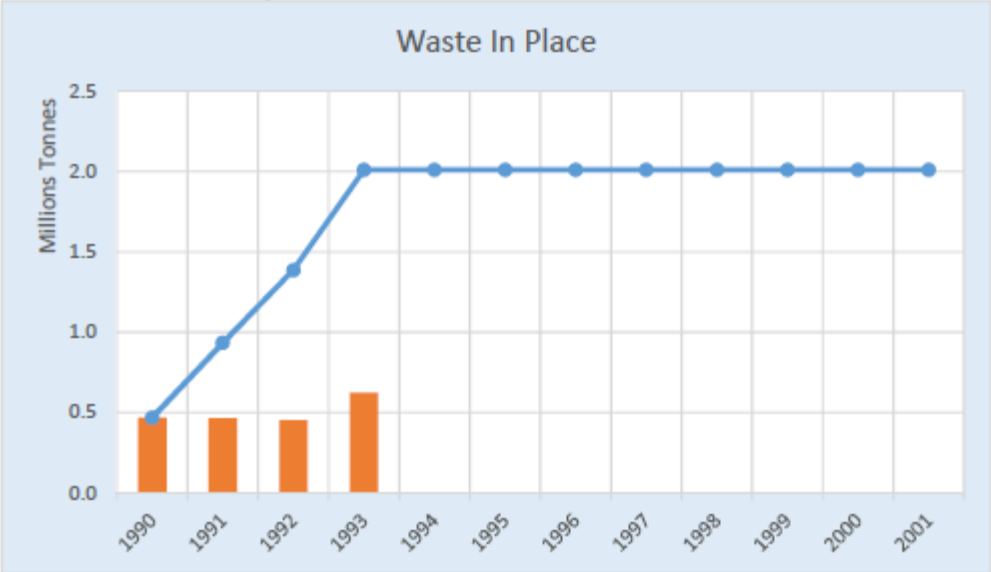
Vancouver Landfill - Area 2W

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**

Average Deposited Waste Composition

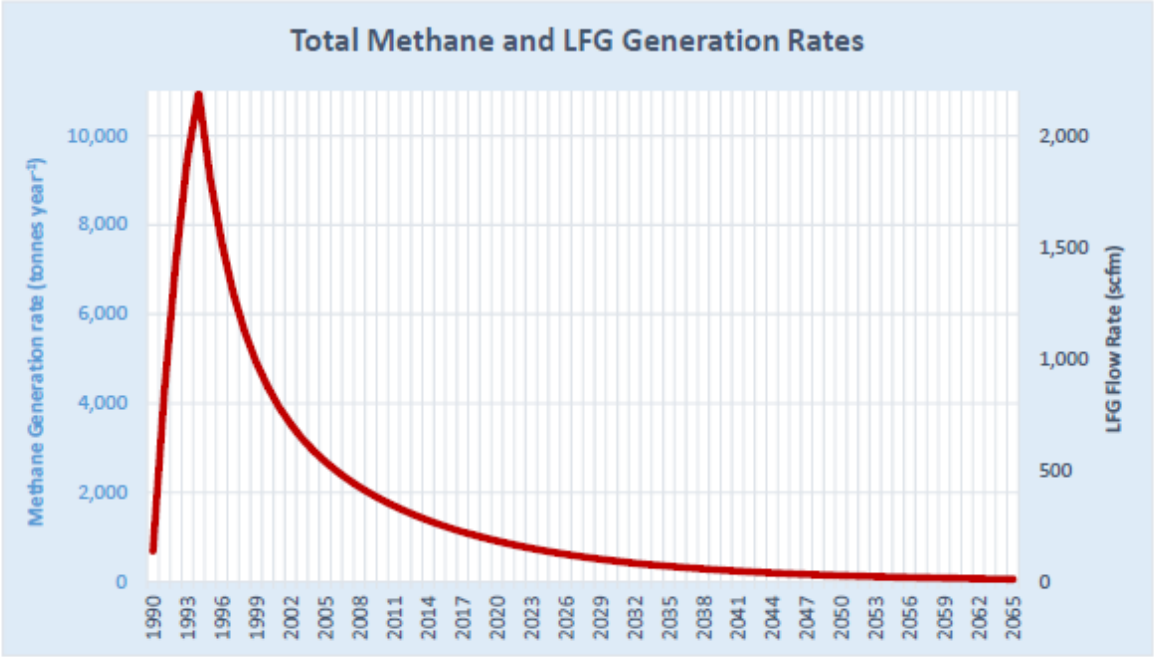


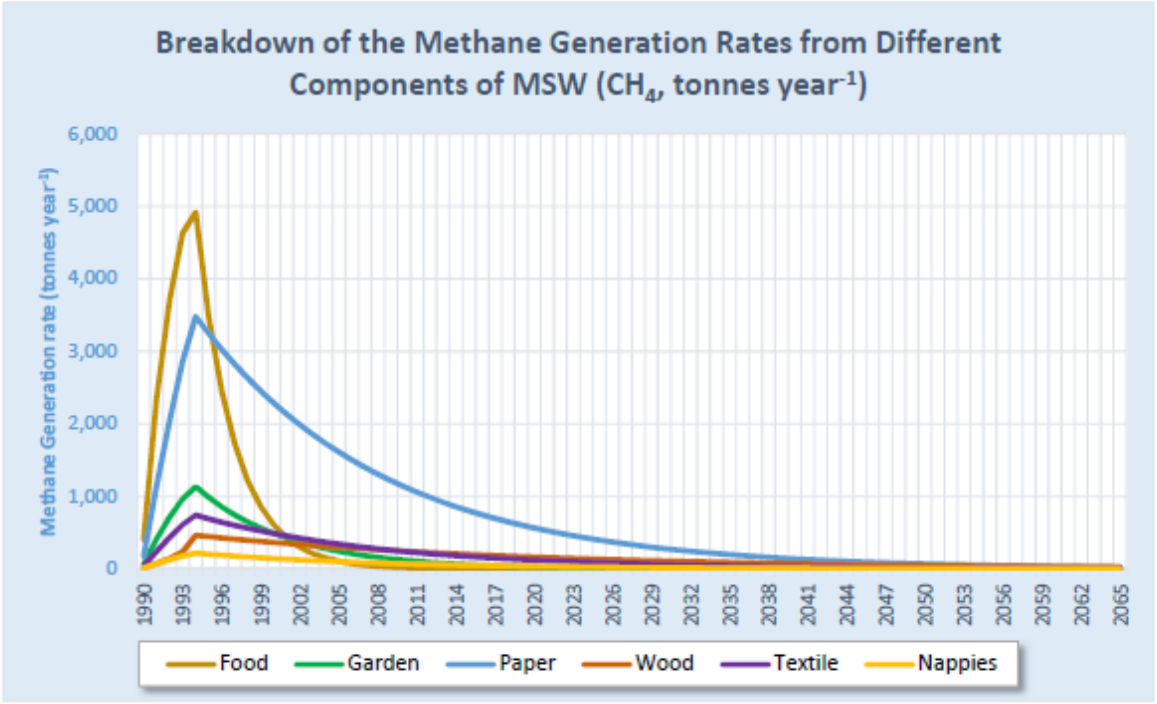
Annual MSW Deposition Rates and Total In Place



Vancouver Landfill - Area 2W

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**





B.2 iModel-110© Modeling Results – Area 2E

Landfill's Site-Specific Information

Enter Site's Name/ ID: Vancouver Landfill - Area 2E

Year Filling Started: 1994 Date OK!

Thesis References and Parameters		Food waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies
		%	%	%	%	%	%
Table 3.1 of Thesis	DOC_{dry}	0.38	0.49	0.44	0.5	0.3	0.3
Table 2.8 of Thesis	Moisture	50%	45%	20%	18%	14%	14%
Degradability Factor	f_{dg}	0.84	0.66	0.46	0.2	0.5	0.5
Climate Factor	f_{cl}	1	1	1	1	1	1
Depth Factor	f_{dp}	0.9	0.9	0.9	0.9	0.9	0.9
Storage Factor	f_{st}	0.8	1	1	1	1	1
$f = f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$	∑Discount	**0.60**	**0.59**	**0.41**	**0.18**	**0.45**	**0.45**
Theoretical Methane Yield	L_o	***113***	***158***	***143***	***73***	***114***	***114***

Dry Degradable Organic Carbon Content and Decay Rates for Different Waste Components

Waste Components	DOC_{dry} (kg in 1kg dry)	k $year^{-1}$
Food waste	**0.38**	**0.35**
Garden	**0.49**	**0.14**
Paper	**0.44**	**0.07**
Wood and straw	**0.50**	**0.04**
Textiles	**0.30**	**0.07**
Disposable nappies	**0.30**	**0.07**

Thesis References: Table 3.1 Table 3.15

Methane Characteristics, Generation Calibration Factor & Delay Time

Parameters	Values & Units
CH_4 Density:	**0.6775** kg/m^3
CH_4 Fraction:	**0.5** m^3/m^3
CH_4/C (16/12):	**1.333** kg/kg
Enter (CF_G) here:	**1**
Delay Time (T_d):	**4** Months

Table 3.16

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2E								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
1994	85,613	23,980	140,344	32,236	37,521	10,964	106,142	**436,800**	**436,800**
1995	84,221	23,591	138,063	87,502	36,911	10,785	128,327	**509,400**	**946,200**
1996	-	-	-	-	-	-	-	**-**	**946,200**
1997	-	-	-	-	-	-	-	**-**	**946,200**
1998	-	-	-	-	-	-	-	**-**	**946,200**
1999	-	-	-	-	-	-	-	**-**	**946,200**
2000	-	-	-	-	-	-	-	**-**	**946,200**
2001	-	-	-	-	-	-	-	**-**	**946,200**
2002	-	-	-	-	-	-	-	**-**	**946,200**
2003	-	-	-	-	-	-	-	**-**	**946,200**
2004	-	-	-	-	-	-	-	**-**	**946,200**
2005	-	-	-	-	-	-	-	**-**	**946,200**
2006	-	-	-	-	-	-	-	**-**	**946,200**
2007	-	-	-	-	-	-	-	**-**	**946,200**
2008	-	-	-	-	-	-	-	**-**	**946,200**
2009	-	-	-	-	-	-	-	**-**	**946,200**
2010	-	-	-	-	-	-	-	**-**	**946,200**
2011	-	-	-	-	-	-	-	**-**	**946,200**
2012	-	-	-	-	-	-	-	**-**	**946,200**
2013	-	-	-	-	-	-	-	**-**	**946,200**
2014	-	-	-	-	-	-	-	**-**	**946,200**
2015	-	-	-	-	-	-	-	**-**	**946,200**
2016	-	-	-	-	-	-	-	**-**	**946,200**
2017	-	-	-	-	-	-	-	**-**	**946,200**
2018	-	-	-	-	-	-	-	**-**	**946,200**
2019	-	-	-	-	-	-	-	**-**	**946,200**
2020	-	-	-	-	-	-	-	**-**	**946,200**
2021	-	-	-	-	-	-	-	**-**	**946,200**
2022	-	-	-	-	-	-	-	**-**	**946,200**
2023	-	-	-	-	-	-	-	**-**	**946,200**
2024	-	-	-	-	-	-	-	**-**	**946,200**
2025	-	-	-	-	-	-	-	**-**	**946,200**
2026	-	-	-	-	-	-	-	**-**	**946,200**
2027	-	-	-	-	-	-	-	**-**	**946,200**
2028	-	-	-	-	-	-	-	**-**	**946,200**
2029	-	-	-	-	-	-	-	**-**	**946,200**
2030	-	-	-	-	-	-	-	**-**	**946,200**
2031	-	-	-	-	-	-	-	**-**	**946,200**
2032	-	-	-	-	-	-	-	**-**	**946,200**
2033	-	-	-	-	-	-	-	**-**	**946,200**
2034	-	-	-	-	-	-	-	**-**	**946,200**
2035	-	-	-	-	-	-	-	**-**	**946,200**
2036	-	-	-	-	-	-	-	**-**	**946,200**
2037	-	-	-	-	-	-	-	**-**	**946,200**
2038	-	-	-	-	-	-	-	**-**	**946,200**
2039	-	-	-	-	-	-	-	**-**	**946,200**
2040	-	-	-	-	-	-	-	**-**	**946,200**
2041	-	-	-	-	-	-	-	**-**	**946,200**
2042	-	-	-	-	-	-	-	**-**	**946,200**
2043	-	-	-	-	-	-	-	**-**	**946,200**
2044	-	-	-	-	-	-	-	**-**	**946,200**
2045	-	-	-	-	-	-	-	**-**	**946,200**
2046	-	-	-	-	-	-	-	**-**	**946,200**
2047	-	-	-	-	-	-	-	**-**	**946,200**
2048	-	-	-	-	-	-	-	**-**	**946,200**
2049	-	-	-	-	-	-	-	**-**	**946,200**
2050	-	-	-	-	-	-	-	**-**	**946,200**

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2E								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2051	-	-	-	-	-	-	-	-	946,200
2052	-	-	-	-	-	-	-	-	946,200
2053	-	-	-	-	-	-	-	-	946,200
2054	-	-	-	-	-	-	-	-	946,200
2055	-	-	-	-	-	-	-	-	946,200
2056	-	-	-	-	-	-	-	-	946,200
2057	-	-	-	-	-	-	-	-	946,200
2058	-	-	-	-	-	-	-	-	946,200
2059	-	-	-	-	-	-	-	-	946,200
2060	-	-	-	-	-	-	-	-	946,200
2061	-	-	-	-	-	-	-	-	946,200
2062	-	-	-	-	-	-	-	-	946,200
2063	-	-	-	-	-	-	-	-	946,200
2064	-	-	-	-	-	-	-	-	946,200
2065	-	-	-	-	-	-	-	-	946,200
2066	-	-	-	-	-	-	-	-	946,200
2067	-	-	-	-	-	-	-	-	946,200
2068	-	-	-	-	-	-	-	-	946,200
2069	-	-	-	-	-	-	-	-	946,200
2070	-	-	-	-	-	-	-	-	946,200
2071	-	-	-	-	-	-	-	-	946,200
2072	-	-	-	-	-	-	-	-	946,200
2073	-	-	-	-	-	-	-	-	946,200
2074	-	-	-	-	-	-	-	-	946,200
2075	-	-	-	-	-	-	-	-	946,200
2076	-	-	-	-	-	-	-	-	946,200
2077	-	-	-	-	-	-	-	-	946,200
2078	-	-	-	-	-	-	-	-	946,200
2079	-	-	-	-	-	-	-	-	946,200
2080	-	-	-	-	-	-	-	-	946,200
2081	-	-	-	-	-	-	-	-	946,200
2082	-	-	-	-	-	-	-	-	946,200
2083	-	-	-	-	-	-	-	-	946,200
2084	-	-	-	-	-	-	-	-	946,200
2085	-	-	-	-	-	-	-	-	946,200
2086	-	-	-	-	-	-	-	-	946,200
2087	-	-	-	-	-	-	-	-	946,200
2088	-	-	-	-	-	-	-	-	946,200
2089	-	-	-	-	-	-	-	-	946,200
2090	-	-	-	-	-	-	-	-	946,200
2091	-	-	-	-	-	-	-	-	946,200
2092	-	-	-	-	-	-	-	-	946,200
2093	-	-	-	-	-	-	-	-	946,200
2094	-	-	-	-	-	-	-	-	946,200
2095	-	-	-	-	-	-	-	-	946,200
2096	-	-	-	-	-	-	-	-	946,200
2097	-	-	-	-	-	-	-	-	946,200
2098	-	-	-	-	-	-	-	-	946,200
2099	-	-	-	-	-	-	-	-	946,200
2100	-	-	-	-	-	-	-	-	946,200
2101	-	-	-	-	-	-	-	-	946,200
2102	-	-	-	-	-	-	-	-	946,200
2103	-	-	-	-	-	-	-	-	946,200
2104	-	-	-	-	-	-	-	-	946,200
2105	-	-	-	-	-	-	-	-	946,200
2106	-	-	-	-	-	-	-	-	946,200
2107	-	-	-	-	-	-	-	-	946,200

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 2E								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2108	-	-	-	-	-	-	-	-	946,200
2109	-	-	-	-	-	-	-	-	946,200
2110	-	-	-	-	-	-	-	-	946,200
2111	-	-	-	-	-	-	-	-	946,200
2112	-	-	-	-	-	-	-	-	946,200
2113	-	-	-	-	-	-	-	-	946,200
2114	-	-	-	-	-	-	-	-	946,200
2115	-	-	-	-	-	-	-	-	946,200
2116	-	-	-	-	-	-	-	-	946,200
2117	-	-	-	-	-	-	-	-	946,200
2118	-	-	-	-	-	-	-	-	946,200
2119	-	-	-	-	-	-	-	-	946,200
2120	-	-	-	-	-	-	-	-	946,200
2121	-	-	-	-	-	-	-	-	946,200
2122	-	-	-	-	-	-	-	-	946,200
2123	-	-	-	-	-	-	-	-	946,200
2124	-	-	-	-	-	-	-	-	946,200
2125	-	-	-	-	-	-	-	-	946,200
2126	-	-	-	-	-	-	-	-	946,200
2127	-	-	-	-	-	-	-	-	946,200
2128	-	-	-	-	-	-	-	-	946,200
2129	-	-	-	-	-	-	-	-	946,200
2130	-	-	-	-	-	-	-	-	946,200
2131	-	-	-	-	-	-	-	-	946,200
2132	-	-	-	-	-	-	-	-	946,200
2133	-	-	-	-	-	-	-	-	946,200
2134	-	-	-	-	-	-	-	-	946,200
2135	-	-	-	-	-	-	-	-	946,200
2136	-	-	-	-	-	-	-	-	946,200
2137	-	-	-	-	-	-	-	-	946,200
2138	-	-	-	-	-	-	-	-	946,200
2139	-	-	-	-	-	-	-	-	946,200
2140	-	-	-	-	-	-	-	-	946,200
2141	-	-	-	-	-	-	-	-	946,200
2142	-	-	-	-	-	-	-	-	946,200
2143	-	-	-	-	-	-	-	-	946,200
2144	-	-	-	-	-	-	-	-	946,200

Dry Tonnages Deposited at the Vancouver Landfill - Area 2E

	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
Moisture	50%	45%	20%	18%	14%	14%	10%	23%
Solid								

Dry Amounts Historically Deposited at the Vancouver Landfill - Area 2E

Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
1994	43	13	112	26	32	9	96	332
1995	42	13	110	72	32	9	115	394
1996	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0	0
1999	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0
2036	0	0	0	0	0	0	0	0
2037	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill - Area 2E							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2041	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0
2051	0	0	0	0	0	0	0	0
2052	0	0	0	0	0	0	0	0
2053	0	0	0	0	0	0	0	0
2054	0	0	0	0	0	0	0	0
2055	0	0	0	0	0	0	0	0
2056	0	0	0	0	0	0	0	0
2057	0	0	0	0	0	0	0	0
2058	0	0	0	0	0	0	0	0
2059	0	0	0	0	0	0	0	0
2060	0	0	0	0	0	0	0	0
2061	0	0	0	0	0	0	0	0
2062	0	0	0	0	0	0	0	0
2063	0	0	0	0	0	0	0	0
2064	0	0	0	0	0	0	0	0
2065	0	0	0	0	0	0	0	0
2066	0	0	0	0	0	0	0	0
2067	0	0	0	0	0	0	0	0
2068	0	0	0	0	0	0	0	0
2069	0	0	0	0	0	0	0	0
2070	0	0	0	0	0	0	0	0
2071	0	0	0	0	0	0	0	0
2072	0	0	0	0	0	0	0	0
2073	0	0	0	0	0	0	0	0
2074	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0
2076	0	0	0	0	0	0	0	0
2077	0	0	0	0	0	0	0	0
2078	0	0	0	0	0	0	0	0
2079	0	0	0	0	0	0	0	0
2080	0	0	0	0	0	0	0	0
2081	0	0	0	0	0	0	0	0
2082	0	0	0	0	0	0	0	0
2083	0	0	0	0	0	0	0	0
2084	0	0	0	0	0	0	0	0
2085	0	0	0	0	0	0	0	0
2086	0	0	0	0	0	0	0	0
2087	0	0	0	0	0	0	0	0

2088	0	0	0	0	0	0	0	0
2089	0	0	0	0	0	0	0	0
2090	0	0	0	0	0	0	0	0
2091	0	0	0	0	0	0	0	0
2092	0	0	0	0	0	0	0	0
2093	0	0	0	0	0	0	0	0

Methane Generation Estimates from the Vancouver Landfill - Area 2E

Actual CH_4 Yields

L_o (m^3/tonne)	113	157	143	72	114	114	91.1

Year	Methane generation estimates for the Vancouver Landfill - Area 2E							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)
1994	372	59	158	11	34	10	643	94.9	128
1995	2,193	385	1,067	90	227	66	4,028	88.0	799
1996	3,085	605	1,746	227	372	109	6,144		1,219
1997	2,174	526	1,628	218	347	101	4,994		991
1998	1,532	457	1,518	210	323	94	4,134		820
1999	1,060	398	1,415	201	301	88	3,483		691
2000	761	346	1,319	193	281	82	2,983		592
2001	536	301	1,230	186	262	77	2,591		514
2002	378	261	1,147	179	244	71	2,280		452
2003	266	227	1,070	172	228	67	2,029		402
2004	188	197	997	165	212	62	1,822		361
2005	132	172	930	158	198	58	1,648		327
2006	93	149	867	152	185	54	1,500		298
2007	66	130	808	146	172	50	1,372		272
2008	46	113	754	140	161	47	1,261		250
2009	33	98	703	135	150	44	1,162		230
2010	23	85	655	130	140	41	1,073		213
2011	16	74	611	125	130	38	994		197
2012	11	64	570	120	121	35	922		183
2013	8	56	531	115	113	33	856		170
2014	6	49	495	111	105	31	796		158
2015	4	42	462	106	98	29	741		147
2016	3	37	431	102	92	27	691		137
2017	2	32	401	98	85	25	644		128
2018	1	28	374	94	80	23	601		119
2019	1	24	349	90	74	22	561		111
2020	1	21	325	87	69	20	524		104
2021	0	18	303	84	65	19	489		97
2022	0	16	283	80	60	18	457		91
2023	0	14	264	77	56	16	427		85
2024	0	12	246	74	52	15	400		79
2025	0	10	229	71	49	14	374		74
2026	0	9	214	68	46	13	350		69
2027	0	8	199	66	42	12	328		65
2028	0	7	186	63	40	12	307		61
2029	0	6	173	61	37	11	288		57
2030	0	5	162	58	34	10	270		53
2031	0	5	151	56	32	9	253		50
2032	0	4	140	54	30	9	237		47
2033	0	3	131	52	28	8	222		44
2034	0	3	122	50	26	8	208		41
2035	0	3	114	48	24	7	195		39
2036	0	2	106	46	23	7	183		36
2037	0	2	99	44	21	6	172		34
2038	0	2	92	42	20	6	162		32
2039	0	1	86	41	18	5	152		30
2040	0	1	80	39	17	5	143		28
2041	0	1	75	38	16	5	134		27
2042	0	1	70	36	15	4	126		25
2043	0	1	65	35	14	4	118		23
2044	0	1	61	33	13	4	111		22
2045	0	1	57	32	12	4	105		21
2046	0	1	53	31	11	3	99		20
2047	0	0	49	30	10	3	93		18
2048	0	0	46	28	10	3	87		17
2049	0	0	43	27	9	3	82		16
2050	0	0	40	26	8	2	77		15
2051	0	0	37	25	8	2	73		14
2052	0	0	35	24	7	2	69		14
2053	0	0	32	23	7	2	65		13
2054	0	0	30	22	6	2	61		12
2055	0	0	28	21	6	2	57		11
2056	0	0	26	21	6	2	54		11
2057	0	0	24	20	5	2	51		10
2058	0	0	23	19	5	1	48		10
2059	0	0	21	18	5	1	45		9
2060	0	0	20	18	4	1	43		9
2061	0	0	18	17	4	1	40		8
2062	0	0	17	16	4	1	38		8
2063	0	0	16	16	3	1	36		7
2064	0	0	15	15	3	1	34		7
2065	0	0	14	14	3	1	32		6
2066	0	0	13	14	3	1	30		6

Year	LFG Generation Magnitude for the Vancouver Landfill - Area 2E
1994	
1995	
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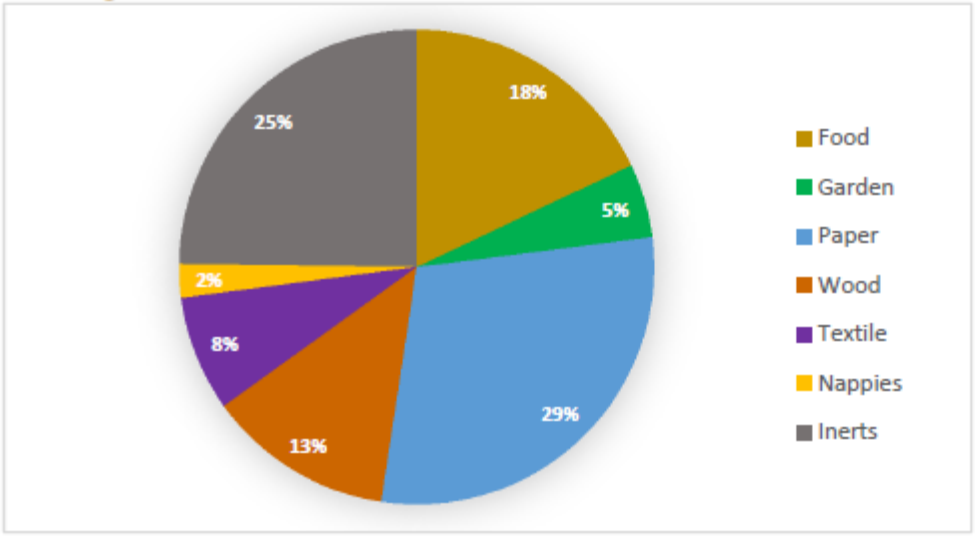
Year	Methane generation estimates for the Vancouver Landfill - Area 2E							Methane Generation Potential	Total LFG Flow Rate Estimated	Year	LFG Generation Magnitude for the Vancouver Landfill - Area 2E
	Food (tonnes)	Garden (tonnes)	Paper (tonnes)	Wood (tonnes)	Textile (tonnes)	Nappies (tonnes)	Total (tonnes)	(L_o m^3/tonne)	(scfm)		
2067	0	0	12	13	3	1	29		6	2067	
2068	0	0	11	13	2	1	27		5	2068	
2069	0	0	11	12	2	1	26		5	2069	
2070	0	0	10	12	2	1	24		5	2070	
2071	0	0	9	11	2	1	23		5	2071	
2072	0	0	9	11	2	1	22		4	2072	
2073	0	0	8	10	2	0	21		4	2073	
2074	0	0	7	10	2	0	20		4	2074	
2075	0	0	7	10	1	0	18		4	2075	
2076	0	0	6	9	1	0	17		3	2076	
2077	0	0	6	9	1	0	17		3	2077	
2078	0	0	6	9	1	0	16		3	2078	
2079	0	0	5	8	1	0	15		3	2079	
2080	0	0	5	8	1	0	14		3	2080	
2081	0	0	5	8	1	0	13		3	2081	
2082	0	0	4	7	1	0	13		3	2082	
2083	0	0	4	7	1	0	12		2	2083	
2084	0	0	4	7	1	0	11		2	2084	
2085	0	0	3	6	1	0	11		2	2085	
2086	0	0	3	6	1	0	10		2	2086	
2087	0	0	3	6	1	0	10		2	2087	
2088	0	0	3	6	1	0	9		2	2088	
2089	0	0	3	6	1	0	9		2	2089	
2090	0	0	2	5	1	0	8		2	2090	
2091	0	0	2	5	0	0	8		2	2091	
2092	0	0	2	5	0	0	8		2	2092	
2093	0	0	2	5	0	0	7		1	2093	
2094	0	0	2	5	0	0	7		1	2094	
2095	0	0	2	4	0	0	7		1	2095	
2096	0	0	2	4	0	0	6		1	2096	
2097	0	0	1	4	0	0	6		1	2097	
2098	0	0	1	4	0	0	6		1	2098	
2099	0	0	1	4	0	0	5		1	2099	
2100	0	0	1	4	0	0	5		1	2100	
2101	0	0	1	3	0	0	5		1	2101	
2102	0	0	1	3	0	0	5		1	2102	
2103	0	0	1	3	0	0	4		1	2103	
2104	0	0	1	3	0	0	4		1	2104	
2105	0	0	1	3	0	0	4		1	2105	
2106	0	0	1	3	0	0	4		1	2106	
2107	0	0	1	3	0	0	4		1	2107	
2108	0	0	1	3	0	0	3		1	2108	
2109	0	0	1	2	0	0	3		1	2109	
2110	0	0	1	2	0	0	3		1	2110	
2111	0	0	1	2	0	0	3		1	2111	
2112	0	0	1	2	0	0	3		1	2112	
2113	0	0	0	2	0	0	3		1	2113	
2114	0	0	0	2	0	0	3		1	2114	
2115	0	0	0	2	0	0	2		0	2115	
2116	0	0	0	2	0	0	2		0	2116	
2117	0	0	0	2	0	0	2		0	2117	
2118	0	0	0	2	0	0	2		0	2118	
2119	0	0	0	2	0	0	2		0	2119	
2120	0	0	0	2	0	0	2		0	2120	
2121	0	0	0	2	0	0	2		0	2121	
2122	0	0	0	1	0	0	2		0	2122	
2123	0	0	0	1	0	0	2		0	2123	
2124	0	0	0	1	0	0	2		0	2124	
2125	0	0	0	1	0	0	2		0	2125	
2126	0	0	0	1	0	0	2		0	2126	
2127	0	0	0	1	0	0	1		0	2127	
2128	0	0	0	1	0	0	1		0	2128	
2129	0	0	0	1	0	0	1		0	2129	
2130	0	0	0	1	0	0	1		0	2130	
2131	0	0	0	1	0	0	1		0	2131	
2132	0	0	0	1	0	0	1		0	2132	
2133	0	0	0	1	0	0	1		0	2133	
2134	0	0	0	1	0	0	1		0	2134	
2135	0	0	0	1	0	0	1		0	2135	
2136	0	0	0	1	0	0	1		0	2136	
2137	0	0	0	1	0	0	1		0	2137	
2138	0	0	0	1	0	0	1		0	2138	
2139	0	0	0	1	0	0	1		0	2139	
2140	0	0	0	1	0	0	1		0	2140	
2141	0	0	0	1	0	0	1		0	2141	
2142	0	0	0	1	0	0	1		0	2142	
2143	0	0	0	1	0	0	1		0	2143	
2144	0	0	0	1	0	0	1		0	2144	

Vancouver Landfill - Area 2E

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**

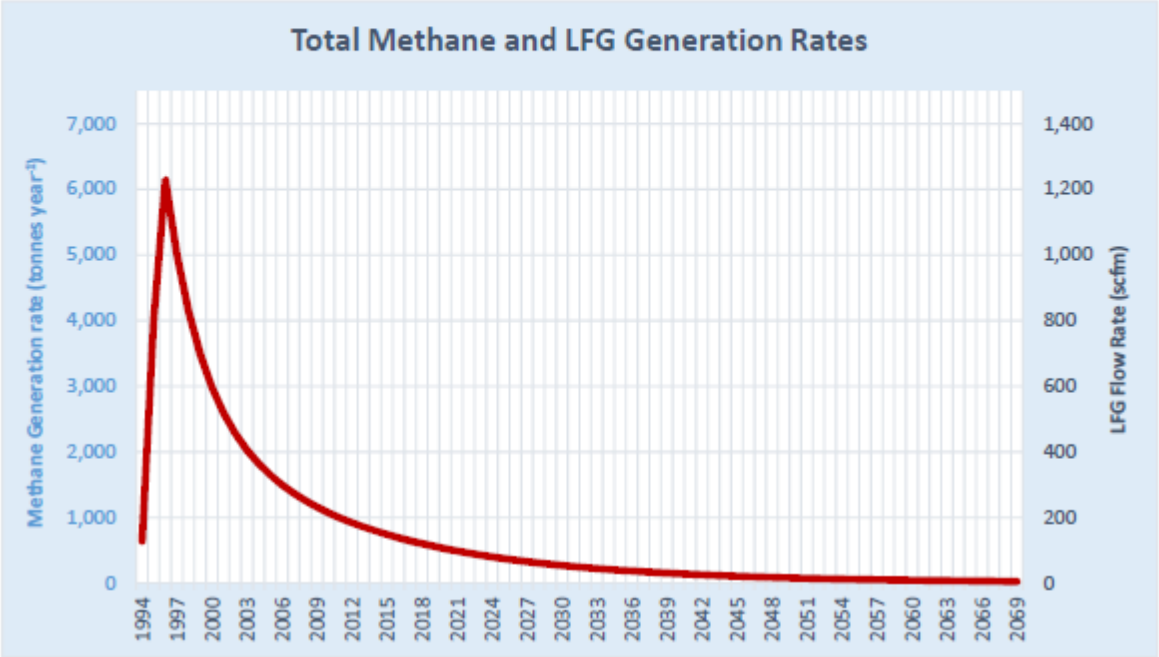
Average Deposited Waste Composition

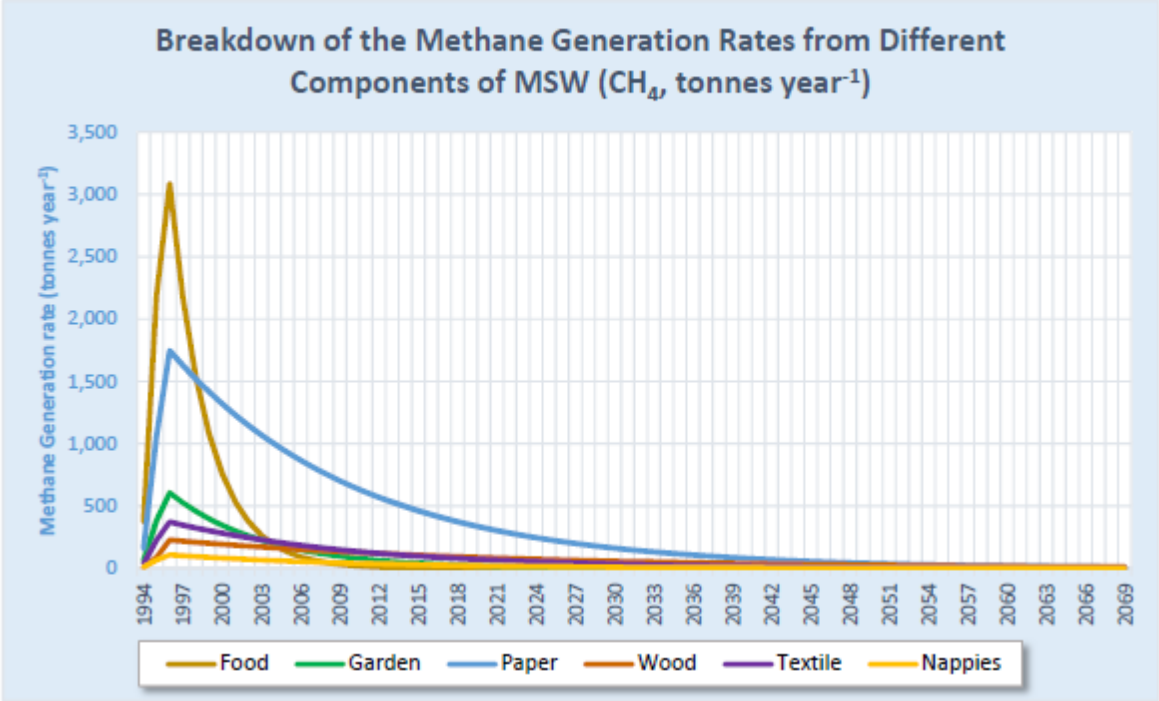


Annual MSW Deposition Rates and Total In Place

Vancouver Landfill - Area 2E

Landfill Gas Generation Analysis GRAPHICAL RESULTS





B.3 iModel-110© Modeling Results – Area 3

Landfill's Site-Specific Information

Enter Site's Name/ ID: Vancouver Landfill - Area 3

Year Filling Started: 1996 Date OK!

Thesis References and Parameters		Food waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies
		%	%	%	%	%	%
Table 3.1 of Thesis	DOC_{dry}	0.38	0.49	0.44	0.5	0.3	0.3
Table 2.8 of Thesis	Moisture	50%	45%	20%	18%	14%	14%
Degradability Factor	f_{dg}	0.84	0.66	0.46	0.2	0.5	0.5
Climate Factor	f_{cl}	1	1	1	1	1	1
Depth Factor	f_{dp}	0.9	0.9	0.9	0.9	0.9	0.9
Storage Factor	f_{st}	0.8	1	1	1	1	1
$f = f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$	∑Discount	**0.60**	**0.59**	**0.41**	**0.18**	**0.45**	**0.45**
Theoretical Methane Yield	L_o	***113***	***158***	***143***	***73***	***114***	***114***

Dry Degradable Organic Carbon Content and Decay Rates for Different Waste Components

Waste Components	DOC_{dry} (kg in 1kg dry)	k $year^{-1}$
Food waste	**0.38**	**0.35**
Garden	**0.49**	**0.14**
Paper	**0.44**	**0.07**
Wood and straw	**0.50**	**0.04**
Textiles	**0.30**	**0.07**
Disposable nappies	**0.30**	**0.07**

Thesis References: Table 3.1 Table 3.15

Methane Characteristics, Generation Calibration Factor & Delay Time

Parameters	Values & Units
CH_4 Density:	**0.6775** kg/m^3
CH_4 Fraction:	**0.5** m^3/m^3
CH_4/C (16/12):	**1.333** kg/kg
Enter (CF_G) here:	**1**
Delay Time (T_d):	**4** Months

Table 3.16

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 3								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
1996	78,755	22,059	129,102	101,264	34,515	10,085	128,330	**504,110**	**504,110**
1997	70,874	19,852	116,182	60,601	31,061	9,076	102,404	**410,050**	**914,160**
1998	68,711	19,246	112,638	96,963	30,114	8,799	115,656	**452,128**	**1,366,288**
1999	-	-	-	-	-	-	-	**-**	**1,366,288**
2000	-	-	-	-	-	-	-	**-**	**1,366,288**
2001	-	-	-	-	-	-	-	**-**	**1,366,288**
2002	-	-	-	-	-	-	-	**-**	**1,366,288**
2003	-	-	-	-	-	-	-	**-**	**1,366,288**
2004	-	-	-	-	-	-	-	**-**	**1,366,288**
2005	-	-	-	-	-	-	-	**-**	**1,366,288**
2006	-	-	-	-	-	-	-	**-**	**1,366,288**
2007	-	-	-	-	-	-	-	**-**	**1,366,288**
2008	-	-	-	-	-	-	-	**-**	**1,366,288**
2009	-	-	-	-	-	-	-	**-**	**1,366,288**
2010	-	-	-	-	-	-	-	**-**	**1,366,288**
2011	-	-	-	-	-	-	-	**-**	**1,366,288**
2012	-	-	-	-	-	-	-	**-**	**1,366,288**
2013	-	-	-	-	-	-	-	**-**	**1,366,288**
2014	-	-	-	-	-	-	-	**-**	**1,366,288**
2015	-	-	-	-	-	-	-	**-**	**1,366,288**
2016	-	-	-	-	-	-	-	**-**	**1,366,288**
2017	-	-	-	-	-	-	-	**-**	**1,366,288**
2018	-	-	-	-	-	-	-	**-**	**1,366,288**
2019	-	-	-	-	-	-	-	**-**	**1,366,288**
2020	-	-	-	-	-	-	-	**-**	**1,366,288**
2021	-	-	-	-	-	-	-	**-**	**1,366,288**
2022	-	-	-	-	-	-	-	**-**	**1,366,288**
2023	-	-	-	-	-	-	-	**-**	**1,366,288**
2024	-	-	-	-	-	-	-	**-**	**1,366,288**
2025	-	-	-	-	-	-	-	**-**	**1,366,288**
2026	-	-	-	-	-	-	-	**-**	**1,366,288**
2027	-	-	-	-	-	-	-	**-**	**1,366,288**
2028	-	-	-	-	-	-	-	**-**	**1,366,288**
2029	-	-	-	-	-	-	-	**-**	**1,366,288**
2030	-	-	-	-	-	-	-	**-**	**1,366,288**
2031	-	-	-	-	-	-	-	**-**	**1,366,288**
2032	-	-	-	-	-	-	-	**-**	**1,366,288**
2033	-	-	-	-	-	-	-	**-**	**1,366,288**
2034	-	-	-	-	-	-	-	**-**	**1,366,288**
2035	-	-	-	-	-	-	-	**-**	**1,366,288**
2036	-	-	-	-	-	-	-	**-**	**1,366,288**
2037	-	-	-	-	-	-	-	**-**	**1,366,288**
2038	-	-	-	-	-	-	-	**-**	**1,366,288**
2039	-	-	-	-	-	-	-	**-**	**1,366,288**
2040	-	-	-	-	-	-	-	**-**	**1,366,288**
2041	-	-	-	-	-	-	-	**-**	**1,366,288**
2042	-	-	-	-	-	-	-	**-**	**1,366,288**
2043	-	-	-	-	-	-	-	**-**	**1,366,288**
2044	-	-	-	-	-	-	-	**-**	**1,366,288**
2045	-	-	-	-	-	-	-	**-**	**1,366,288**
2046	-	-	-	-	-	-	-	**-**	**1,366,288**
2047	-	-	-	-	-	-	-	**-**	**1,366,288**
2048	-	-	-	-	-	-	-	**-**	**1,366,288**
2049	-	-	-	-	-	-	-	**-**	**1,366,288**
2050	-	-	-	-	-	-	-	**-**	**1,366,288**
2051	-	-	-	-	-	-	-	**-**	**1,366,288**
2052	-	-	-	-	-	-	-	**-**	**1,366,288**

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 3								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2053	-	-	-	-	-	-	-	-	1,366,288
2054	-	-	-	-	-	-	-	-	1,366,288
2055	-	-	-	-	-	-	-	-	1,366,288
2056	-	-	-	-	-	-	-	-	1,366,288
2057	-	-	-	-	-	-	-	-	1,366,288
2058	-	-	-	-	-	-	-	-	1,366,288
2059	-	-	-	-	-	-	-	-	1,366,288
2060	-	-	-	-	-	-	-	-	1,366,288
2061	-	-	-	-	-	-	-	-	1,366,288
2062	-	-	-	-	-	-	-	-	1,366,288
2063	-	-	-	-	-	-	-	-	1,366,288
2064	-	-	-	-	-	-	-	-	1,366,288
2065	-	-	-	-	-	-	-	-	1,366,288
2066	-	-	-	-	-	-	-	-	1,366,288
2067	-	-	-	-	-	-	-	-	1,366,288
2068	-	-	-	-	-	-	-	-	1,366,288
2069	-	-	-	-	-	-	-	-	1,366,288
2070	-	-	-	-	-	-	-	-	1,366,288
2071	-	-	-	-	-	-	-	-	1,366,288
2072	-	-	-	-	-	-	-	-	1,366,288
2073	-	-	-	-	-	-	-	-	1,366,288
2074	-	-	-	-	-	-	-	-	1,366,288
2075	-	-	-	-	-	-	-	-	1,366,288
2076	-	-	-	-	-	-	-	-	1,366,288
2077	-	-	-	-	-	-	-	-	1,366,288
2078	-	-	-	-	-	-	-	-	1,366,288
2079	-	-	-	-	-	-	-	-	1,366,288
2080	-	-	-	-	-	-	-	-	1,366,288
2081	-	-	-	-	-	-	-	-	1,366,288
2082	-	-	-	-	-	-	-	-	1,366,288
2083	-	-	-	-	-	-	-	-	1,366,288
2084	-	-	-	-	-	-	-	-	1,366,288
2085	-	-	-	-	-	-	-	-	1,366,288
2086	-	-	-	-	-	-	-	-	1,366,288
2087	-	-	-	-	-	-	-	-	1,366,288
2088	-	-	-	-	-	-	-	-	1,366,288
2089	-	-	-	-	-	-	-	-	1,366,288
2090	-	-	-	-	-	-	-	-	1,366,288
2091	-	-	-	-	-	-	-	-	1,366,288
2092	-	-	-	-	-	-	-	-	1,366,288
2093	-	-	-	-	-	-	-	-	1,366,288
2094	-	-	-	-	-	-	-	-	1,366,288
2095	-	-	-	-	-	-	-	-	1,366,288
2096	-	-	-	-	-	-	-	-	1,366,288
2097	-	-	-	-	-	-	-	-	1,366,288
2098	-	-	-	-	-	-	-	-	1,366,288
2099	-	-	-	-	-	-	-	-	1,366,288
2100	-	-	-	-	-	-	-	-	1,366,288
2101	-	-	-	-	-	-	-	-	1,366,288
2102	-	-	-	-	-	-	-	-	1,366,288
2103	-	-	-	-	-	-	-	-	1,366,288
2104	-	-	-	-	-	-	-	-	1,366,288
2105	-	-	-	-	-	-	-	-	1,366,288
2106	-	-	-	-	-	-	-	-	1,366,288
2107	-	-	-	-	-	-	-	-	1,366,288
2108	-	-	-	-	-	-	-	-	1,366,288
2109	-	-	-	-	-	-	-	-	1,366,288

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Area 3								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2110	-	-	-	-	-	-	-	-	1,366,288
2111	-	-	-	-	-	-	-	-	1,366,288
2112	-	-	-	-	-	-	-	-	1,366,288
2113	-	-	-	-	-	-	-	-	1,366,288
2114	-	-	-	-	-	-	-	-	1,366,288
2115	-	-	-	-	-	-	-	-	1,366,288
2116	-	-	-	-	-	-	-	-	1,366,288
2117	-	-	-	-	-	-	-	-	1,366,288
2118	-	-	-	-	-	-	-	-	1,366,288
2119	-	-	-	-	-	-	-	-	1,366,288
2120	-	-	-	-	-	-	-	-	1,366,288
2121	-	-	-	-	-	-	-	-	1,366,288
2122	-	-	-	-	-	-	-	-	1,366,288
2123	-	-	-	-	-	-	-	-	1,366,288
2124	-	-	-	-	-	-	-	-	1,366,288
2125	-	-	-	-	-	-	-	-	1,366,288
2126	-	-	-	-	-	-	-	-	1,366,288
2127	-	-	-	-	-	-	-	-	1,366,288
2128	-	-	-	-	-	-	-	-	1,366,288
2129	-	-	-	-	-	-	-	-	1,366,288
2130	-	-	-	-	-	-	-	-	1,366,288
2131	-	-	-	-	-	-	-	-	1,366,288
2132	-	-	-	-	-	-	-	-	1,366,288
2133	-	-	-	-	-	-	-	-	1,366,288
2134	-	-	-	-	-	-	-	-	1,366,288
2135	-	-	-	-	-	-	-	-	1,366,288
2136	-	-	-	-	-	-	-	-	1,366,288
2137	-	-	-	-	-	-	-	-	1,366,288
2138	-	-	-	-	-	-	-	-	1,366,288
2139	-	-	-	-	-	-	-	-	1,366,288
2140	-	-	-	-	-	-	-	-	1,366,288
2141	-	-	-	-	-	-	-	-	1,366,288
2142	-	-	-	-	-	-	-	-	1,366,288
2143	-	-	-	-	-	-	-	-	1,366,288
2144	-	-	-	-	-	-	-	-	1,366,288
2145	-	-	-	-	-	-	-	-	1,366,288
2146	-	-	-	-	-	-	-	-	1,366,288

Dry Tonnages Deposited at the Vancouver Landfill - Area 3

	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
Moisture	50%	45%	20%	18%	14%	14%	10%	22%
Solid	50%	55%	80%	82%	86%	86%	90%	78%

Dry Amounts Historically Deposited at the Vancouver Landfill - Area 3

Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
1996	39	12	103	83	30	9	115	392
1997	35	11	93	50	27	8	92	316
1998	34	11	90	80	26	8	104	352
1999	0	0	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0
2036	0	0	0	0	0	0	0	0
2037	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill - Area 3							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0
2051	0	0	0	0	0	0	0	0
2052	0	0	0	0	0	0	0	0
2053	0	0	0	0	0	0	0	0
2054	0	0	0	0	0	0	0	0
2055	0	0	0	0	0	0	0	0
2056	0	0	0	0	0	0	0	0
2057	0	0	0	0	0	0	0	0
2058	0	0	0	0	0	0	0	0
2059	0	0	0	0	0	0	0	0
2060	0	0	0	0	0	0	0	0
2061	0	0	0	0	0	0	0	0
2062	0	0	0	0	0	0	0	0
2063	0	0	0	0	0	0	0	0
2064	0	0	0	0	0	0	0	0
2065	0	0	0	0	0	0	0	0
2066	0	0	0	0	0	0	0	0
2067	0	0	0	0	0	0	0	0
2068	0	0	0	0	0	0	0	0
2069	0	0	0	0	0	0	0	0
2070	0	0	0	0	0	0	0	0
2071	0	0	0	0	0	0	0	0
2072	0	0	0	0	0	0	0	0
2073	0	0	0	0	0	0	0	0
2074	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0
2076	0	0	0	0	0	0	0	0
2077	0	0	0	0	0	0	0	0
2078	0	0	0	0	0	0	0	0
2079	0	0	0	0	0	0	0	0
2080	0	0	0	0	0	0	0	0
2081	0	0	0	0	0	0	0	0
2082	0	0	0	0	0	0	0	0
2083	0	0	0	0	0	0	0	0
2084	0	0	0	0	0	0	0	0
2085	0	0	0	0	0	0	0	0
2086	0	0	0	0	0	0	0	0
2087	0	0	0	0	0	0	0	0
2088	0	0	0	0	0	0	0	0
2089	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill - Area 3							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2090	0	0	0	0	0	0	0	0
2091	0	0	0	0	0	0	0	0
2092	0	0	0	0	0	0	0	0
2093	0	0	0	0	0	0	0	0
2094	0	0	0	0	0	0	0	0
2095	0	0	0	0	0	0	0	0

Methane Generation Estimates from the Vancouver Landfill - Area 3

Actual CH_4 Yields

L_o (m^3/tonne)	113	157	143	72	114	114	86.7

Year	Methane generation estimates for the Vancouver Landfill - Area 3							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)
1996	342	54	145	33	31	9	615	86.0	122
1997	1,988	349	969	214	206	60	3,787	89.7	751
1998	2,995	579	1,663	334	354	103	6,029	85.0	1,196
1999	3,367	724	2,163	477	461	135	7,326		1,453
2000	2,373	630	2,017	458	430	126	6,032		1,196
2001	1,672	547	1,881	440	401	117	5,057		1,003
2002	1,178	476	1,753	423	373	109	4,313		855
2003	830	414	1,635	406	348	102	3,735		741
2004	585	360	1,524	390	325	95	3,279		650
2005	412	313	1,421	375	303	88	2,912		578
2006	291	272	1,325	360	282	82	2,612		518
2007	205	236	1,236	346	263	77	2,363		469
2008	144	205	1,152	332	245	72	2,151		427
2009	102	179	1,074	319	229	67	1,970		391
2010	72	155	1,002	307	213	62	1,811		359
2011	50	135	934	295	199	58	1,671		331
2012	36	117	871	283	185	54	1,547		307
2013	25	102	812	272	173	51	1,435		285
2014	18	89	757	262	161	47	1,333		264
2015	12	77	706	251	150	44	1,241		246
2016	9	67	658	241	140	41	1,156		229
2017	6	58	614	232	131	38	1,079		214
2018	4	51	572	223	122	36	1,007		200
2019	3	44	533	214	114	33	941		187
2020	2	38	497	206	106	31	880		175
2021	2	33	464	198	99	29	824		163
2022	1	29	432	190	92	27	771		153
2023	1	25	403	182	86	25	722		143
2024	1	22	376	175	80	23	677		134
2025	0	19	350	168	75	22	635		126
2026	0	17	327	162	70	20	595		118
2027	0	14	305	155	65	19	559		111
2028	0	12	284	149	61	18	524		104
2029	0	11	265	144	56	16	492		98
2030	0	9	247	138	53	15	462		92
2031	0	8	230	132	49	14	434		86
2032	0	7	215	127	46	13	408		81
2033	0	6	200	122	43	12	384		76
2034	0	5	187	118	40	12	361		72
2035	0	5	174	113	37	11	340		67
2036	0	4	162	108	35	10	320		63
2037	0	4	151	104	32	9	301		60
2038	0	3	141	100	30	9	283		56
2039	0	3	132	96	28	8	267		53
2040	0	2	123	92	26	8	251		50
2041	0	2	114	89	24	7	237		47
2042	0	2	107	85	23	7	223		44
2043	0	2	99	82	21	6	210		42
2044	0	1	93	79	20	6	198		39
2045	0	1	86	76	18	5	187		37
2046	0	1	81	73	17	5	176		35
2047	0	1	75	70	16	5	167		33
2048	0	1	70	67	15	4	157		31
2049	0	1	65	64	14	4	148		29
2050	0	1	61	62	13	4	140		28
2051	0	0	57	60	12	4	132		26
2052	0	0	53	57	11	3	125		25
2053	0	0	49	55	11	3	118		23
2054	0	0	46	53	10	3	112		22
2055	0	0	43	51	9	3	106		21
2056	0	0	40	49	9	2	100		20
2057	0	0	37	47	8	2	95		19
2058	0	0	35	45	7	2	90		18
2059	0	0	32	43	7	2	85		17
2060	0	0	30	42	6	2	80		16
2061	0	0	28	40	6	2	76		15
2062	0	0	26	38	6	2	72		14
2063	0	0	25	37	5	2	68		14
2064	0	0	23	35	5	1	65		13
2065	0	0	21	34	5	1	61		12
2066	0	0	20	33	4	1	58		12
2067	0	0	19	31	4	1	55		11
2068	0	0	17	30	4	1	52		10

Year	LFG Generation Magnitude for the Vancouver Landfill - Area 3
1996	
1997	
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Year	Methane generation estimates for the Vancouver Landfill - Area 3							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)
2069	0	0	16	29	3	1	50		10
2070	0	0	15	28	3	1	47		9
2071	0	0	14	27	3	1	45		9
2072	0	0	13	26	3	1	42		8
2073	0	0	12	25	3	1	40		8
2074	0	0	11	24	2	1	38		8
2075	0	0	11	23	2	1	36		7
2076	0	0	10	22	2	1	35		7
2077	0	0	9	21	2	1	33		7
2078	0	0	9	20	2	1	31		6
2079	0	0	8	19	2	0	30		6
2080	0	0	7	19	2	0	28		6
2081	0	0	7	18	1	0	27		5
2082	0	0	6	17	1	0	26		5
2083	0	0	6	17	1	0	24		5
2084	0	0	6	16	1	0	23		5
2085	0	0	5	15	1	0	22		4
2086	0	0	5	15	1	0	21		4
2087	0	0	5	14	1	0	20		4
2088	0	0	4	14	1	0	19		4
2089	0	0	4	13	1	0	18		4
2090	0	0	4	13	1	0	17		3
2091	0	0	3	12	1	0	16		3
2092	0	0	3	12	1	0	16		3
2093	0	0	3	11	1	0	15		3
2094	0	0	3	11	1	0	14		3
2095	0	0	3	10	1	0	14		3
2096	0	0	2	10	1	0	13		3
2097	0	0	2	9	0	0	12		2
2098	0	0	2	9	0	0	12		2
2099	0	0	2	9	0	0	11		2
2100	0	0	2	8	0	0	11		2
2101	0	0	2	8	0	0	10		2
2102	0	0	2	8	0	0	10		2
2103	0	0	1	7	0	0	9		2
2104	0	0	1	7	0	0	9		2
2105	0	0	1	7	0	0	9		2
2106	0	0	1	7	0	0	8		2
2107	0	0	1	6	0	0	8		2
2108	0	0	1	6	0	0	7		1
2109	0	0	1	6	0	0	7		1
2110	0	0	1	6	0	0	7		1
2111	0	0	1	5	0	0	6		1
2112	0	0	1	5	0	0	6		1
2113	0	0	1	5	0	0	6		1
2114	0	0	1	5	0	0	6		1
2115	0	0	1	5	0	0	5		1
2116	0	0	1	4	0	0	5		1
2117	0	0	1	4	0	0	5		1
2118	0	0	1	4	0	0	5		1
2119	0	0	0	4	0	0	5		1
2120	0	0	0	4	0	0	4		1
2121	0	0	0	4	0	0	4		1
2122	0	0	0	3	0	0	4		1
2123	0	0	0	3	0	0	4		1
2124	0	0	0	3	0	0	4		1
2125	0	0	0	3	0	0	3		1
2126	0	0	0	3	0	0	3		1
2127	0	0	0	3	0	0	3		1
2128	0	0	0	3	0	0	3		1
2129	0	0	0	3	0	0	3		1
2130	0	0	0	3	0	0	3		1
2131	0	0	0	2	0	0	3		1
2132	0	0	0	2	0	0	3		1
2133	0	0	0	2	0	0	2		0
2134	0	0	0	2	0	0	2		0
2135	0	0	0	2	0	0	2		0
2136	0	0	0	2	0	0	2		0
2137	0	0	0	2	0	0	2		0
2138	0	0	0	2	0	0	2		0
2139	0	0	0	2	0	0	2		0
2140	0	0	0	2	0	0	2		0
2141	0	0	0	2	0	0	2		0
2142	0	0	0	2	0	0	2		0
2143	0	0	0	2	0	0	2		0
2144	0	0	0	1	0	0	2		0
2145	0	0	0	1	0	0	1		0
2146	0	0	0	1	0	0	1		0

Year	LFG Generation Magnitude for the Vancouver Landfill - Area 3
2069	
2070	
2071	
2072	
2073	
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2098	
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2100	
2101	
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2107	
2108	
2109	
2110	
2111	
2112	
2113	
2114	
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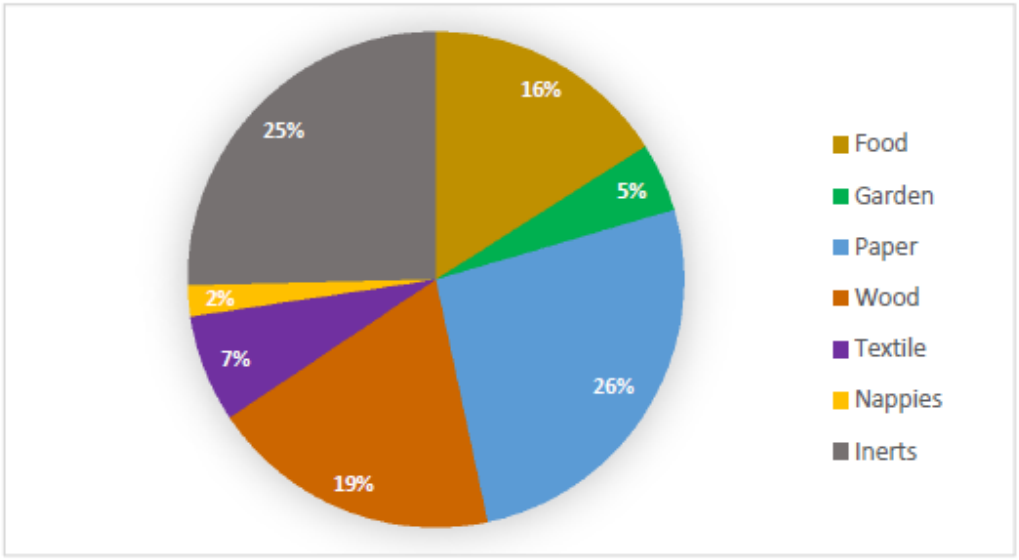
2145	
2146	

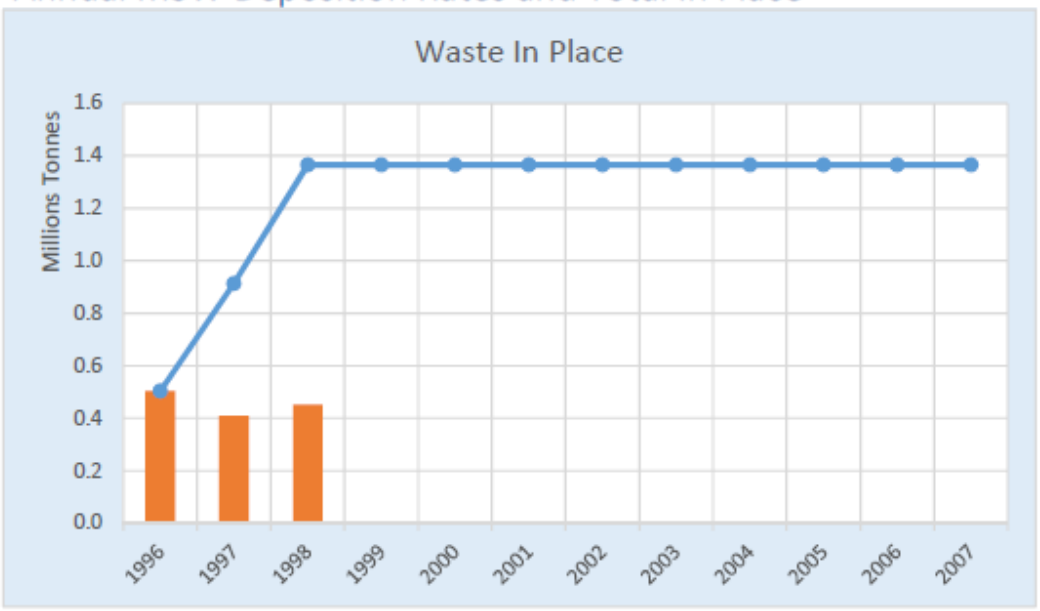
Vancouver Landfill - Area 3

Landfill Gas Generation Analysis GRAPHICAL RESULTS

Average Deposited Waste Composition

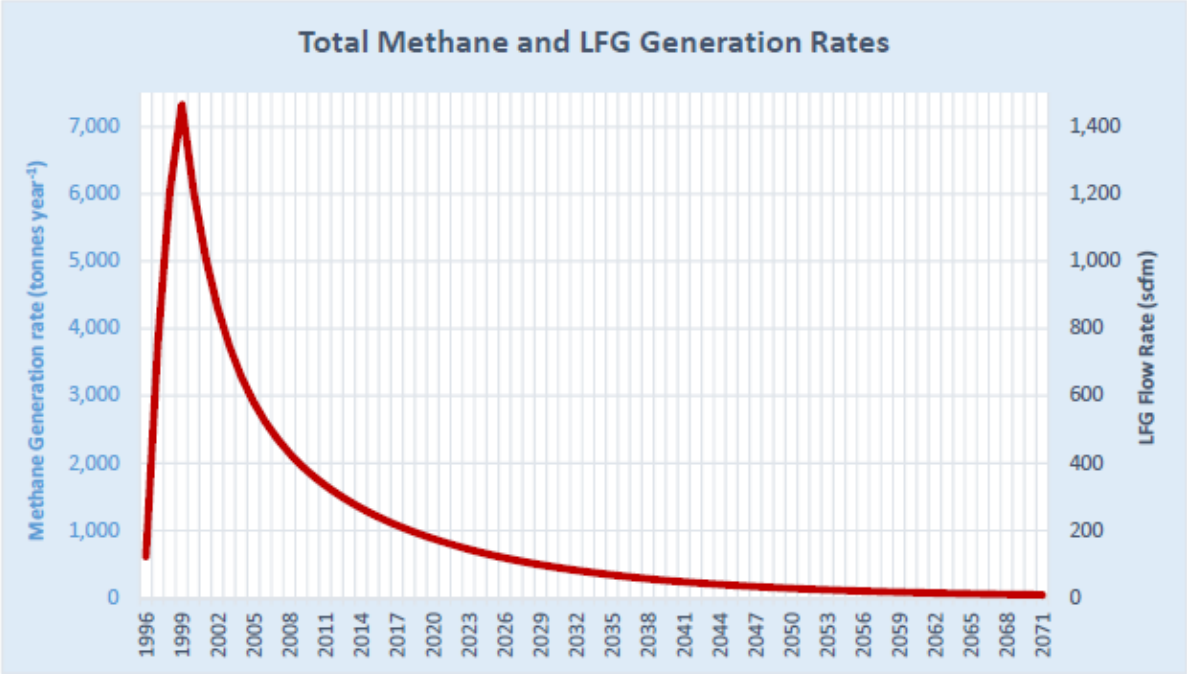


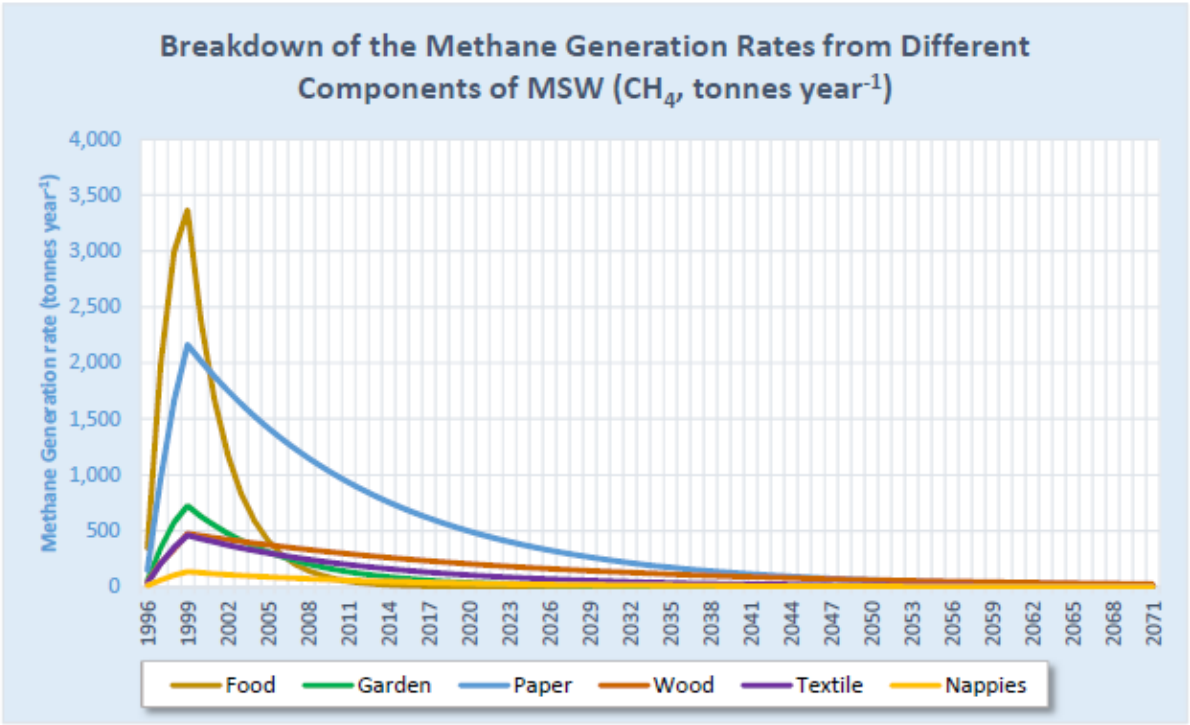
Annual MSW Deposition Rates and Total In Place



Vancouver Landfill - Area 3

Landfill Gas Generation Analysis GRAPHICAL RESULTS





B.4 iModel-110© Modeling Results – Phase 1

Landfill's Site-Specific Information

Enter Site's Name/ ID: Vancouver Landfill - Phase 1

Year Filling Started: 1999 Date OK!

Thesis References and Parameters		Food waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies
		%	%	%	%	%	%
Table 3.1 of Thesis	DOC_{dry}	0.38	0.49	0.44	0.5	0.3	0.3
Table 2.8 of Thesis	Moisture	50%	45%	20%	18%	14%	14%
Degradability Factor	f_{dg}	0.84	0.66	0.46	0.2	0.5	0.5
Climate Factor	f_{cl}	1	1	1	1	1	1
Depth Factor	f_{dp}	0.9	0.9	0.9	0.9	0.9	0.9
Storage Factor	f_{st}	0.8	1	1	1	1	1
$f = f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$	∑Discount	**0.60**	**0.59**	**0.41**	**0.18**	**0.45**	**0.45**
Theoretical Methane Yield	L_o	***113***	***158***	***143***	***73***	***114***	***114***

Dry Degradable Organic Carbon Content and Decay Rates for Different Waste Components

Waste Components	DOC_{dry} (kg in 1kg dry)	k $year^{-1}$
Food waste	**0.38**	**0.35**
Garden	**0.49**	**0.14**
Paper	**0.44**	**0.07**
Wood and straw	**0.50**	**0.04**
Textiles	**0.30**	**0.07**
Disposable nappies	**0.30**	**0.07**

Thesis References: Table 3.1 Table 3.15

Methane Characteristics, Generation Calibration Factor & Delay Time

Parameters	Values & Units
CH_4 Density:	**0.6775** kg/m^3
CH_4 Fraction:	**0.5** m^3/m^3
CH_4/C (16/12):	**1.333** kg/kg
Enter (CF_G) here:	**1**
Delay Time (T_d):	**4** Months

Table 3.16

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Phase 1								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
1999	72,717	20,368	119,204	106,177	31,869	9,312	123,924	**483,572**	**483,572**
2000	60,520	16,952	99,209	126,312	26,524	7,750	119,400	**456,666**	**940,237**
2001	63,516	38,839	58,872	95,664	48,971	8,136	140,382	**454,381**	**1,394,618**
2002	64,307	39,322	59,605	146,372	49,580	8,237	163,351	**530,775**	**1,925,393**
2003	73,819	45,139	68,422	129,289	56,914	9,456	170,913	**553,951**	**2,479,344**
2004	104,033	19,839	107,614	138,337	45,049	8,855	199,293	**623,019**	**3,102,363**
2005	117,325	22,374	121,363	148,472	50,804	9,986	221,524	**691,847**	**3,794,211**
2006	89,073	16,986	92,138	105,330	38,571	7,582	165,014	**514,692**	**4,308,903**
2007	-	-	-	-	-	-	-	**-**	**4,308,903**
2008	31,120	4,570	34,238	35,252	6,186	2,639	47,994	**162,000**	**4,470,903**
2009	-	-	-	-	-	-	-	**-**	**4,470,903**
2010	-	-	-	-	-	-	-	**-**	**4,470,903**
2011	-	-	-	-	-	-	-	**-**	**4,470,903**
2012	-	-	-	-	-	-	-	**-**	**4,470,903**
2013	-	-	-	-	-	-	-	**-**	**4,470,903**
2014	-	-	-	-	-	-	-	**-**	**4,470,903**
2015	-	-	-	-	-	-	-	**-**	**4,470,903**
2016	-	-	-	-	-	-	-	**-**	**4,470,903**
2017	-	-	-	-	-	-	-	**-**	**4,470,903**
2018	-	-	-	-	-	-	-	**-**	**4,470,903**
2019	-	-	-	-	-	-	-	**-**	**4,470,903**
2020	-	-	-	-	-	-	-	**-**	**4,470,903**
2021	-	-	-	-	-	-	-	**-**	**4,470,903**
2022	-	-	-	-	-	-	-	**-**	**4,470,903**
2023	-	-	-	-	-	-	-	**-**	**4,470,903**
2024	-	-	-	-	-	-	-	**-**	**4,470,903**
2025	-	-	-	-	-	-	-	**-**	**4,470,903**
2026	-	-	-	-	-	-	-	**-**	**4,470,903**
2027	-	-	-	-	-	-	-	**-**	**4,470,903**
2028	-	-	-	-	-	-	-	**-**	**4,470,903**
2029	-	-	-	-	-	-	-	**-**	**4,470,903**
2030	-	-	-	-	-	-	-	**-**	**4,470,903**
2031	-	-	-	-	-	-	-	**-**	**4,470,903**
2032	-	-	-	-	-	-	-	**-**	**4,470,903**
2033	-	-	-	-	-	-	-	**-**	**4,470,903**
2034	-	-	-	-	-	-	-	**-**	**4,470,903**
2035	-	-	-	-	-	-	-	**-**	**4,470,903**
2036	-	-	-	-	-	-	-	**-**	**4,470,903**
2037	-	-	-	-	-	-	-	**-**	**4,470,903**
2038	-	-	-	-	-	-	-	**-**	**4,470,903**
2039	-	-	-	-	-	-	-	**-**	**4,470,903**
2040	-	-	-	-	-	-	-	**-**	**4,470,903**
2041	-	-	-	-	-	-	-	**-**	**4,470,903**
2042	-	-	-	-	-	-	-	**-**	**4,470,903**
2043	-	-	-	-	-	-	-	**-**	**4,470,903**
2044	-	-	-	-	-	-	-	**-**	**4,470,903**
2045	-	-	-	-	-	-	-	**-**	**4,470,903**
2046	-	-	-	-	-	-	-	**-**	**4,470,903**
2047	-	-	-	-	-	-	-	**-**	**4,470,903**
2048	-	-	-	-	-	-	-	**-**	**4,470,903**
2049	-	-	-	-	-	-	-	**-**	**4,470,903**
2050	-	-	-	-	-	-	-	**-**	**4,470,903**
2051	-	-	-	-	-	-	-	**-**	**4,470,903**
2052	-	-	-	-	-	-	-	**-**	**4,470,903**
2053	-	-	-	-	-	-	-	**-**	**4,470,903**
2054	-	-	-	-	-	-	-	**-**	**4,470,903**
2055	-	-	-	-	-	-	-	**-**	**4,470,903**

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Phase 1								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2056	-	-	-	-	-	-	-	-	4,470,903
2057	-	-	-	-	-	-	-	-	4,470,903
2058	-	-	-	-	-	-	-	-	4,470,903
2059	-	-	-	-	-	-	-	-	4,470,903
2060	-	-	-	-	-	-	-	-	4,470,903
2061	-	-	-	-	-	-	-	-	4,470,903
2062	-	-	-	-	-	-	-	-	4,470,903
2063	-	-	-	-	-	-	-	-	4,470,903
2064	-	-	-	-	-	-	-	-	4,470,903
2065	-	-	-	-	-	-	-	-	4,470,903
2066	-	-	-	-	-	-	-	-	4,470,903
2067	-	-	-	-	-	-	-	-	4,470,903
2068	-	-	-	-	-	-	-	-	4,470,903
2069	-	-	-	-	-	-	-	-	4,470,903
2070	-	-	-	-	-	-	-	-	4,470,903
2071	-	-	-	-	-	-	-	-	4,470,903
2072	-	-	-	-	-	-	-	-	4,470,903
2073	-	-	-	-	-	-	-	-	4,470,903
2074	-	-	-	-	-	-	-	-	4,470,903
2075	-	-	-	-	-	-	-	-	4,470,903
2076	-	-	-	-	-	-	-	-	4,470,903
2077	-	-	-	-	-	-	-	-	4,470,903
2078	-	-	-	-	-	-	-	-	4,470,903
2079	-	-	-	-	-	-	-	-	4,470,903
2080	-	-	-	-	-	-	-	-	4,470,903
2081	-	-	-	-	-	-	-	-	4,470,903
2082	-	-	-	-	-	-	-	-	4,470,903
2083	-	-	-	-	-	-	-	-	4,470,903
2084	-	-	-	-	-	-	-	-	4,470,903
2085	-	-	-	-	-	-	-	-	4,470,903
2086	-	-	-	-	-	-	-	-	4,470,903
2087	-	-	-	-	-	-	-	-	4,470,903
2088	-	-	-	-	-	-	-	-	4,470,903
2089	-	-	-	-	-	-	-	-	4,470,903
2090	-	-	-	-	-	-	-	-	4,470,903
2091	-	-	-	-	-	-	-	-	4,470,903
2092	-	-	-	-	-	-	-	-	4,470,903
2093	-	-	-	-	-	-	-	-	4,470,903
2094	-	-	-	-	-	-	-	-	4,470,903
2095	-	-	-	-	-	-	-	-	4,470,903
2096	-	-	-	-	-	-	-	-	4,470,903
2097	-	-	-	-	-	-	-	-	4,470,903
2098	-	-	-	-	-	-	-	-	4,470,903
2099	-	-	-	-	-	-	-	-	4,470,903
2100	-	-	-	-	-	-	-	-	4,470,903
2101	-	-	-	-	-	-	-	-	4,470,903
2102	-	-	-	-	-	-	-	-	4,470,903
2103	-	-	-	-	-	-	-	-	4,470,903
2104	-	-	-	-	-	-	-	-	4,470,903
2105	-	-	-	-	-	-	-	-	4,470,903
2106	-	-	-	-	-	-	-	-	4,470,903
2107	-	-	-	-	-	-	-	-	4,470,903
2108	-	-	-	-	-	-	-	-	4,470,903
2109	-	-	-	-	-	-	-	-	4,470,903
2110	-	-	-	-	-	-	-	-	4,470,903
2111	-	-	-	-	-	-	-	-	4,470,903
2112	-	-	-	-	-	-	-	-	4,470,903

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill - Phase 1								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2113	-	-	-	-	-	-	-	-	4,470,903
2114	-	-	-	-	-	-	-	-	4,470,903
2115	-	-	-	-	-	-	-	-	4,470,903
2116	-	-	-	-	-	-	-	-	4,470,903
2117	-	-	-	-	-	-	-	-	4,470,903
2118	-	-	-	-	-	-	-	-	4,470,903
2119	-	-	-	-	-	-	-	-	4,470,903
2120	-	-	-	-	-	-	-	-	4,470,903
2121	-	-	-	-	-	-	-	-	4,470,903
2122	-	-	-	-	-	-	-	-	4,470,903
2123	-	-	-	-	-	-	-	-	4,470,903
2124	-	-	-	-	-	-	-	-	4,470,903
2125	-	-	-	-	-	-	-	-	4,470,903
2126	-	-	-	-	-	-	-	-	4,470,903
2127	-	-	-	-	-	-	-	-	4,470,903
2128	-	-	-	-	-	-	-	-	4,470,903
2129	-	-	-	-	-	-	-	-	4,470,903
2130	-	-	-	-	-	-	-	-	4,470,903
2131	-	-	-	-	-	-	-	-	4,470,903
2132	-	-	-	-	-	-	-	-	4,470,903
2133	-	-	-	-	-	-	-	-	4,470,903
2134	-	-	-	-	-	-	-	-	4,470,903
2135	-	-	-	-	-	-	-	-	4,470,903
2136	-	-	-	-	-	-	-	-	4,470,903
2137	-	-	-	-	-	-	-	-	4,470,903
2138	-	-	-	-	-	-	-	-	4,470,903
2139	-	-	-	-	-	-	-	-	4,470,903
2140	-	-	-	-	-	-	-	-	4,470,903
2141	-	-	-	-	-	-	-	-	4,470,903
2142	-	-	-	-	-	-	-	-	4,470,903
2143	-	-	-	-	-	-	-	-	4,470,903
2144	-	-	-	-	-	-	-	-	4,470,903
2145	-	-	-	-	-	-	-	-	4,470,903
2146	-	-	-	-	-	-	-	-	4,470,903
2147	-	-	-	-	-	-	-	-	4,470,903
2148	-	-	-	-	-	-	-	-	4,470,903
2149	-	-	-	-	-	-	-	-	4,470,903

Dry Tonnages Deposited at the Vancouver Landfill - Phase 1

	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
Moisture	50%	45%	20%	18%	14%	14%	10%	22%
Solid	50%	55%	80%	82%	86%	86%	90%	78%

Dry Amounts Historically Deposited at the Vancouver Landfill - Phase 1

Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
1999	36	11	95	87	27	8	112	377
2000	30	9	79	104	23	7	107	359
2001	32	21	47	78	42	7	126	354
2002	32	22	48	120	43	7	147	418
2003	37	25	55	106	49	8	154	433
2004	52	11	86	113	39	8	179	488
2005	59	12	97	122	44	9	199	541
2006	45	9	74	86	33	7	149	402
2007	0	0	0	0	0	0	0	0
2008	16	3	27	29	5	2	43	125
2009	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0
2036	0	0	0	0	0	0	0	0
2037	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill - Phase 1							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2046	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0
2051	0	0	0	0	0	0	0	0
2052	0	0	0	0	0	0	0	0
2053	0	0	0	0	0	0	0	0
2054	0	0	0	0	0	0	0	0
2055	0	0	0	0	0	0	0	0
2056	0	0	0	0	0	0	0	0
2057	0	0	0	0	0	0	0	0
2058	0	0	0	0	0	0	0	0
2059	0	0	0	0	0	0	0	0
2060	0	0	0	0	0	0	0	0
2061	0	0	0	0	0	0	0	0
2062	0	0	0	0	0	0	0	0
2063	0	0	0	0	0	0	0	0
2064	0	0	0	0	0	0	0	0
2065	0	0	0	0	0	0	0	0
2066	0	0	0	0	0	0	0	0
2067	0	0	0	0	0	0	0	0
2068	0	0	0	0	0	0	0	0
2069	0	0	0	0	0	0	0	0
2070	0	0	0	0	0	0	0	0
2071	0	0	0	0	0	0	0	0
2072	0	0	0	0	0	0	0	0
2073	0	0	0	0	0	0	0	0
2074	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0
2076	0	0	0	0	0	0	0	0
2077	0	0	0	0	0	0	0	0
2078	0	0	0	0	0	0	0	0
2079	0	0	0	0	0	0	0	0
2080	0	0	0	0	0	0	0	0
2081	0	0	0	0	0	0	0	0
2082	0	0	0	0	0	0	0	0
2083	0	0	0	0	0	0	0	0
2084	0	0	0	0	0	0	0	0
2085	0	0	0	0	0	0	0	0
2086	0	0	0	0	0	0	0	0
2087	0	0	0	0	0	0	0	0
2088	0	0	0	0	0	0	0	0
2089	0	0	0	0	0	0	0	0
2090	0	0	0	0	0	0	0	0
2091	0	0	0	0	0	0	0	0
2092	0	0	0	0	0	0	0	0

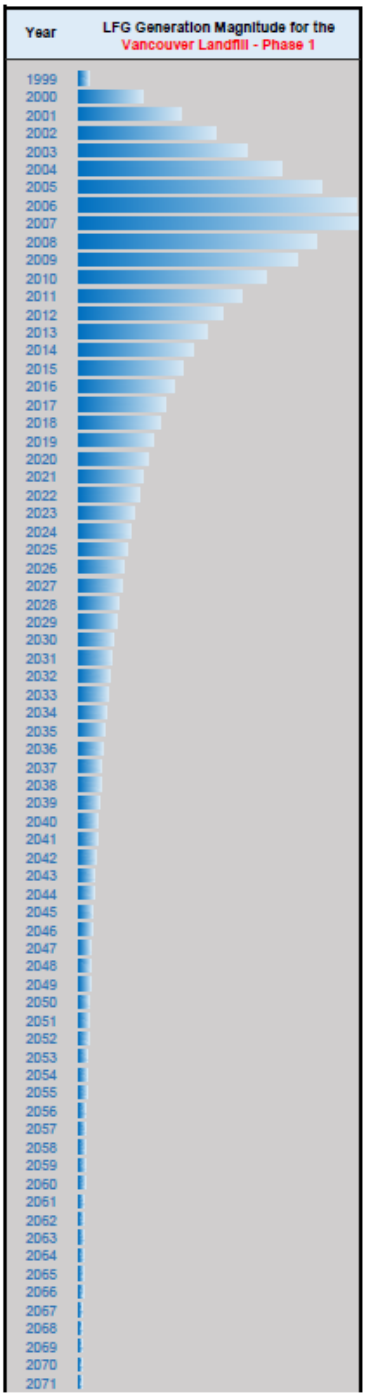
	Dry Amounts Historically Deposited at the Vancouver Landfill - Phase 1							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2093	0	0	0	0	0	0	0	0
2094	0	0	0	0	0	0	0	0
2095	0	0	0	0	0	0	0	0
2096	0	0	0	0	0	0	0	0
2097	0	0	0	0	0	0	0	0
2098	0	0	0	0	0	0	0	0

Methane Generation Estimates from the Vancouver Landfill - Phase 1

Actual CH_4 Yields

L_o (m^3/tonne)	113	157	143	72	114	114	77.0

Year	Methane generation estimates for the Vancouver Landfill - Phase 1							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)
1999	316	50	134	35	29	8	572	84.7	113
2000	1,815	319	886	245	189	55	3,508	80.6	696
2001	2,661	568	1,432	469	335	92	5,556	77.5	1,102
2002	3,315	1,036	1,723	652	569	129	7,424	73.9	1,472
2003	3,832	1,463	2,008	903	797	164	9,167	76.3	1,818
2004	4,502	1,839	2,365	1,120	1,030	202	11,058	74.7	2,193
2005	5,584	1,882	2,928	1,346	1,201	236	13,176	75.0	2,613
2006	6,466	1,935	3,494	1,566	1,375	270	15,105	75.5	2,996
2007	6,185	1,877	3,759	1,673	1,449	285	15,228		3,020
2008	4,494	1,543	3,544	1,619	1,357	268	12,924	78.5	2,563
2009	3,736	1,481	3,490	1,612	1,292	261	11,871		2,355
2010	2,632	1,287	3,254	1,549	1,204	243	10,171		2,017
2011	1,855	1,119	3,034	1,488	1,123	227	8,846		1,755
2012	1,307	973	2,829	1,430	1,047	212	7,798		1,547
2013	921	846	2,638	1,374	976	197	6,952		1,379
2014	649	735	2,460	1,320	910	184	6,258		1,241
2015	457	639	2,293	1,268	849	171	5,678		1,126
2016	322	556	2,138	1,218	791	160	5,186		1,029
2017	227	483	1,994	1,170	738	149	4,761		944
2018	160	420	1,859	1,125	688	139	4,391		871
2019	113	365	1,733	1,081	641	130	4,063		806
2020	79	317	1,616	1,038	598	121	3,770		748
2021	56	276	1,507	997	558	113	3,507		696
2022	39	240	1,405	958	520	105	3,268		648
2023	28	209	1,310	921	485	98	3,050		605
2024	20	181	1,221	885	452	91	2,850		565
2025	14	158	1,139	850	421	85	2,667		529
2026	10	137	1,062	817	393	79	2,498		495
2027	7	119	990	785	366	74	2,341		464
2028	5	104	923	754	342	69	2,196		436
2029	3	90	861	724	319	64	2,061		409
2030	2	78	803	696	297	60	1,936		384
2031	2	68	748	669	277	56	1,819		361
2032	1	59	698	642	258	52	1,711		339
2033	1	51	651	617	241	49	1,609		319
2034	1	45	607	593	224	45	1,515		300
2035	0	39	566	570	209	42	1,426		283
2036	0	34	527	547	195	39	1,343		266
2037	0	29	492	526	182	37	1,266		251
2038	0	26	458	505	170	34	1,193		237
2039	0	22	427	486	158	32	1,125		223
2040	0	19	399	466	147	30	1,062		211
2041	0	17	372	448	138	28	1,002		199
2042	0	15	346	431	128	26	946		188
2043	0	13	323	414	120	24	893		177
2044	0	11	301	397	111	23	844		167
2045	0	10	281	382	104	21	797		158
2046	0	8	262	367	97	20	754		149
2047	0	7	244	353	90	18	713		141
2048	0	6	228	339	84	17	674		134
2049	0	5	212	325	79	16	638		126
2050	0	5	198	313	73	15	603		120
2051	0	4	185	300	68	14	571		113
2052	0	4	172	289	64	13	541		107
2053	0	3	160	277	59	12	512		102
2054	0	3	150	266	55	11	485		96
2055	0	2	139	256	52	10	460		91
2056	0	2	130	246	48	10	436		86
2057	0	2	121	236	45	9	413		82
2058	0	2	113	227	42	8	392		78
2059	0	1	105	218	39	8	372		74
2060	0	1	98	210	36	7	353		70
2061	0	1	92	201	34	7	335		66
2062	0	1	85	193	32	6	318		63
2063	0	1	80	186	29	6	302		60
2064	0	1	74	179	27	6	287		57
2065	0	1	69	172	26	5	272		54
2066	0	1	65	165	24	5	259		51
2067	0	0	60	158	22	5	246		49
2068	0	0	56	152	21	4	234		46
2069	0	0	52	146	19	4	222		44
2070	0	0	49	140	18	4	211		42
2071	0	0	46	135	17	3	201		40



Year	Methane generation estimates for the Vancouver Landfill - Phase 1							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)
2072	0	0	42	130	16	3	191		38
2073	0	0	40	125	15	3	182		36
2074	0	0	37	120	14	3	173		34
2075	0	0	34	115	13	3	165		33
2076	0	0	32	111	12	2	157		31
2077	0	0	30	106	11	2	149		30
2078	0	0	28	102	10	2	142		28
2079	0	0	26	98	10	2	136		27
2080	0	0	24	94	9	2	129		26
2081	0	0	23	90	8	2	123		24
2082	0	0	21	87	8	2	117		23
2083	0	0	20	84	7	1	112		22
2084	0	0	18	80	7	1	107		21
2085	0	0	17	77	6	1	102		20
2086	0	0	16	74	6	1	97		19
2087	0	0	15	71	5	1	93		18
2088	0	0	14	68	5	1	88		18
2089	0	0	13	66	5	1	84		17
2090	0	0	12	63	4	1	81		16
2091	0	0	11	61	4	1	77		15
2092	0	0	10	58	4	1	73		15
2093	0	0	10	56	4	1	70		14
2094	0	0	9	54	3	1	67		13
2095	0	0	8	52	3	1	64		13
2096	0	0	8	50	3	1	61		12
2097	0	0	7	48	3	1	58		12
2098	0	0	7	46	3	1	56		11
2099	0	0	6	44	2	0	53		11
2100	0	0	6	42	2	0	51		10
2101	0	0	6	41	2	0	49		10
2102	0	0	5	39	2	0	47		9
2103	0	0	5	38	2	0	45		9
2104	0	0	5	36	2	0	43		8
2105	0	0	4	35	2	0	41		8
2106	0	0	4	33	1	0	39		8
2107	0	0	4	32	1	0	37		7
2108	0	0	3	31	1	0	36		7
2109	0	0	3	30	1	0	34		7
2110	0	0	3	28	1	0	33		6
2111	0	0	3	27	1	0	31		6
2112	0	0	3	26	1	0	30		6
2113	0	0	2	25	1	0	29		6
2114	0	0	2	24	1	0	27		5
2115	0	0	2	23	1	0	26		5
2116	0	0	2	22	1	0	25		5
2117	0	0	2	21	1	0	24		5
2118	0	0	2	21	1	0	23		5
2119	0	0	2	20	1	0	22		4
2120	0	0	1	19	1	0	21		4
2121	0	0	1	18	1	0	20		4
2122	0	0	1	18	0	0	19		4
2123	0	0	1	17	0	0	19		4
2124	0	0	1	16	0	0	18		4
2125	0	0	1	16	0	0	17		3
2126	0	0	1	15	0	0	16		3
2127	0	0	1	14	0	0	16		3
2128	0	0	1	14	0	0	15		3
2129	0	0	1	13	0	0	14		3
2130	0	0	1	13	0	0	14		3
2131	0	0	1	12	0	0	13		3
2132	0	0	1	12	0	0	13		3
2133	0	0	1	11	0	0	12		2
2134	0	0	1	11	0	0	12		2
2135	0	0	1	10	0	0	11		2
2136	0	0	0	10	0	0	11		2
2137	0	0	0	10	0	0	10		2
2138	0	0	0	9	0	0	10		2
2139	0	0	0	9	0	0	9		2
2140	0	0	0	9	0	0	9		2
2141	0	0	0	8	0	0	9		2
2142	0	0	0	8	0	0	8		2
2143	0	0	0	8	0	0	8		2
2144	0	0	0	7	0	0	8		2
2145	0	0	0	7	0	0	7		1
2146	0	0	0	7	0	0	7		1
2147	0	0	0	6	0	0	7		1
2148	0	0	0	6	0	0	7		1
2149	0	0	0	6	0	0	6		1

Year	LFG Generation Magnitude for the Vancouver Landfill - Phase 1
2072	
2073	
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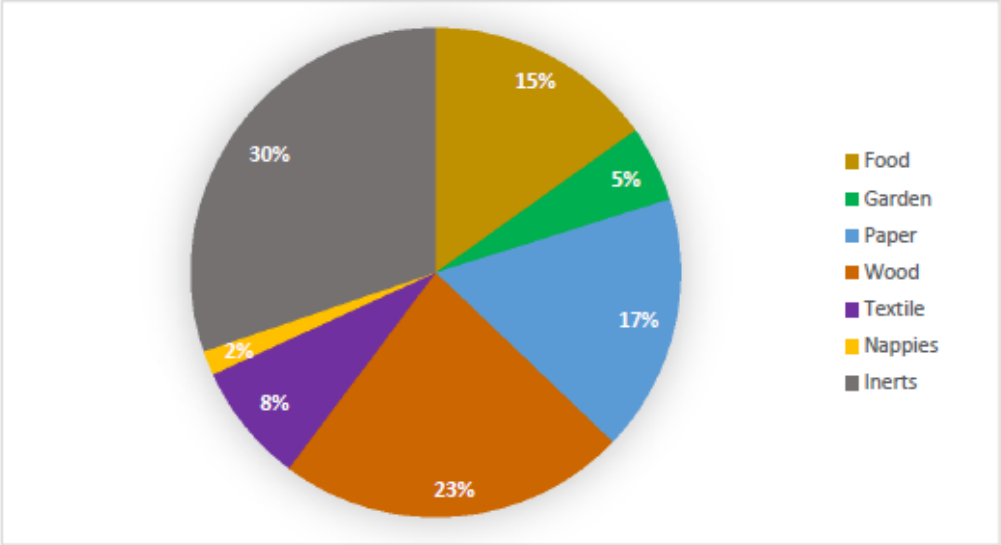
2148	
2149	

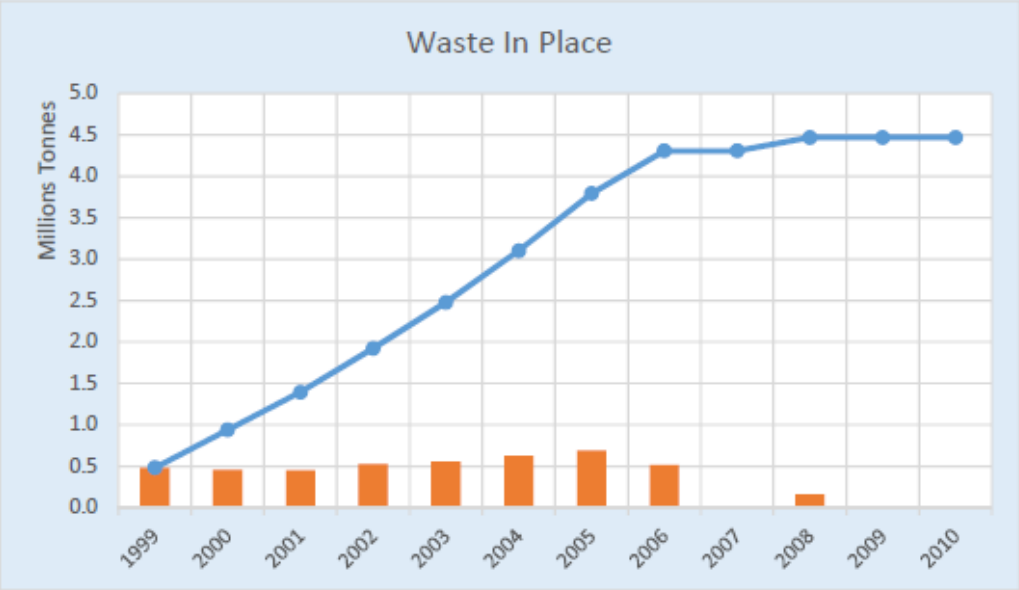
Vancouver Landfill - Phase 1

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**

Average Deposited Waste Composition

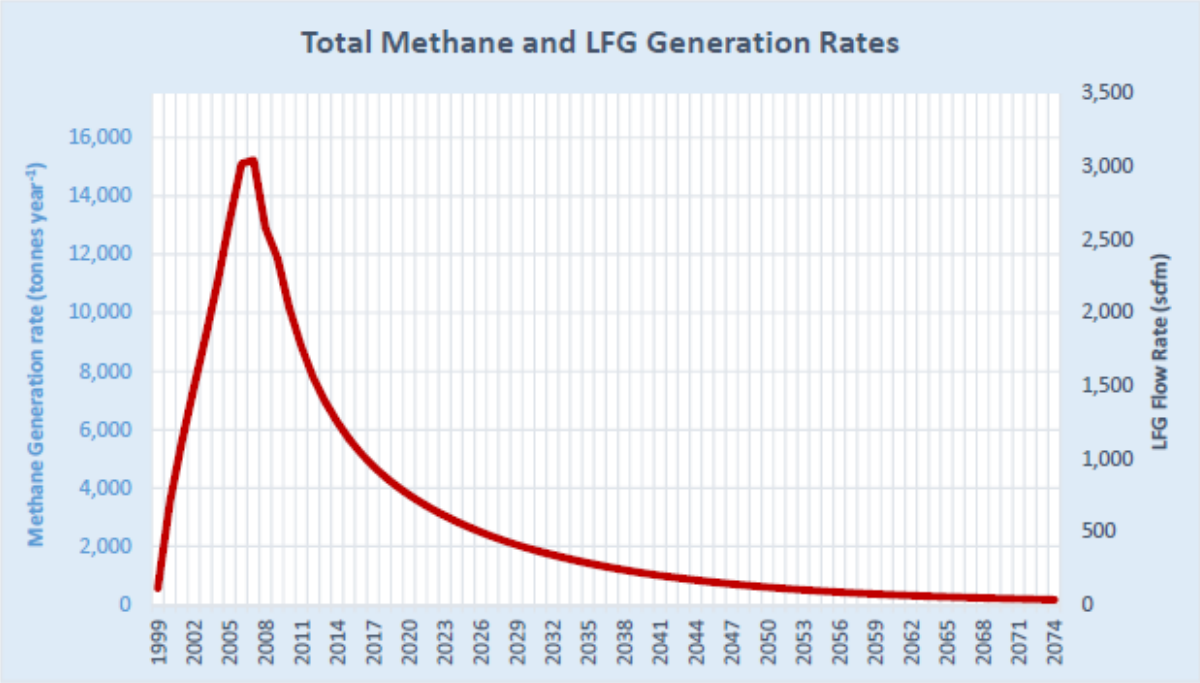


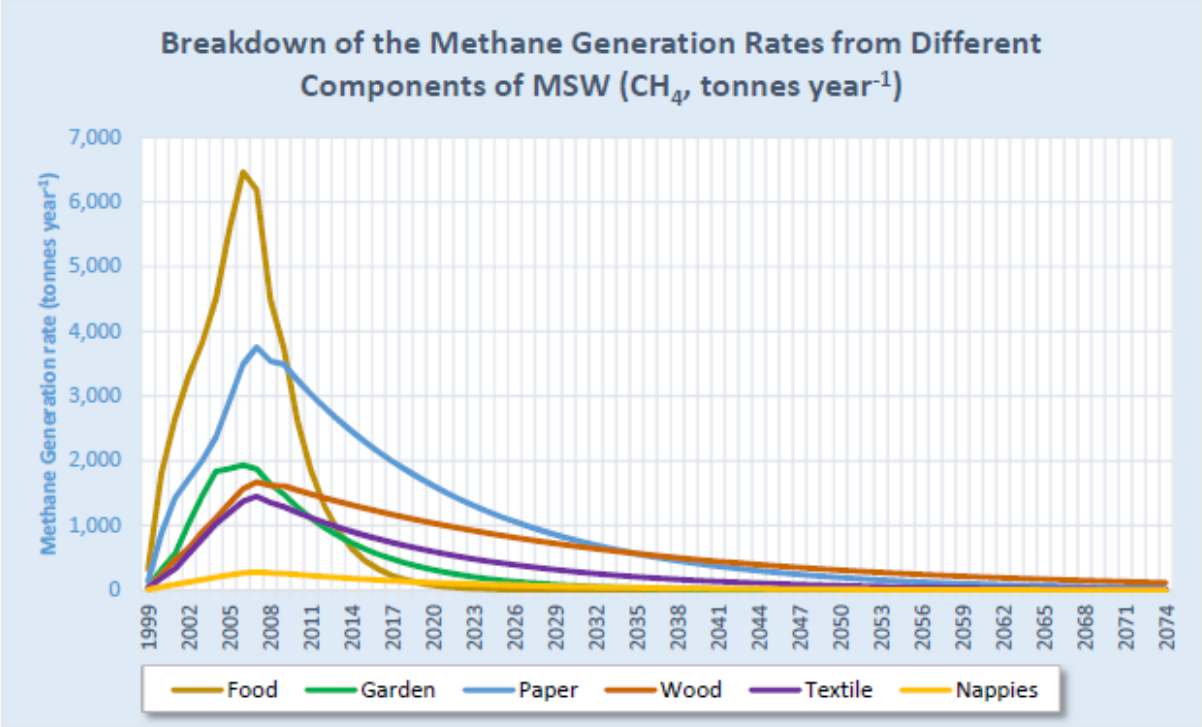
Annual MSW Deposition Rates and Total In Place



Vancouver Landfill - Phase 1

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**





B.5 iModel-110© Modeling Results – Entire Research Boundary

Landfill's Site-Specific Information

Enter Site's Name/ ID: Vancouver Landfill - Research Boundary

Year Filling Started: 1990 Date OK!

Thesis References and Parameters		Food waste	Garden waste	Paper &Rubber	Wood	Textile	Nappies
		%	%	%	%	%	%
Table 3.1 of Thesis	DOC_{dry}	0.38	0.49	0.44	0.5	0.3	0.3
Table 2.8 of Thesis	Moisture	50%	45%	20%	18%	14%	14%
Degradability Factor	f_{dg}	0.84	0.66	0.46	0.2	0.5	0.5
Climate Factor	f_{cl}	1	1	1	1	1	1
Depth Factor	f_{dp}	0.9	0.9	0.9	0.9	0.9	0.9
Storage Factor	f_{st}	0.8	1	1	1	1	1
$f = f_{dg} \times f_{cl} \times f_{dp} \times f_{st}$	**∑Discount**	**0.60**	**0.59**	**0.41**	**0.18**	**0.45**	**0.45**
Theoretical Methane Yield	L_o	***113***	***158***	***143***	***73***	***114***	***114***

Dry Degradable Organic Carbon Content and Decay Rates for Different Waste Components

Waste Components	DOC_{dry} (kg in 1kg dry)	k $year^{-1}$
Food waste	**0.38**	**0.35**
Garden	**0.49**	**0.14**
Paper	**0.44**	**0.07**
Wood and straw	**0.50**	**0.04**
Textiles	**0.30**	**0.07**
Disposable nappies	**0.30**	**0.07**

Thesis References: Table 3.1 Table 3.15

Methane Characteristics, Generation Calibration Factor & Delay Time

Parameters	Values & Units
CH_4 Density:	**0.6775** kg/m^3
CH_4 Fraction:	**0.5** m^3/m^3
CH_4/C (16/12):	**1.333** kg/kg
Enter (CF_G) here:	**1**
Delay Time (T_d):	**4** Months

Table 3.16

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill-Research Boundary								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
1990	91,901	25,742	150,652	34,604	40,277	11,769	113,939	**468,883**	**468,883**
1991	91,117	25,522	149,366	34,308	39,933	11,669	112,966	**464,881**	**933,764**
1992	88,793	24,871	145,558	33,433	38,915	11,371	110,086	**453,028**	**1,386,792**
1993	90,493	25,347	148,344	147,473	39,660	11,589	160,793	**623,700**	**2,010,492**
1994	85,613	23,980	140,344	32,236	37,521	10,964	106,142	**436,800**	**2,447,292**
1995	84,221	23,591	138,063	87,502	36,911	10,785	128,327	**509,400**	**2,956,692**
1996	78,755	22,059	129,102	101,264	34,515	10,085	128,330	**504,110**	**3,460,802**
1997	70,874	19,852	116,182	60,601	31,061	9,076	102,404	**410,050**	**3,870,852**
1998	68,711	19,246	112,638	96,963	30,114	8,799	115,656	**452,128**	**4,322,980**
1999	72,717	20,368	119,204	106,177	31,869	9,312	123,924	**483,572**	**4,806,551**
2000	60,520	16,952	99,209	126,312	26,524	7,750	119,400	**456,666**	**5,263,217**
2001	63,516	38,839	58,872	95,664	48,971	8,136	140,382	**454,381**	**5,717,598**
2002	64,307	39,322	59,605	146,372	49,580	8,237	163,351	**530,775**	**6,248,372**
2003	73,819	45,139	68,422	129,289	56,914	9,456	170,913	**553,951**	**6,802,324**
2004	104,033	19,839	107,614	138,337	45,049	8,855	199,293	**623,019**	**7,425,343**
2005	117,325	22,374	121,363	148,472	50,804	9,986	221,524	**691,847**	**8,117,190**
2006	89,073	16,986	92,138	105,330	38,571	7,582	165,014	**514,692**	**8,631,883**
2007	-	-	-	-	-	-	-	**-**	**8,631,883**
2008	31,120	4,570	34,238	35,252	6,186	2,639	47,994	**162,000**	**8,793,883**
2009	-	-	-	-	-	-	-	**-**	**8,793,883**
2010	-	-	-	-	-	-	-	**-**	**8,793,883**
2011	-	-	-	-	-	-	-	**-**	**8,793,883**
2012	-	-	-	-	-	-	-	**-**	**8,793,883**
2013	-	-	-	-	-	-	-	**-**	**8,793,883**
2014	-	-	-	-	-	-	-	**-**	**8,793,883**
2015	-	-	-	-	-	-	-	**-**	**8,793,883**
2016	-	-	-	-	-	-	-	**-**	**8,793,883**
2017	-	-	-	-	-	-	-	**-**	**8,793,883**
2018	-	-	-	-	-	-	-	**-**	**8,793,883**
2019	-	-	-	-	-	-	-	**-**	**8,793,883**
2020	-	-	-	-	-	-	-	**-**	**8,793,883**
2021	-	-	-	-	-	-	-	**-**	**8,793,883**
2022	-	-	-	-	-	-	-	**-**	**8,793,883**
2023	-	-	-	-	-	-	-	**-**	**8,793,883**
2024	-	-	-	-	-	-	-	**-**	**8,793,883**
2025	-	-	-	-	-	-	-	**-**	**8,793,883**
2026	-	-	-	-	-	-	-	**-**	**8,793,883**
2027	-	-	-	-	-	-	-	**-**	**8,793,883**
2028	-	-	-	-	-	-	-	**-**	**8,793,883**
2029	-	-	-	-	-	-	-	**-**	**8,793,883**
2030	-	-	-	-	-	-	-	**-**	**8,793,883**
2031	-	-	-	-	-	-	-	**-**	**8,793,883**
2032	-	-	-	-	-	-	-	**-**	**8,793,883**
2033	-	-	-	-	-	-	-	**-**	**8,793,883**
2034	-	-	-	-	-	-	-	**-**	**8,793,883**
2035	-	-	-	-	-	-	-	**-**	**8,793,883**
2036	-	-	-	-	-	-	-	**-**	**8,793,883**
2037	-	-	-	-	-	-	-	**-**	**8,793,883**
2038	-	-	-	-	-	-	-	**-**	**8,793,883**
2039	-	-	-	-	-	-	-	**-**	**8,793,883**
2040	-	-	-	-	-	-	-	**-**	**8,793,883**
2041	-	-	-	-	-	-	-	**-**	**8,793,883**
2042	-	-	-	-	-	-	-	**-**	**8,793,883**
2043	-	-	-	-	-	-	-	**-**	**8,793,883**
2044	-	-	-	-	-	-	-	**-**	**8,793,883**
2045	-	-	-	-	-	-	-	**-**	**8,793,883**
2046	-	-	-	-	-	-	-	**-**	**8,793,883**

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill-Research Boundary								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2047	-	-	-	-	-	-	-	-	8,793,883
2048	-	-	-	-	-	-	-	-	8,793,883
2049	-	-	-	-	-	-	-	-	8,793,883
2050	-	-	-	-	-	-	-	-	8,793,883
2051	-	-	-	-	-	-	-	-	8,793,883
2052	-	-	-	-	-	-	-	-	8,793,883
2053	-	-	-	-	-	-	-	-	8,793,883
2054	-	-	-	-	-	-	-	-	8,793,883
2055	-	-	-	-	-	-	-	-	8,793,883
2056	-	-	-	-	-	-	-	-	8,793,883
2057	-	-	-	-	-	-	-	-	8,793,883
2058	-	-	-	-	-	-	-	-	8,793,883
2059	-	-	-	-	-	-	-	-	8,793,883
2060	-	-	-	-	-	-	-	-	8,793,883
2061	-	-	-	-	-	-	-	-	8,793,883
2062	-	-	-	-	-	-	-	-	8,793,883
2063	-	-	-	-	-	-	-	-	8,793,883
2064	-	-	-	-	-	-	-	-	8,793,883
2065	-	-	-	-	-	-	-	-	8,793,883
2066	-	-	-	-	-	-	-	-	8,793,883
2067	-	-	-	-	-	-	-	-	8,793,883
2068	-	-	-	-	-	-	-	-	8,793,883
2069	-	-	-	-	-	-	-	-	8,793,883
2070	-	-	-	-	-	-	-	-	8,793,883
2071	-	-	-	-	-	-	-	-	8,793,883
2072	-	-	-	-	-	-	-	-	8,793,883
2073	-	-	-	-	-	-	-	-	8,793,883
2074	-	-	-	-	-	-	-	-	8,793,883
2075	-	-	-	-	-	-	-	-	8,793,883
2076	-	-	-	-	-	-	-	-	8,793,883
2077	-	-	-	-	-	-	-	-	8,793,883
2078	-	-	-	-	-	-	-	-	8,793,883
2079	-	-	-	-	-	-	-	-	8,793,883
2080	-	-	-	-	-	-	-	-	8,793,883
2081	-	-	-	-	-	-	-	-	8,793,883
2082	-	-	-	-	-	-	-	-	8,793,883
2083	-	-	-	-	-	-	-	-	8,793,883
2084	-	-	-	-	-	-	-	-	8,793,883
2085	-	-	-	-	-	-	-	-	8,793,883
2086	-	-	-	-	-	-	-	-	8,793,883
2087	-	-	-	-	-	-	-	-	8,793,883
2088	-	-	-	-	-	-	-	-	8,793,883
2089	-	-	-	-	-	-	-	-	8,793,883
2090	-	-	-	-	-	-	-	-	8,793,883
2091	-	-	-	-	-	-	-	-	8,793,883
2092	-	-	-	-	-	-	-	-	8,793,883
2093	-	-	-	-	-	-	-	-	8,793,883
2094	-	-	-	-	-	-	-	-	8,793,883
2095	-	-	-	-	-	-	-	-	8,793,883
2096	-	-	-	-	-	-	-	-	8,793,883
2097	-	-	-	-	-	-	-	-	8,793,883
2098	-	-	-	-	-	-	-	-	8,793,883
2099	-	-	-	-	-	-	-	-	8,793,883
2100	-	-	-	-	-	-	-	-	8,793,883
2101	-	-	-	-	-	-	-	-	8,793,883
2102	-	-	-	-	-	-	-	-	8,793,883
2103	-	-	-	-	-	-	-	-	8,793,883

Deposited tonnages for each waste component

Year	Overall Tonnages Deposited at the Vancouver Landfill-Research Boundary								
	Food	Garden	Paper	Wood	Textile	Nappies	Inerts	Total	In Place
	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)	(tonnes)
2104	-	-	-	-	-	-	-	-	8,793,883
2105	-	-	-	-	-	-	-	-	8,793,883
2106	-	-	-	-	-	-	-	-	8,793,883
2107	-	-	-	-	-	-	-	-	8,793,883
2108	-	-	-	-	-	-	-	-	8,793,883
2109	-	-	-	-	-	-	-	-	8,793,883
2110	-	-	-	-	-	-	-	-	8,793,883
2111	-	-	-	-	-	-	-	-	8,793,883
2112	-	-	-	-	-	-	-	-	8,793,883
2113	-	-	-	-	-	-	-	-	8,793,883
2114	-	-	-	-	-	-	-	-	8,793,883
2115	-	-	-	-	-	-	-	-	8,793,883
2116	-	-	-	-	-	-	-	-	8,793,883
2117	-	-	-	-	-	-	-	-	8,793,883
2118	-	-	-	-	-	-	-	-	8,793,883
2119	-	-	-	-	-	-	-	-	8,793,883
2120	-	-	-	-	-	-	-	-	8,793,883
2121	-	-	-	-	-	-	-	-	8,793,883
2122	-	-	-	-	-	-	-	-	8,793,883
2123	-	-	-	-	-	-	-	-	8,793,883
2124	-	-	-	-	-	-	-	-	8,793,883
2125	-	-	-	-	-	-	-	-	8,793,883
2126	-	-	-	-	-	-	-	-	8,793,883
2127	-	-	-	-	-	-	-	-	8,793,883
2128	-	-	-	-	-	-	-	-	8,793,883
2129	-	-	-	-	-	-	-	-	8,793,883
2130	-	-	-	-	-	-	-	-	8,793,883
2131	-	-	-	-	-	-	-	-	8,793,883
2132	-	-	-	-	-	-	-	-	8,793,883
2133	-	-	-	-	-	-	-	-	8,793,883
2134	-	-	-	-	-	-	-	-	8,793,883
2135	-	-	-	-	-	-	-	-	8,793,883
2136	-	-	-	-	-	-	-	-	8,793,883
2137	-	-	-	-	-	-	-	-	8,793,883
2138	-	-	-	-	-	-	-	-	8,793,883
2139	-	-	-	-	-	-	-	-	8,793,883
2140	-	-	-	-	-	-	-	-	8,793,883

Dry Tonnages Deposited at the Vancouver Landfill-Research Boundary

	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
Moisture	50%	45%	20%	18%	14%	14%	10%	22%
Solid	50%	55%	80%	82%	86%	86%	90%	78%

Dry Amounts Historically Deposited at the Vancouver Landfill-Research Boundary

Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
1990	46	14	121	28	35	10	103	356
1991	46	14	119	28	34	10	102	353
1992	44	14	116	27	33	10	99	344
1993	45	14	119	121	34	10	145	488
1994	43	13	112	26	32	9	96	332
1995	42	13	110	72	32	9	115	394
1996	39	12	103	83	30	9	115	392
1997	35	11	93	50	27	8	92	316
1998	34	11	90	80	26	8	104	352
1999	36	11	95	87	27	8	112	377
2000	30	9	79	104	23	7	107	359
2001	32	21	47	78	42	7	126	354
2002	32	22	48	120	43	7	147	418
2003	37	25	55	106	49	8	154	433
2004	52	11	86	113	39	8	179	488
2005	59	12	97	122	44	9	199	541
2006	45	9	74	86	33	7	149	402
2007	0	0	0	0	0	0	0	0
2008	16	3	27	29	5	2	43	125
2009	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0	0
2011	0	0	0	0	0	0	0	0
2012	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill-Research Boundary							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2037	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0
2051	0	0	0	0	0	0	0	0
2052	0	0	0	0	0	0	0	0
2053	0	0	0	0	0	0	0	0
2054	0	0	0	0	0	0	0	0
2055	0	0	0	0	0	0	0	0
2056	0	0	0	0	0	0	0	0
2057	0	0	0	0	0	0	0	0
2058	0	0	0	0	0	0	0	0
2059	0	0	0	0	0	0	0	0
2060	0	0	0	0	0	0	0	0
2061	0	0	0	0	0	0	0	0
2062	0	0	0	0	0	0	0	0
2063	0	0	0	0	0	0	0	0
2064	0	0	0	0	0	0	0	0
2065	0	0	0	0	0	0	0	0
2066	0	0	0	0	0	0	0	0
2067	0	0	0	0	0	0	0	0
2068	0	0	0	0	0	0	0	0
2069	0	0	0	0	0	0	0	0
2070	0	0	0	0	0	0	0	0
2071	0	0	0	0	0	0	0	0
2072	0	0	0	0	0	0	0	0
2073	0	0	0	0	0	0	0	0
2074	0	0	0	0	0	0	0	0
2075	0	0	0	0	0	0	0	0
2076	0	0	0	0	0	0	0	0
2077	0	0	0	0	0	0	0	0
2078	0	0	0	0	0	0	0	0
2079	0	0	0	0	0	0	0	0
2080	0	0	0	0	0	0	0	0
2081	0	0	0	0	0	0	0	0
2082	0	0	0	0	0	0	0	0

	Dry Amounts Historically Deposited at the Vancouver Landfill-Research Boundary							
Year	Food	Garden	Paper	Wood	Textile	Nappies	Inert	Deposited MSW
	Gg	Gg	Gg	Gg	Gg	Gg	Gg	Gg
2083	0	0	0	0	0	0	0	0
2084	0	0	0	0	0	0	0	0
2085	0	0	0	0	0	0	0	0
2086	0	0	0	0	0	0	0	0
2087	0	0	0	0	0	0	0	0
2088	0	0	0	0	0	0	0	0
2089	0	0	0	0	0	0	0	0

Methane Generation Estimates from the Vancouver Landfill-Research Boundary

Actual CH_4 Yields

L_o (m^3/tonne)	113	157	143	72	114	114	83.2

Year	Methane generation estimates for the Vancouver Landfill-Research Boundary							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)
1990	399	63	170	11	36	11	690	94.9	137
1991	2,357	413	1,146	78	244	71	4,310	94.9	855
1992	3,712	714	2,046	140	436	127	7,175	94.9	1,423
1993	4,632	968	2,866	237	611	178	9,492	83.5	1,883
1994	5,290	1,192	3,638	474	775	226	11,596	94.9	2,300
1995	5,659	1,370	4,311	536	918	268	13,062	88.0	2,591
1996	5,869	1,516	4,917	688	1,047	306	14,343	86.0	2,845
1997	5,883	1,620	5,418	843	1,154	337	15,255	89.7	3,026
1998	5,740	1,684	5,810	939	1,238	362	15,772	85.0	3,128
1999	5,617	1,735	6,165	1,092	1,313	384	16,305	84.7	3,234
2000	5,550	1,784	6,508	1,261	1,386	405	16,894	80.6	3,351
2001	5,293	1,841	6,675	1,445	1,451	419	17,124	77.5	3,396
2002	5,171	2,143	6,611	1,590	1,610	433	17,557	73.9	3,482
2003	5,140	2,426	6,565	1,804	1,767	448	18,150	76.3	3,600
2004	5,423	2,676	6,615	1,986	1,935	467	19,101	74.7	3,789
2005	6,233	2,609	6,890	2,178	2,045	482	20,437	75.0	4,054
2006	6,924	2,567	7,188	2,365	2,162	500	21,706	75.5	4,305
2007	6,508	2,427	7,204	2,441	2,183	499	21,261		4,217
2008	4,721	2,121	6,755	2,357	2,041	468	18,462	78.5	3,662
2009	3,896	1,896	6,485	2,321	1,930	447	16,975		3,367
2010	2,745	1,648	6,047	2,230	1,799	417	14,886		2,953
2011	1,935	1,433	5,638	2,142	1,677	389	13,214		2,621
2012	1,363	1,246	5,257	2,058	1,564	363	11,851		2,351
2013	961	1,083	4,901	1,978	1,458	338	10,719		2,126
2014	677	942	4,570	1,900	1,360	315	9,764		1,937
2015	477	819	4,261	1,826	1,268	294	8,944		1,774
2016	336	712	3,973	1,754	1,182	274	8,231		1,633
2017	237	619	3,704	1,685	1,102	256	7,603		1,508
2018	167	538	3,454	1,619	1,028	238	7,044		1,397
2019	118	468	3,220	1,556	958	222	6,542		1,297
2020	83	407	3,003	1,495	893	207	6,087		1,207
2021	58	353	2,800	1,436	833	193	5,674		1,125
2022	41	307	2,610	1,380	777	180	5,295		1,050
2023	29	267	2,434	1,326	724	168	4,948		981
2024	20	232	2,269	1,274	675	157	4,627		918
2025	14	202	2,116	1,224	630	146	4,331		859
2026	10	175	1,973	1,176	587	136	4,057		805
2027	7	153	1,839	1,130	547	127	3,803		754
2028	5	133	1,715	1,085	510	118	3,567		707
2029	4	115	1,599	1,043	476	110	3,347		664
2030	3	100	1,491	1,002	444	103	3,142		623
2031	2	87	1,390	963	414	96	2,951		585
2032	1	76	1,296	925	386	89	2,773		550
2033	1	66	1,209	889	360	83	2,607		517
2034	1	57	1,127	854	335	78	2,452		486
2035	0	50	1,051	820	313	72	2,306		457
2036	0	43	980	788	292	68	2,171		431
2037	0	38	913	757	272	63	2,043		405
2038	0	33	852	728	253	59	1,924		382
2039	0	28	794	699	236	55	1,813		360
2040	0	25	740	672	220	51	1,708		339
2041	0	21	690	645	205	48	1,610		319
2042	0	19	644	620	192	44	1,518		301
2043	0	16	600	596	179	41	1,432		284
2044	0	14	560	572	167	39	1,351		268
2045	0	12	522	550	155	36	1,275		253
2046	0	11	487	528	145	34	1,204		239
2047	0	9	454	508	135	31	1,137		225
2048	0	8	423	488	126	29	1,074		213
2049	0	7	394	469	117	27	1,014		201
2050	0	6	368	450	109	25	959		190
2051	0	5	343	433	102	24	906		180
2052	0	5	320	416	95	22	857		170
2053	0	4	298	399	89	21	811		161
2054	0	3	278	384	83	19	767		152
2055	0	3	259	369	77	18	726		144
2056	0	3	242	354	72	17	687		136
2057	0	2	225	340	67	16	650		129
2058	0	2	210	327	62	14	616		122
2059	0	2	196	314	58	14	583		116
2060	0	2	183	302	54	13	553		110
2061	0	1	170	290	51	12	524		104
2062	0	1	159	279	47	11	497		99

Year	LFG Generation Magnitude for the Vancouver Landfill-Research Boundary
1990	
1991	
1992	
1993	
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Year	Methane generation estimates for the Vancouver Landfill-Research Boundary							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)
2063	0	1	148	268	44	10	471		93
2064	0	1	138	257	41	10	447		89
2065	0	1	129	247	38	9	424		84
2066	0	1	120	237	36	8	402		80
2067	0	1	112	228	33	8	381		76
2068	0	0	104	219	31	7	362		72
2069	0	0	97	211	29	7	344		68
2070	0	0	91	202	27	6	327		65
2071	0	0	85	194	25	6	310		62
2072	0	0	79	187	23	5	295		58
2073	0	0	73	179	22	5	280		56
2074	0	0	69	172	20	5	266		53
2075	0	0	64	166	19	4	253		50
2076	0	0	60	159	18	4	241		48
2077	0	0	56	153	17	4	229		45
2078	0	0	52	147	15	4	218		43
2079	0	0	48	141	14	3	207		41
2080	0	0	45	136	13	3	197		39
2081	0	0	42	130	12	3	188		37
2082	0	0	39	125	12	3	179		35
2083	0	0	36	120	11	3	170		34
2084	0	0	34	116	10	2	162		32
2085	0	0	32	111	9	2	154		31
2086	0	0	30	107	9	2	147		29
2087	0	0	28	102	8	2	140		28
2088	0	0	26	98	8	2	134		27
2089	0	0	24	95	7	2	127		25
2090	0	0	22	91	7	2	121		24
2091	0	0	21	87	6	1	116		23
2092	0	0	19	84	6	1	110		22
2093	0	0	18	81	5	1	105		21
2094	0	0	17	77	5	1	101		20
2095	0	0	16	74	5	1	96		19
2096	0	0	15	71	4	1	92		18
2097	0	0	14	69	4	1	87		17
2098	0	0	13	66	4	1	83		17
2099	0	0	12	63	4	1	80		16
2100	0	0	11	61	3	1	76		15
2101	0	0	10	59	3	1	73		14
2102	0	0	10	56	3	1	69		14
2103	0	0	9	54	3	1	66		13
2104	0	0	8	52	2	1	63		13
2105	0	0	8	50	2	1	61		12
2106	0	0	7	48	2	1	58		11
2107	0	0	7	46	2	0	55		11
2108	0	0	6	44	2	0	53		10
2109	0	0	6	43	2	0	51		10
2110	0	0	6	41	2	0	48		10
2111	0	0	5	39	2	0	46		9
2112	0	0	5	38	1	0	44		9
2113	0	0	4	36	1	0	42		8
2114	0	0	4	35	1	0	40		8
2115	0	0	4	33	1	0	39		8
2116	0	0	4	32	1	0	37		7
2117	0	0	3	31	1	0	35		7
2118	0	0	3	30	1	0	34		7
2119	0	0	3	28	1	0	33		6
2120	0	0	3	27	1	0	31		6
2121	0	0	3	26	1	0	30		6
2122	0	0	2	25	1	0	29		6
2123	0	0	2	24	1	0	27		5
2124	0	0	2	23	1	0	26		5
2125	0	0	2	22	1	0	25		5
2126	0	0	2	22	1	0	24		5
2127	0	0	2	21	0	0	23		5
2128	0	0	2	20	0	0	22		4
2129	0	0	1	19	0	0	21		4
2130	0	0	1	18	0	0	20		4
2131	0	0	1	18	0	0	19		4
2132	0	0	1	17	0	0	19		4
2133	0	0	1	16	0	0	18		4
2134	0	0	1	16	0	0	17		3
2135	0	0	1	15	0	0	16		3
2136	0	0	1	14	0	0	16		3
2137	0	0	1	14	0	0	15		3
2138	0	0	1	13	0	0	14		3
2139	0	0	1	13	0	0	14		3
2140	0	0	1	12	0	0	13		3

Year	LFG Generation Magnitude for the Vancouver Landfill-Research Boundary
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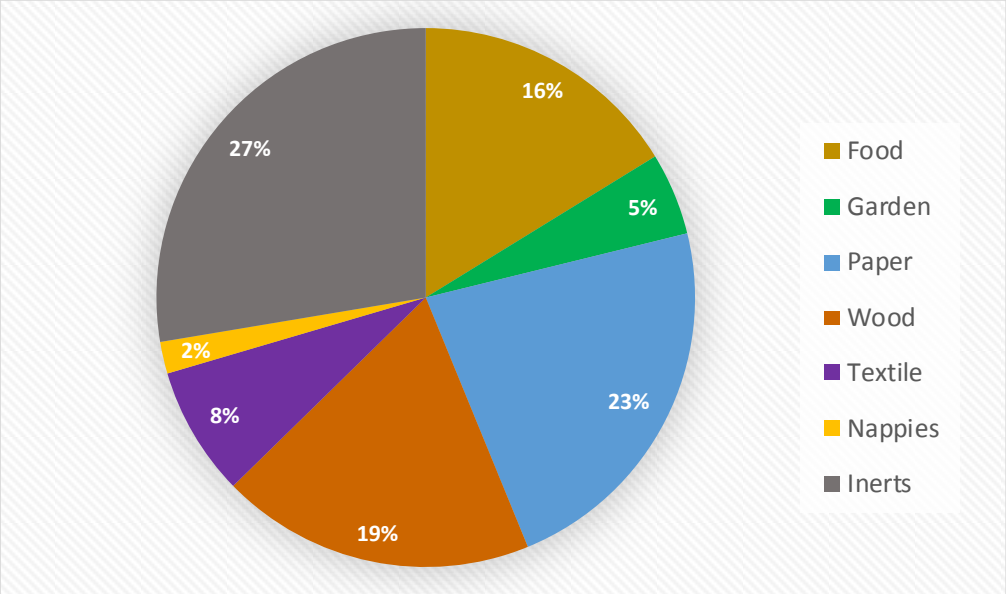
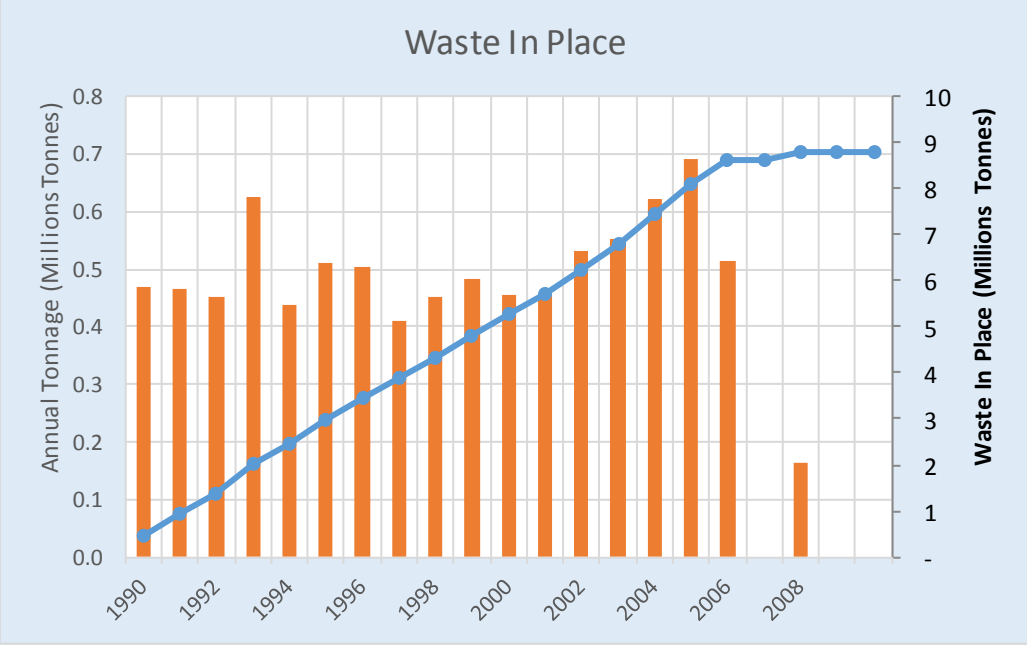
Vancouver Landfill-Research Boundary

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**

Average Deposited Waste Composition

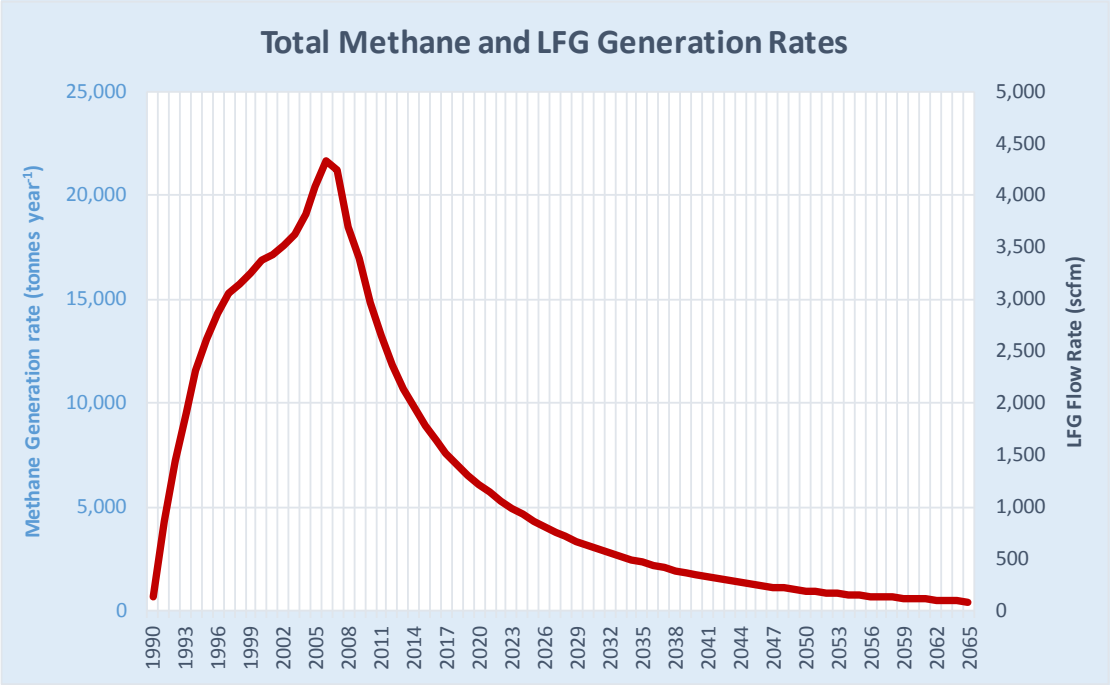


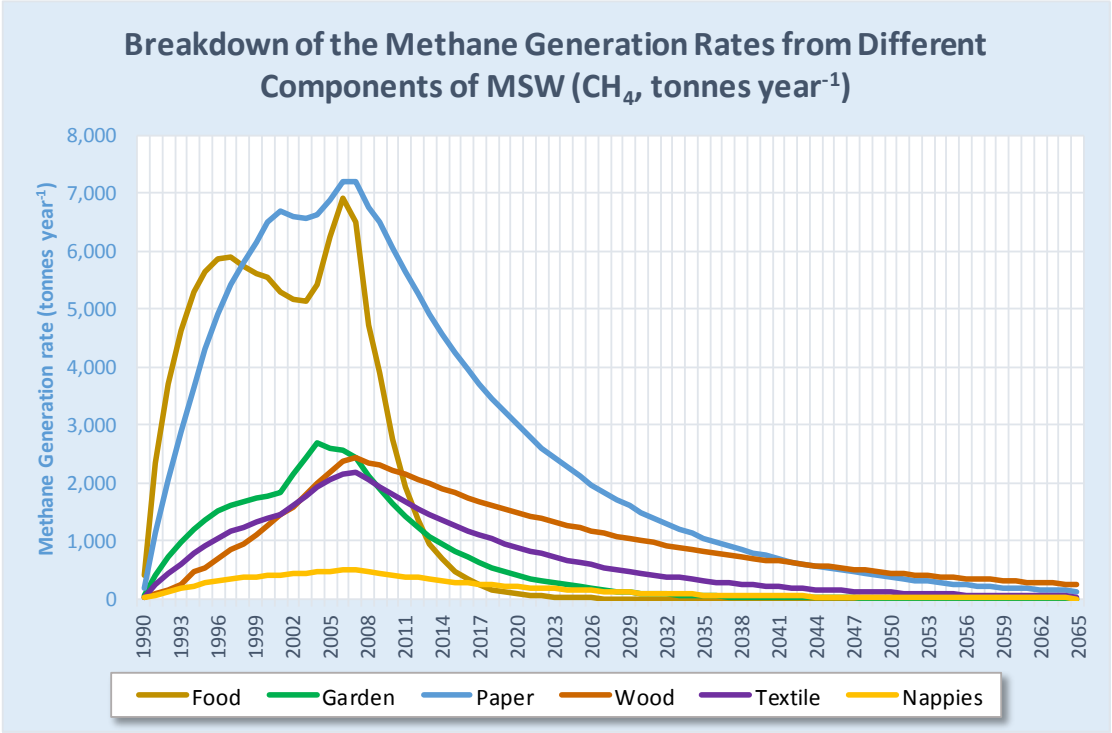
Annual MSW Deposition Rates and Total In Place



Vancouver Landfill-Research Boundary

Landfill Gas Generation Analysis **GRAPHICAL RESULTS**





Appendix C Wellfield Inspection and Temperature Investigations

C.1 LFG Wells and Coordinates

Phase 1 (42 Wells)				choose 10			
	WellName	Northing	Easting	G.Elevation (m)	Top Casing Elevation(m)	Pipe ID (in)	Water Depth below ground level (m)
1	F01	5438436.9	500789.2	21.55	23.35	2.070	6.50
2	F02	5438465.4	500792.7	21.51	23.08	2.070	8.60
3	F03	5438493.9	500795.5	21.37	22.84	2.070	9.27
4	F04	5438521.9	500799.8	21.93	23.52	2.070	7.25
5	F05	5438557.1	500793.9	21.98	23.37	2.070	7.60
6	F06	5438587.0	500806.4	23.53	24.85	2.070	9.69
7	F07	5438634.3	500804.2	24.10	25.67	2.070	11.73
8	F08	5438692.0	500809.0	24.81	26.24	2.070	8.96
9	F09	5438745.9	500808.9	25.05	26.70	2.070	11.86
10	F10	5438777.7	500810.0	24.69	26.15	2.070	13.35
11	F11	5438830.1	500811.6	26.21	27.39	2.070	13.20
12	F12	5438893.9	500796.8	24.19	25.86	2.070	11.90
13	F21	5438463.8	500836.3	30.09	32.03	2.070	8.45
14	F22	5438498.0	500838.1	30.11	31.99	2.070	9.66
15	F23	5438538.9	500843.1	30.27	32.21	2.070	8.00
16	F24	5438725.6	500848.0	30.87	33.50	2.070	8.60
17	F25	5438789.2	500848.0	31.05	32.83	2.070	9.28
18	F26	5438831.8	500845.1	30.76	33.04	2.070	11.23
19	F27	5438892.4	500853.8	29.11	31.12	2.070	8.35
20	P01-V030	5438480.6	500885.9	33.21	34.47	2.070	10.60
21	P01-V031	5438540.4	500940.1	19.97	21.63	2.070	11.50
22	P01-V032	5438517.5	500885.0	33.48	34.93	2.070	9.10
23	P01-V033	5438590.3	500945.1	18.75	20.09	2.070	10.45
24	P01-V034	5438576.2	500883.9	35.24	36.70	2.070	11.00
25	P01-V035	5438647.1	500951.7	17.06	18.56	2.070	5.85
26	P01-V036	5438623.7	500881.2	35.76	37.41	2.070	9.75
27	P01-V037	5438692.8	500949.2	18.37	19.93	2.070	7.90
28	P01-V038	5438673.3	500874.0	35.59	37.14	2.070	7.90
29	P01-V039	5438741.0	500940.1	20.05	21.40	2.070	7.90
30	P01-V040	5438723.9	500873.5	35.66	37.36	2.070	7.75
31	P01-V041	5438793.4	500944.3	18.48	20.35	2.070	9.80
32	P01-V042	5438773.2	500883.8	34.18	35.73	2.070	8.55
33	P01-V043	5438846.9	500947.5	17.78	19.00	2.070	8.60

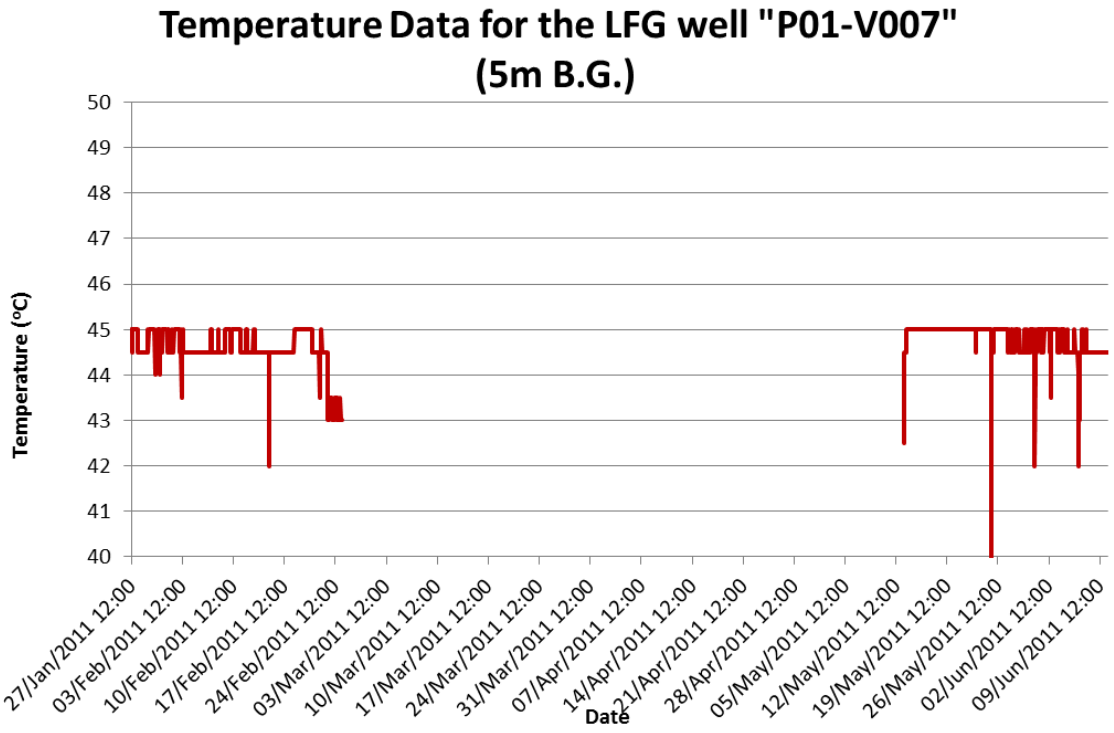
34	P01-V044	5438815.9	500884.8	33.11	34.53	2.070	8.37
35	P01-V045	5438893.3	500943.1	19.33	20.94	2.070	8.10
36	P01-V046	5438853.5	500885.7	32.42	33.53	2.070	7.80
37	P01-V047	5438952.1	500934.1	20.52	22.31	2.070	10.65
38	P01-V048	5438897.6	500892.7	30.17	31.69	2.070	8.30
39	P01-V050	5438960.4	500870.9	19.02	20.78	2.070	10.30
40	P01-V053	5438436.6	500897.2	30.20	31.69	2.070	9.90
41	P01-V054	5438386.0	500934.7	19.88	21.24	2.070	13.95
42	P01-V056	5438379.3	500881.7	18.71	20.14	2.070	11.00
Area 2W (70 Wells)				**choose 8**			
	WellName	Northing	Easting	G.Elevation(m)	CasingElevation	Pipe ID (in)	Water Depth below ground level (m)
1	A2W-V001	5438568.516	500047.430	9.9175	11.3486	2.095	7.73
2	A2W-V002	5438554.671	500009.188	9.4983	10.6960	2.095	7.48
3	A2W-V003	5438571.592	499947.475	10.8126	12.0799	2.095	6.43
4	A2W-V004	5438564.762	499887.119	11.2274	12.6399	2.095	7.55
5	A2W-V005	5438563.670	499846.501	10.0840	11.4735	2.095	8.17
6	A2W-V006	5438618.103	500037.676	10.1395	11.4209	2.095	5.63
7	A2W-V007	5438615.683	499977.220	11.5869	12.7667	2.095	9.02
8	A2W-V008	5438616.146	499916.965	13.1224	14.4393	2.095	7.58
9	A2W-V009	5438616.968	499857.041	11.6512	12.9797	2.095	8.24
10	A2W-V010	5438668.283	500055.567	9.6080	11.0599	2.095	4.75
11	A2W-V011	5438668.216	499998.789	11.0693	12.4593	2.095	6.72
12	A2W-V012	5438668.814	499937.582	12.6335	13.8852	2.095	9.20
13	A2W-V013	5438668.777	499886.700	12.0596	13.3367	2.095	7.10
14	A2W-V014	5438671.806	499843.761	11.4107	12.7161	2.095	6.33
15	A2W-V015	5438720.162	500062.060	9.6651	11.0094	2.095	5.44
16	A2W-V016	5438720.291	500028.840	10.5700	11.8849	2.095	6.04
17	A2W-V017	5438720.080	499975.745	12.2699	13.7410	2.095	7.97
18	A2W-V018	5438720.679	499907.897	12.6386	13.7835	2.095	8.56
19	A2W-V019	5438718.413	499857.937	11.6263	12.8593	2.095	6.98
20	A2W-V020	5438734.639	499831.235	11.5810	12.7883	2.095	5.68
21	A2W-V021	5438769.798	500065.021	9.3162	10.5938	2.095	6.06
22	A2W-V022	5438770.150	500005.159	11.4787	12.8266	2.095	5.82
23	A2W-V023	5438770.191	499955.700	12.6075	13.8562	2.095	7.32
24	A2W-V024	5438770.506	499888.223	13.0037	14.3275	2.095	6.25
25	A2W-V025	5438770.712	499828.342	12.2058	13.5969	2.095	4.68
26	A2W-V026	5438770.696	499768.283	11.7590	12.9796	2.095	7.28
27	A2W-V027	5438770.897	499708.194	10.4464	11.8422	2.095	7.67
28	A2W-V028	5438771.154	499647.913	10.0196	11.2764	2.095	7.77
29	A2W-V029	5438779.329	499606.591	9.8131	11.0670	2.095	8.43

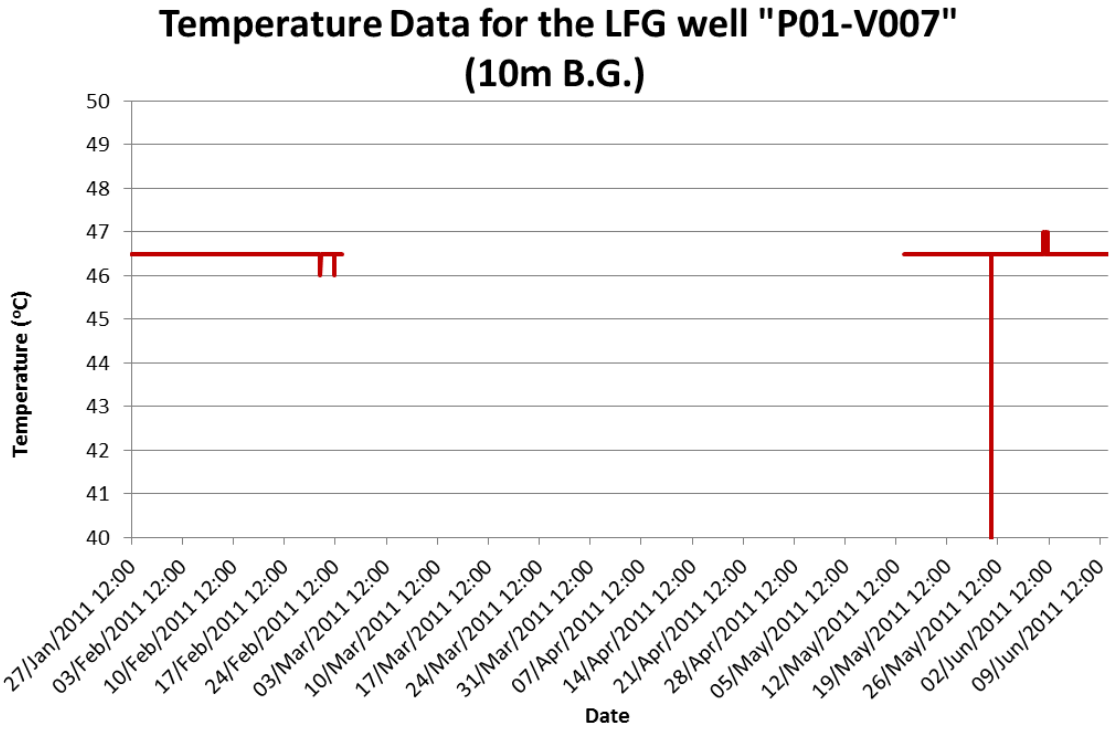
30	A2W-V030	5438821.812	500065.316	9.4500	10.6705	2.095	5.95
31	A2W-V031	5438821.591	500030.448	10.7527	12.0265	2.095	6.80
32	A2W-V032	5438822.015	499972.983	12.1729	13.5315	2.095	-1.35
33	A2W-V033	5438822.407	499907.881	13.1081	14.4540	2.095	7.06
34	A2W-V034	5438822.543	499855.327	13.3470	14.6803	2.095	6.82
35	A2W-V035	5438822.741	499794.921	13.6073	14.9639	2.095	6.07
36	A2W-V036	5438822.684	499738.447	12.3507	13.7955	2.095	5.40
37	A2W-V037	5438822.718	499678.086	12.3048	13.6146	2.095	7.44
38	A2W-V038	5438823.209	499633.880	12.2587	13.5947	2.095	7.48
39	A2W-V039	5438822.543	499590.801	10.4702	11.7740	2.095	7.72
40	A2W-V040	5438873.555	500063.639	9.8694	11.1729	2.095	6.33
41	A2W-V041	5438874.133	500005.061	11.5151	12.8144	2.095	6.44
42	A2W-V042	5438874.137	499955.640	12.6711	13.9481	2.095	7.20
43	A2W-V043	5438874.668	499885.189	12.8807	14.3196	2.095	6.76
44	A2W-V044	5438874.636	499828.272	13.9763	15.2480	2.095	6.52
45	A2W-V045	5438874.576	499768.070	14.2411	15.5362	2.095	8.68
46	A2W-V046	5438874.440	499707.712	13.9957	15.3235	2.095	7.06
47	A2W-V047	5438874.539	499648.239	13.0748	14.4629	2.095	7.60
48	A2W-V048	5438874.244	499596.260	10.6974	11.9829	2.095	5.68
49	A2W-V049	5438925.774	500063.907	10.0252	11.3003	2.095	7.10
50	A2W-V050	5438925.899	500031.935	10.8498	12.1874	2.095	8.02
51	A2W-V051	5438925.538	499972.252	12.1689	13.4922	2.095	7.04
52	A2W-V052	5438926.254	499915.132	12.6065	13.8094	2.095	6.27
53	A2W-V053	5438926.341	499855.503	12.5455	13.8135	2.095	7.18
54	A2W-V054	5438926.415	499798.258	14.1409	15.3699	2.095	7.73
55	A2W-V055	5438926.585	499738.361	13.7373	15.0517	2.095	10.45
56	A2W-V056	5438926.479	499678.091	13.4981	14.8397	2.095	9.05
57	A2W-V057	5438927.242	499631.339	12.5568	13.9630	2.095	7.71
58	A2W-V058	5438926.702	499593.758	10.3776	11.5434	2.095	6.30
59	A2W-V059	5438978.429	500057.993	10.1767	11.4178	2.095	7.85
60	A2W-V060	5438971.697	500002.997	11.2648	12.5123	2.095	8.65
61	A2W-V061	5438981.381	499946.874	10.9083	12.2764	2.095	5.97
62	A2W-V062	5438978.163	499885.310	11.4891	12.7533	2.095	6.28
63	A2W-V063	5438978.080	499828.386	11.3884	12.6612	2.095	5.25
64	A2W-V064	5438978.665	499765.884	12.1720	13.4907	2.095	10.92
65	A2W-V065	5438978.458	499708.542	12.2619	13.6923	2.095	9.77
66	A2W-V066	5438978.431	499648.295	12.2778	13.6361	2.095	11.08
67	A2W-V067	5438978.530	499591.977	10.6090	12.0693	2.095	9.38
68	A2W-V068	5439008.319	499738.417	11.4089	12.6977	2.095	7.92
69	A2W-V069	5439010.860	499678.186	10.7073	11.9756	2.095	9.30
70	A2W-V070	5439011.373	499618.354	10.4825	12.0557	2.095	8.10

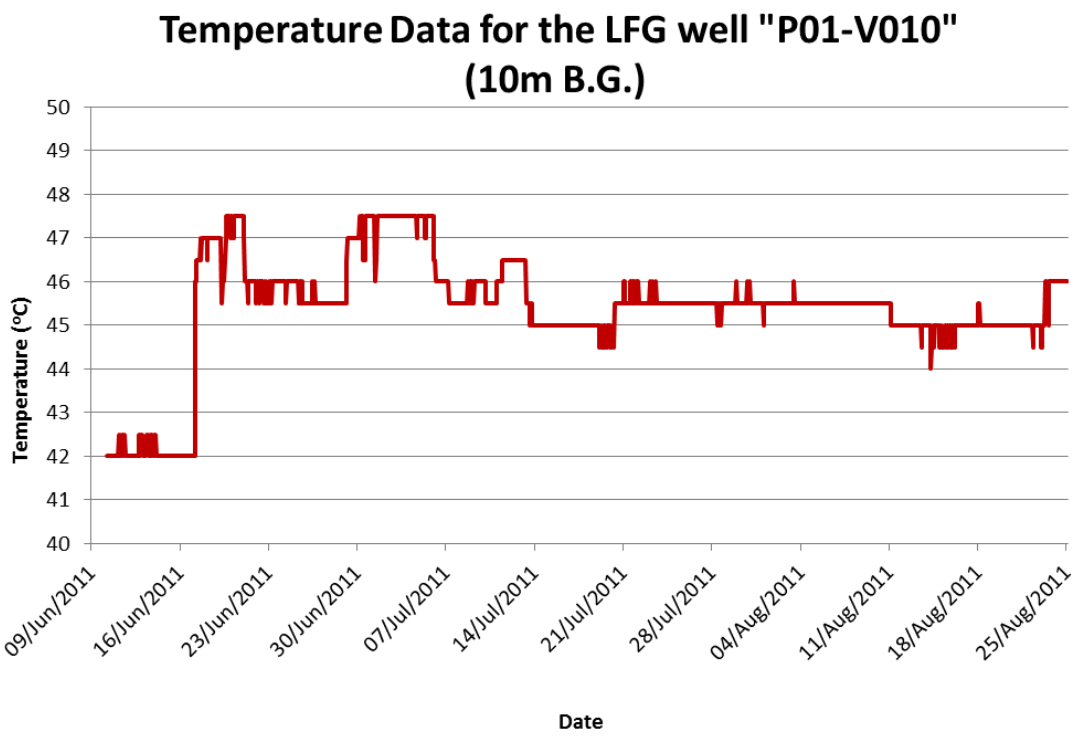
Area 2E (45 Wells)				choose 6			
	WellName	Northing	Easting	G.Elevation(m)	CasingElevation	Pipe ID (in)	Water Depth below ground level (m)
1	A2E-V001	5438372.246	500314.585	10.7193	12.0041	2.095	4.9
2	A2E-V002	5438372.725	500251.167	10.7103	12.2144	2.095	7.5
3	A2E-V003	5438402.144	500342.419	10.6944	12.1206	2.095	6.55
4	A2E-V004	5438402.539	500282.279	10.6178	12.0096	2.095	6.7
5	A2E-V005	5438402.588	500237.025	10.2920	11.7981	2.095	8.4
6	A2E-V006	5438458.611	500361.118	10.2848	11.5516	2.095	7.55
7	A2E-V007	5438454.736	500312.559	11.0958	12.4496	2.095	7.7
8	A2E-V008	5438454.790	500252.623	10.8819	12.4062	2.095	5.45
9	A2E-V009	5438506.440	500337.494	10.7600	12.0914	2.095	7.3
10	A2E-V010	5438506.100	500282.449	12.2374	13.6055	2.095	9.85
11	A2E-V011	5438506.448	500228.937	12.1708	13.4764	2.095	7.45
12	A2E-V012	5438558.313	500369.579	10.1407	11.4045	2.095	5.65
13	A2E-V013	5438558.658	500312.633	11.8628	13.3392	2.095	9.9
14	A2E-V014	5438558.698	500252.566	12.6978	14.1417	2.095	6.9
15	A2E-V015	5438558.769	500215.352	11.9424	13.4162	2.095	5.8
16	A2E-V016	5438610.080	500342.434	11.2646	12.5271	2.095	6.4
17	A2E-V017	5438610.518	500282.767	11.9232	13.2526	2.095	8.7
18	A2E-V018	5438610.627	500219.663	11.1071	12.5233	2.095	7.5
19	A2E-V019	5438662.045	500366.502	10.0546	11.5246	2.095	6.3
20	A2E-V020	5438661.796	500316.736	11.5887	12.8794	2.095	7
21	A2E-V021	5438662.381	500252.755	11.9839	13.3229	2.095	6.7
22	A2E-V022	5438662.333	500218.290	10.3838	11.8330	2.095	6.2
23	A2E-V023	5438713.628	500367.872	10.6756	12.0460	2.095	5.65
24	A2E-V024	5438713.685	500333.987	10.8921	12.3757	2.095	4.4
25	A2E-V025	5438713.858	500282.721	12.4939	13.8072	2.095	5.7
26	A2E-V026	5438714.594	500222.743	11.0166	12.4805	2.095	7.3
27	A2E-V027	5438765.481	500371.603	10.0509	11.5663	2.095	5.3
28	A2E-V028	5438765.656	500312.890	11.7268	13.0623	2.095	6.6
29	A2E-V029	5438766.280	500256.685	12.3473	13.7522	2.095	7.35
30	A2E-V030	5438766.428	500222.117	10.8018	12.1577	2.095	6.9
31	A2E-V031	5438817.394	500373.471	10.0936	11.2676	2.095	4.95
32	A2E-V032	5438817.901	500341.956	10.7833	12.0630	2.095	6.8
33	A2E-V033	5438817.977	500281.917	12.0258	13.2470	2.095	8.2
34	A2E-V034	5438818.397	500222.168	10.8418	12.2079	2.095	5.85
35	A2E-V035	5438871.399	500371.961	9.8364	11.2079	2.095	4.8

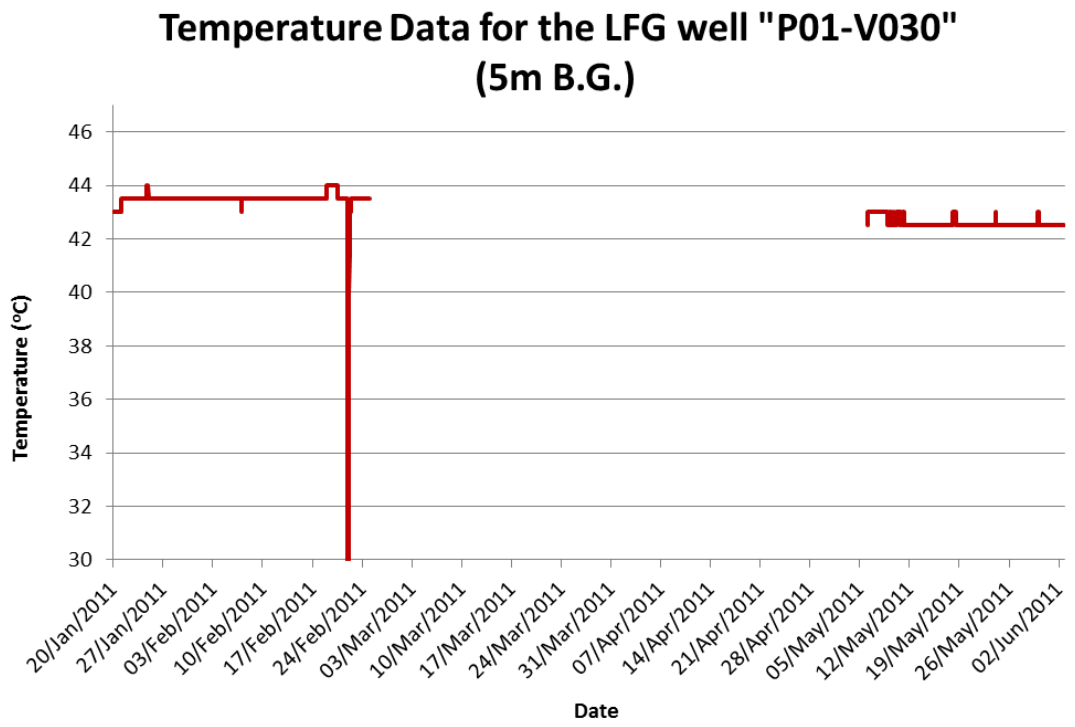
	WellName	Northing	Easting	G.Elevation(m)	CasingElevation	Pipe ID (in)	Water Depth below ground level (m)
36	A2E-V036	5438870.095	500312.115	11.0117	12.3676	2.095	5.4
37	A2E-V037	5438869.697	500251.898	11.1275	12.5159	2.095	6.4
38	A2E-V038	5438870.213	500221.799	10.1644	11.5789	2.095	6.9
39	A2E-V039	5438922.270	500368.281	9.7939	11.1925	2.095	4.5
40	A2E-V040	5438921.577	500336.785	10.6323	12.0381	2.095	6.1
41	A2E-V041	5438921.902	500281.898	11.0337	12.5170	2.095	6.35
42	A2E-V042	5438922.217	500222.185	10.1382	11.4182	2.095	7.3
43	A2E-V043	5438958.441	500355.244	9.6931	11.1372	2.095	6.6
44	A2E-V044	5438962.809	500288.907	10.5684	11.9760	2.095	7.3
45	A2E-V045	5438967.176	500234.873	9.7526	11.2472	2.095	6.4

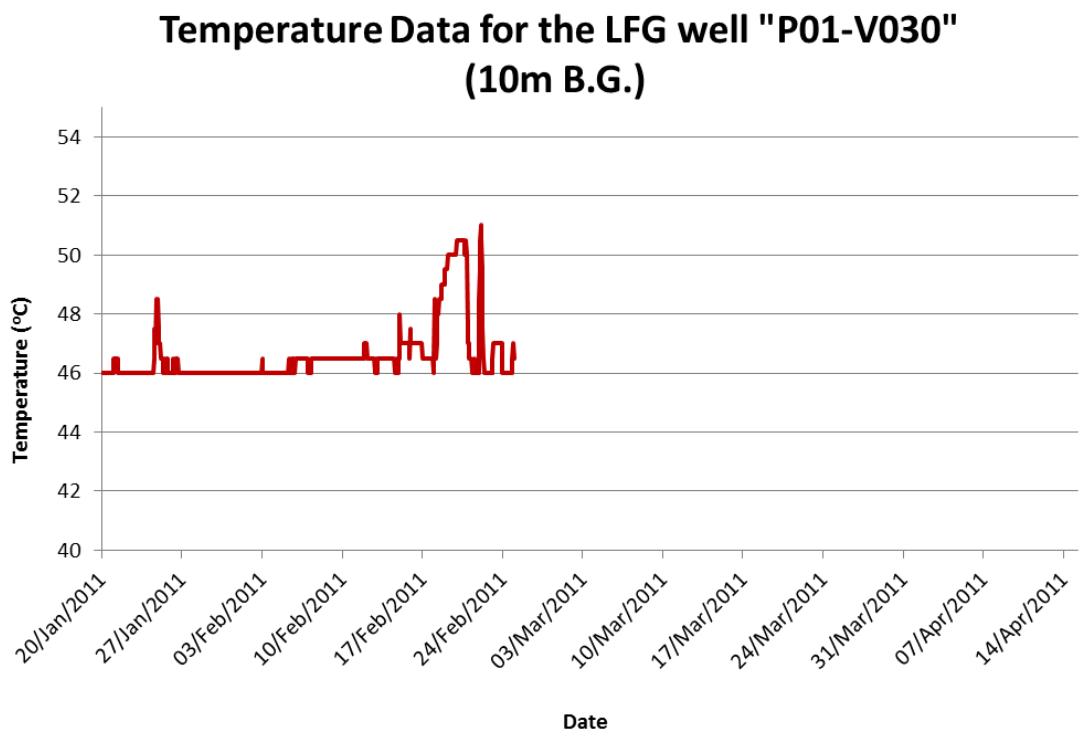
C.2 LFG Wells Temperature Survey Results

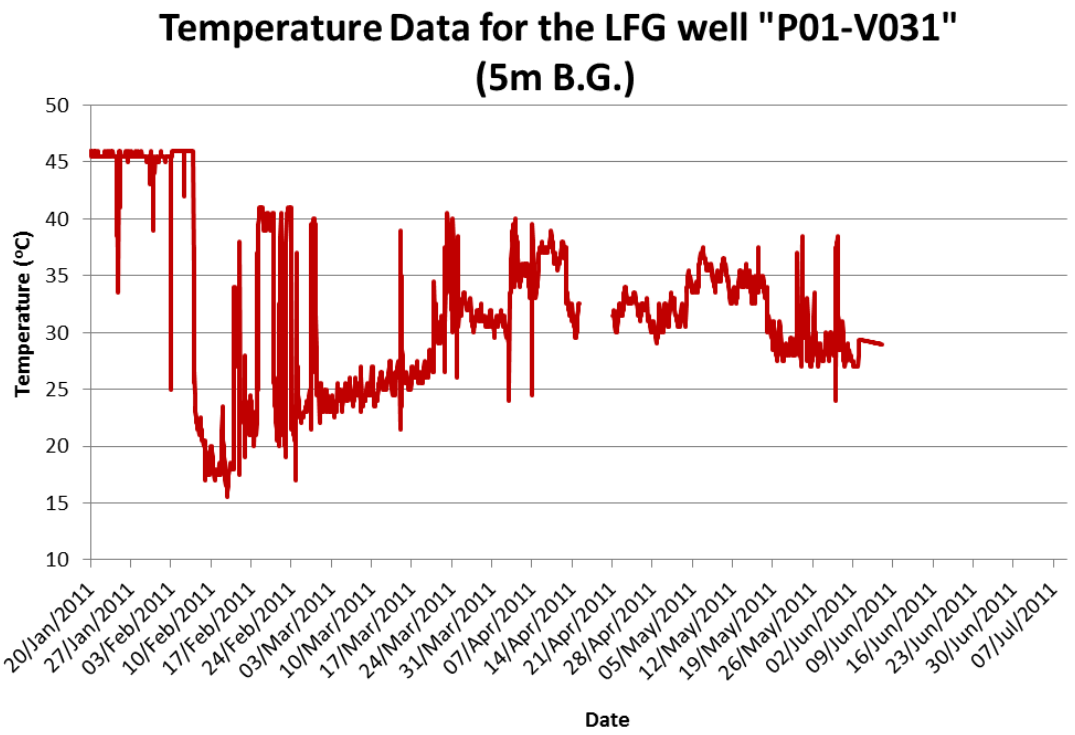


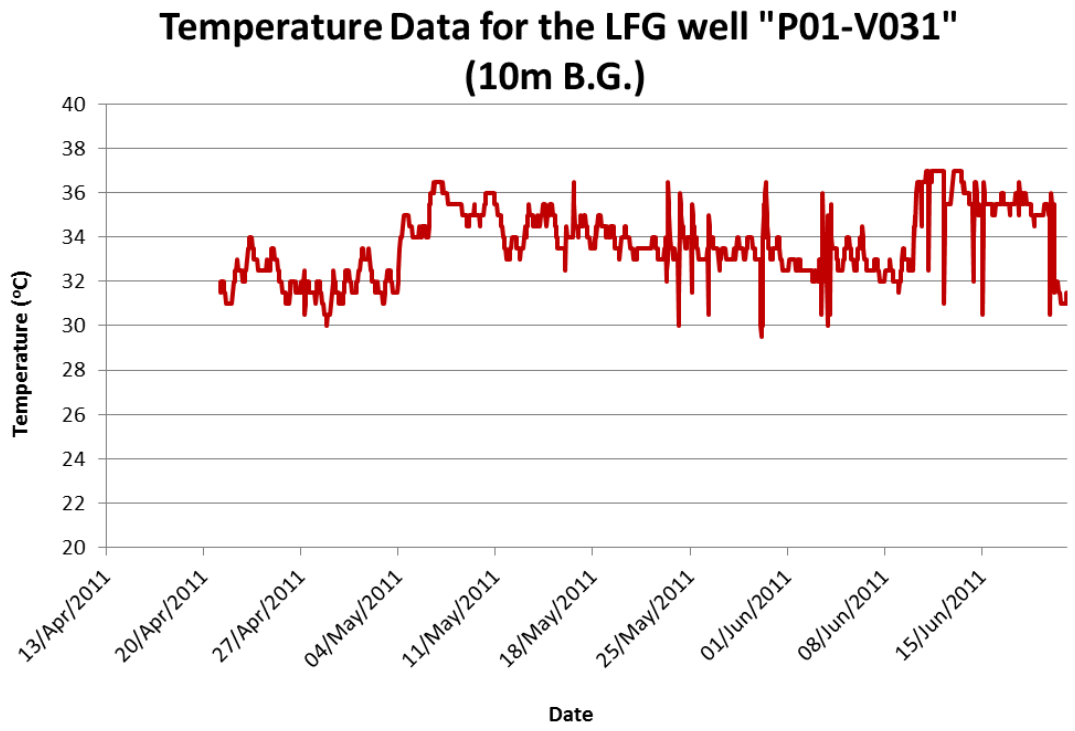


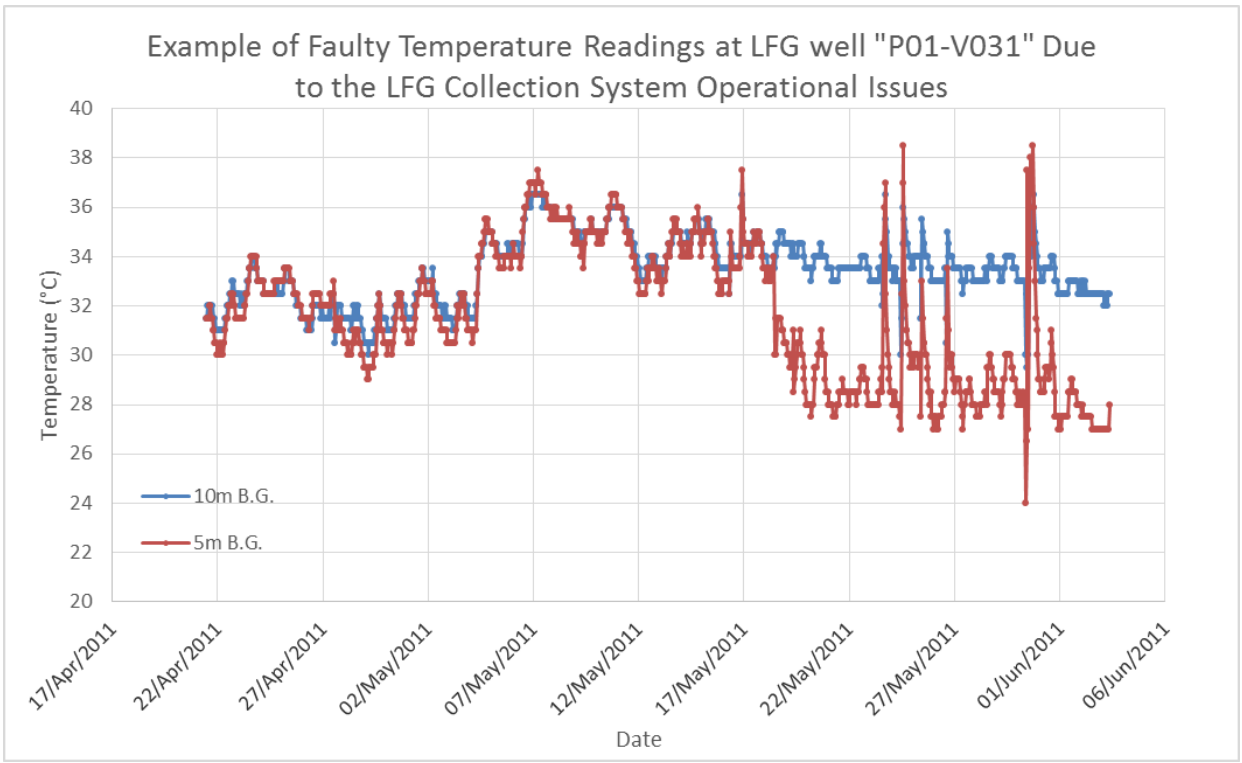

Temperature Data for the LFG well "P01-V010"
(10m B.G.)
Temperature (°C)
50
49
48
47
46
45
44
43
42
41
40
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
14/Jul/2011
21/Jul/2011
28/Jul/2011
04/Aug/2011
11/Aug/2011
18/Aug/2011
25/Aug/2011
Date

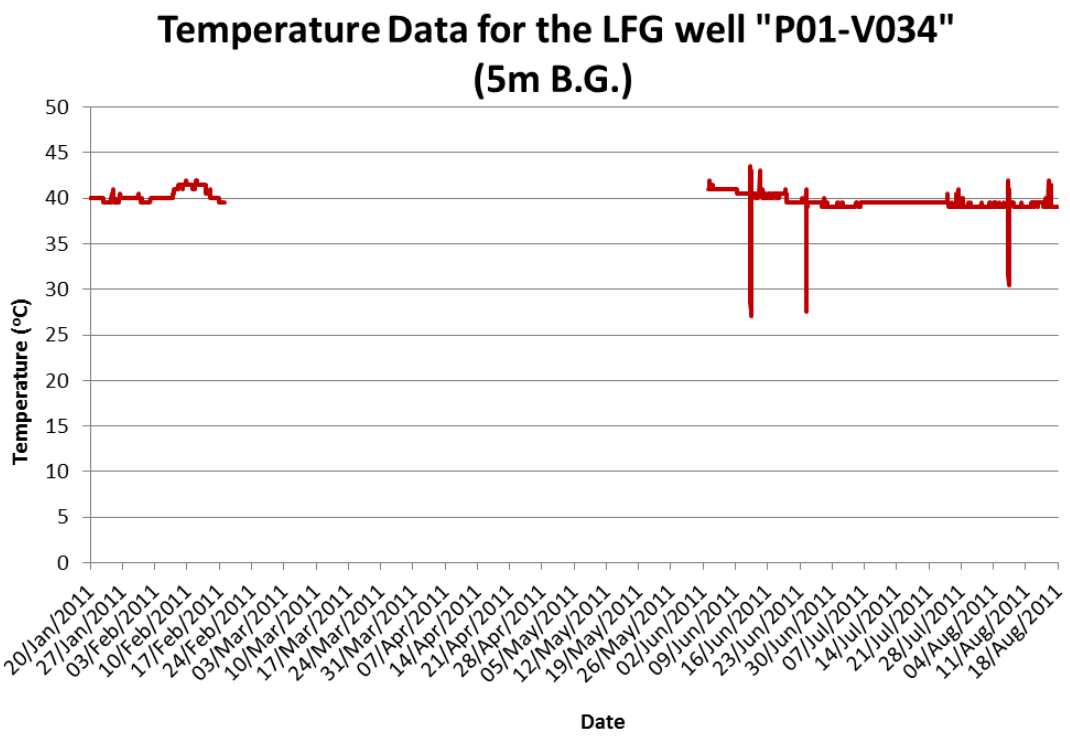

Temperature Data for the LFG well "P01-V030"
(5m B.G.)
Temperature (°C)
46
44
42
40
38
36
34
32
30
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
Date

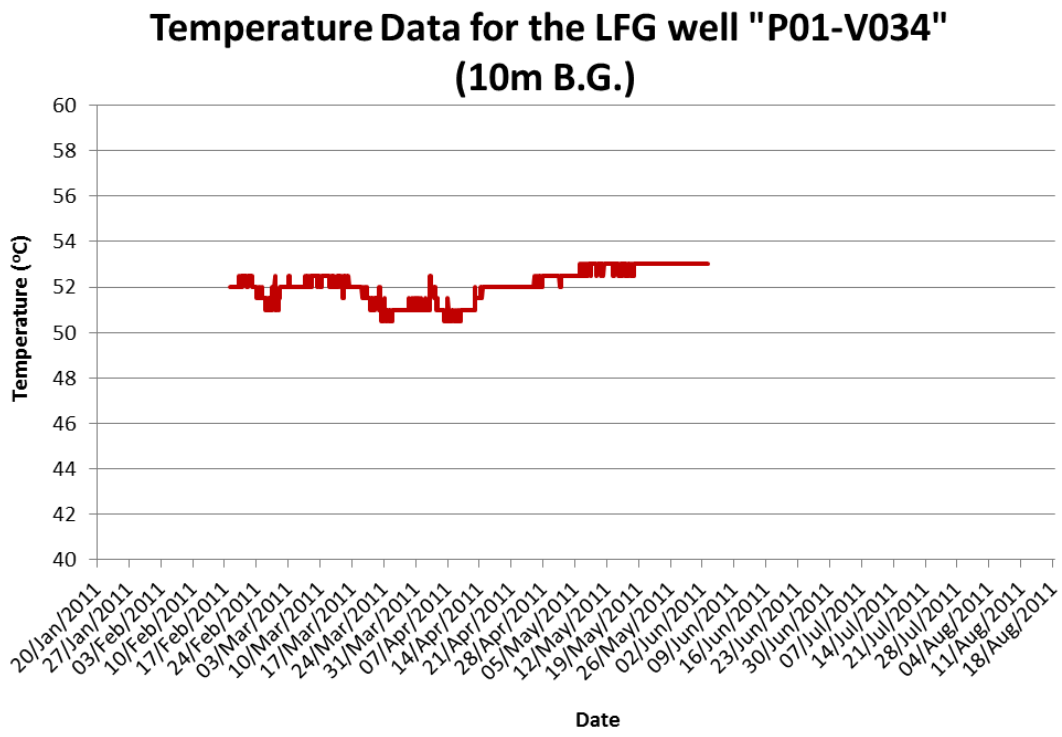

Temperature Data for the LFG well "P01-V030"
(10m B.G.)
Temperature (ºC)
54
52
50
48
46
44
42
40
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
Date

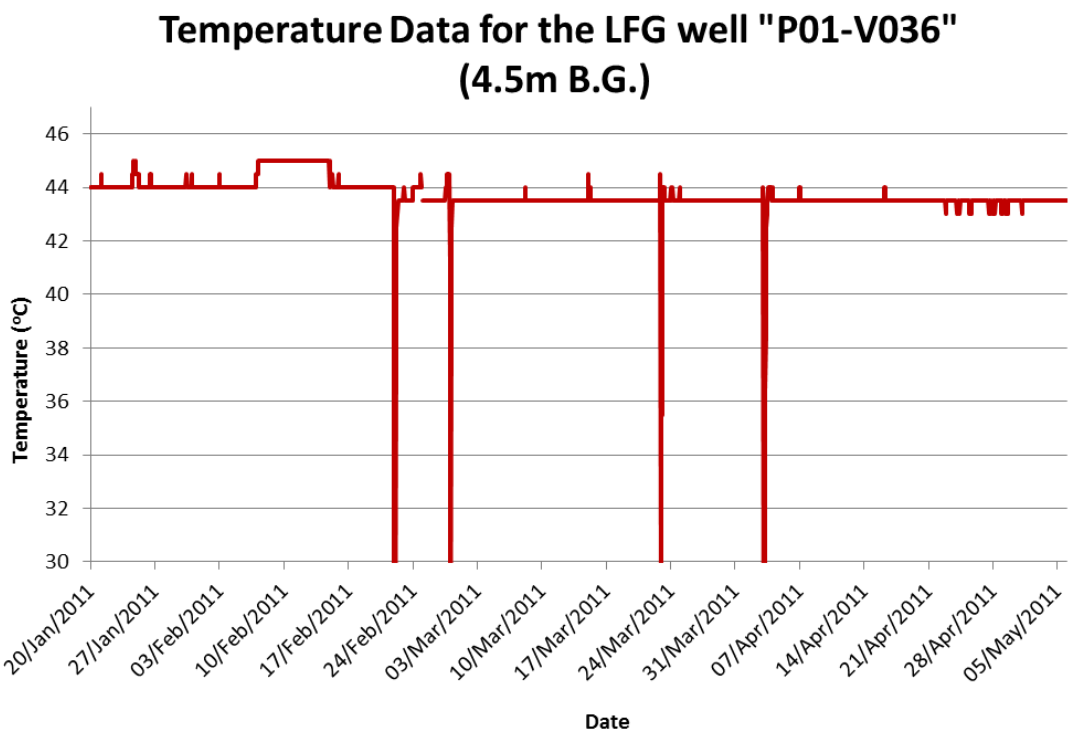

Temperature Data for the LFG well "P01-V031"
(5m B.G.)
Temperature (ºC)
50
45
40
35
30
25
20
15
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

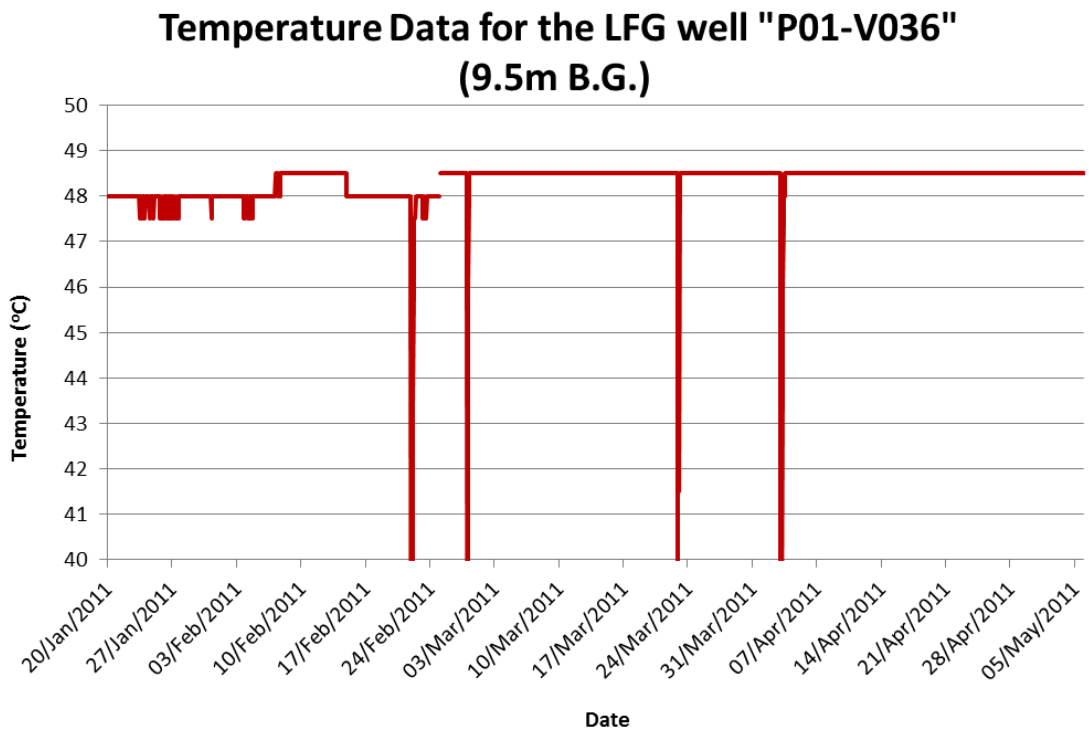

Temperature Data for the LFG well "P01-V031" (10m B.G.)
Temperature (°C)
40
38
36
34
32
30
28
26
24
22
20
13/Apr/2011
20/Apr/2011
27/Apr/2011
04/May/2011
11/May/2011
18/May/2011
25/May/2011
01/Jun/2011
08/Jun/2011
15/Jun/2011
Date

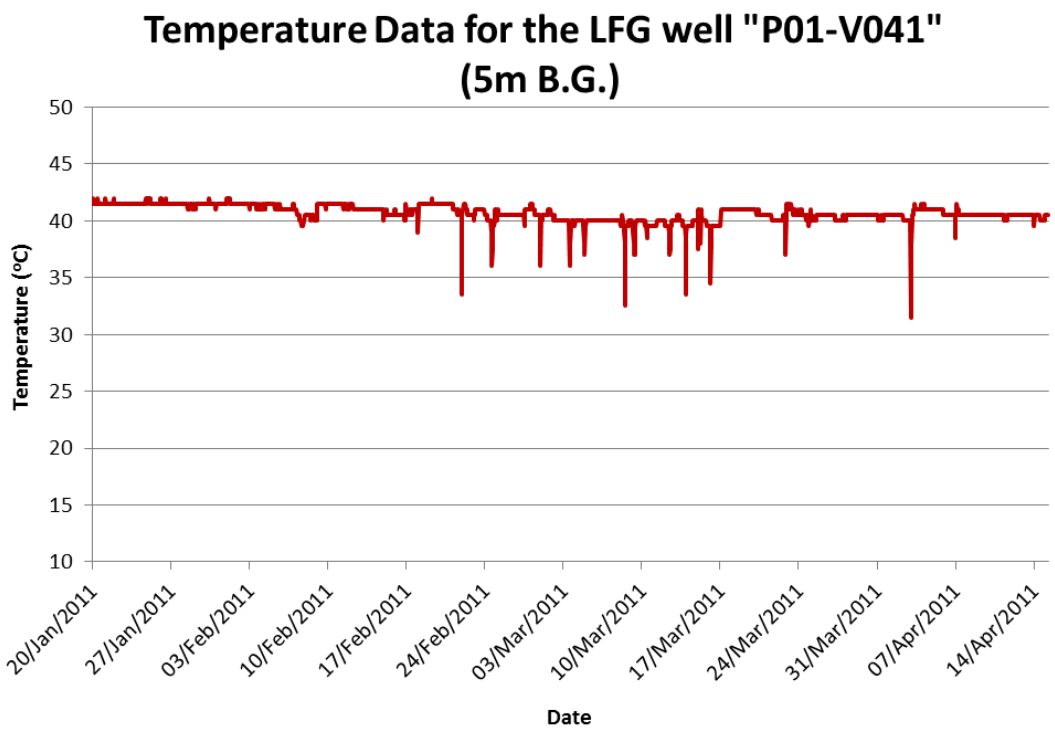

Example of Faulty Temperature Readings at LFG well "P01-V031" Due to the LFG Collection System Operational Issues
Temperature (°C)
40
38
36
34
32
30
28
26
24
22
20
10m B.G.
5m B.G.
17/Apr/2011
22/Apr/2011
27/Apr/2011
02/May/2011
07/May/2011
12/May/2011
17/May/2011
22/May/2011
27/May/2011
01/Jun/2011
06/Jun/2011
Date

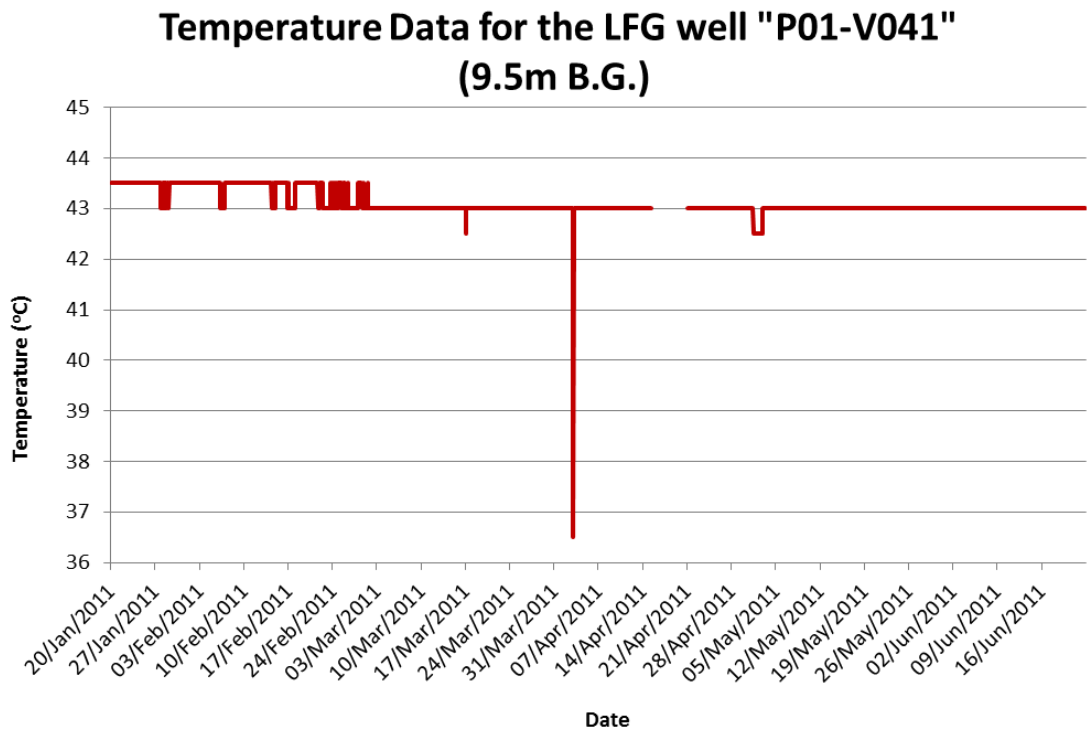

Temperature Data for the LFG well "P01-V034"
(5m B.G.)
Temperature (°C)
50
45
40
35
30
25
20
15
10
5
0
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
14/Jul/2011
21/Jul/2011
28/Jul/2011
04/Aug/2011
11/Aug/2011
18/Aug/2011
Date

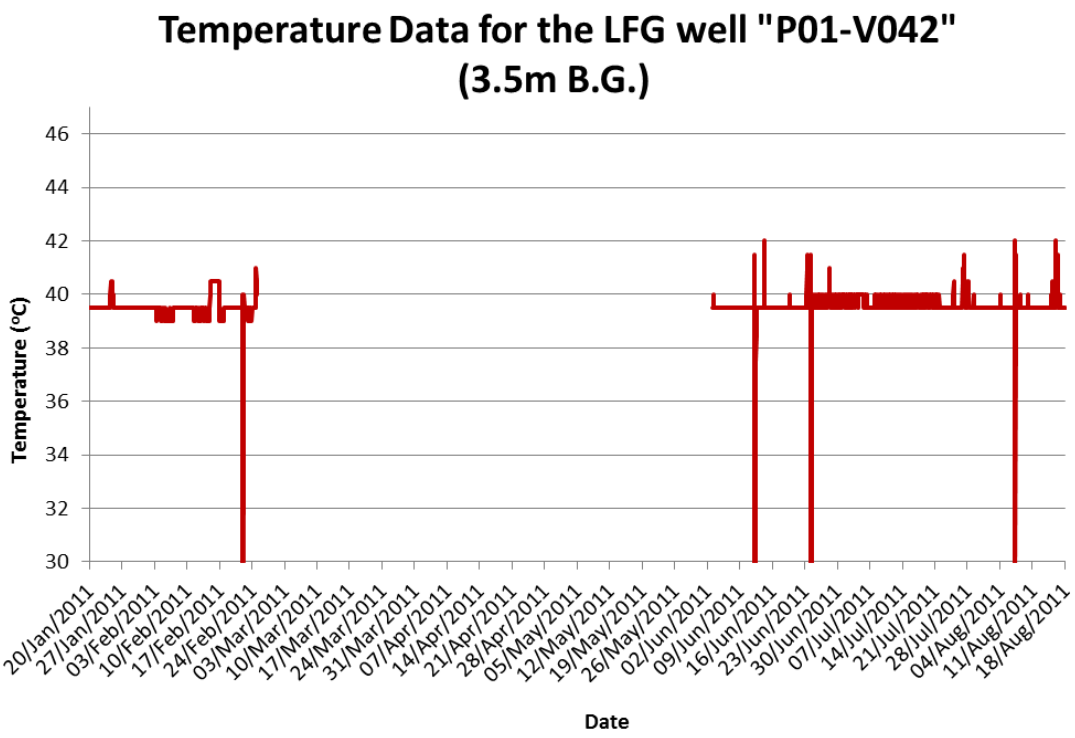

Temperature Data for the LFG well "P01-V034"
(10m B.G.)
Temperature (°C)
60
58
56
54
52
50
48
46
44
42
40
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
14/Jul/2011
21/Jul/2011
28/Jul/2011
04/Aug/2011
11/Aug/2011
18/Aug/2011
Date

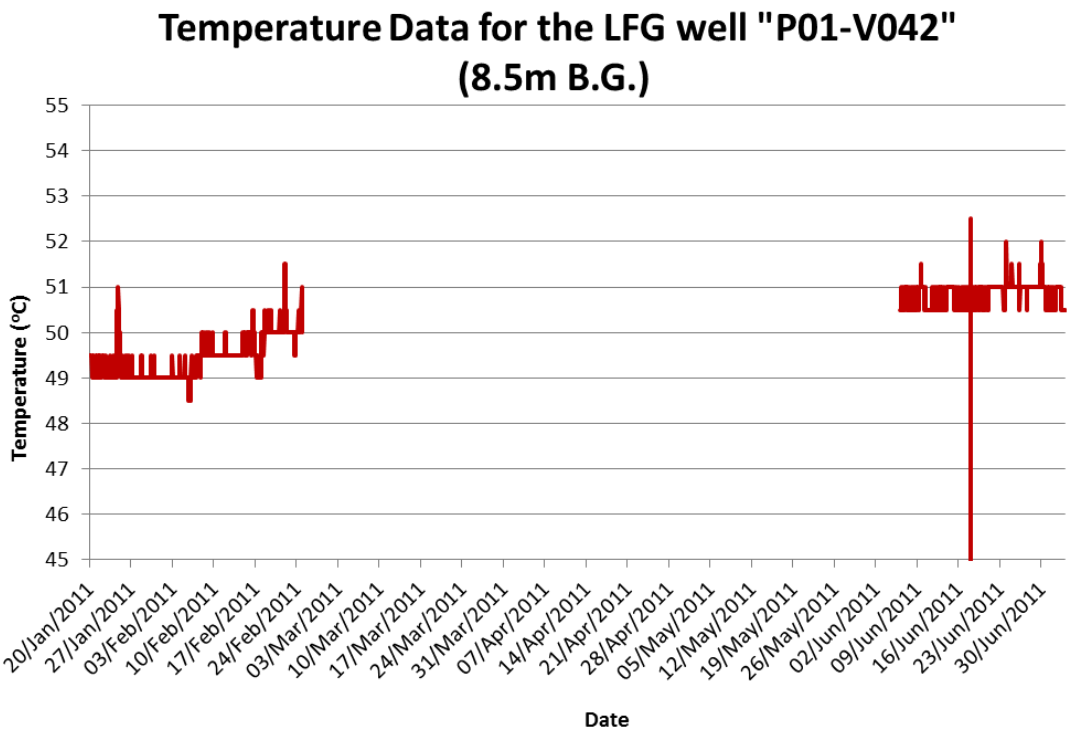

Temperature Data for the LFG well "P01-V036"
(4.5m B.G.)
Temperature (ºC)
46
44
42
40
38
36
34
32
30
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
Date


Temperature Data for the LFG well "P01-V036"
(9.5m B.G.)
Temperature (ºC)
50
49
48
47
46
45
44
43
42
41
40
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
Date


Temperature Data for the LFG well "P01-V041"
(5m B.G.)
Temperature (°C)
50
45
40
35
30
25
20
15
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
Date


Temperature Data for the LFG well "P01-V041"
(9.5m B.G.)
Temperature (°C)
45
44
43
42
41
40
39
38
37
36
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
Date


Temperature Data for the LFG well "P01-V042"
(3.5m B.G.)
Temperature (°C)
46
44
42
40
38
36
34
32
30
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
14/Jul/2011
21/Jul/2011
28/Jul/2011
04/Aug/2011
11/Aug/2011
18/Aug/2011
Date


Temperature Data for the LFG well "P01-V042"
(8.5m B.G.)
Temperature (°C)
55
54
53
52
51
50
49
48
47
46
45
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
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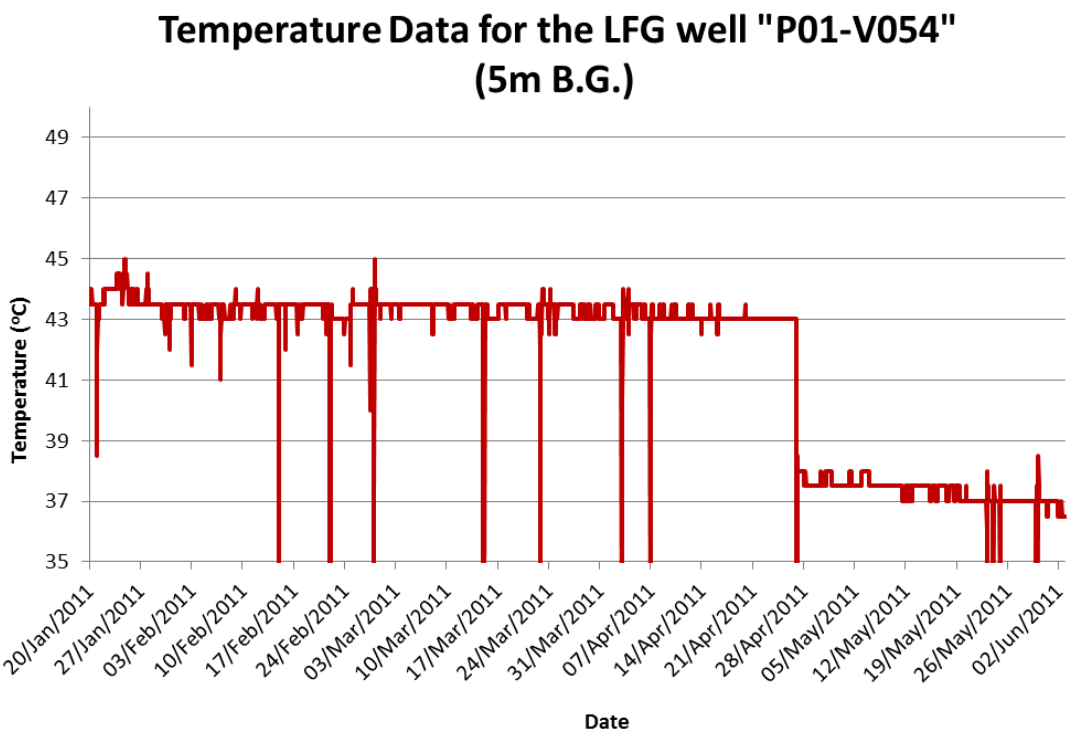
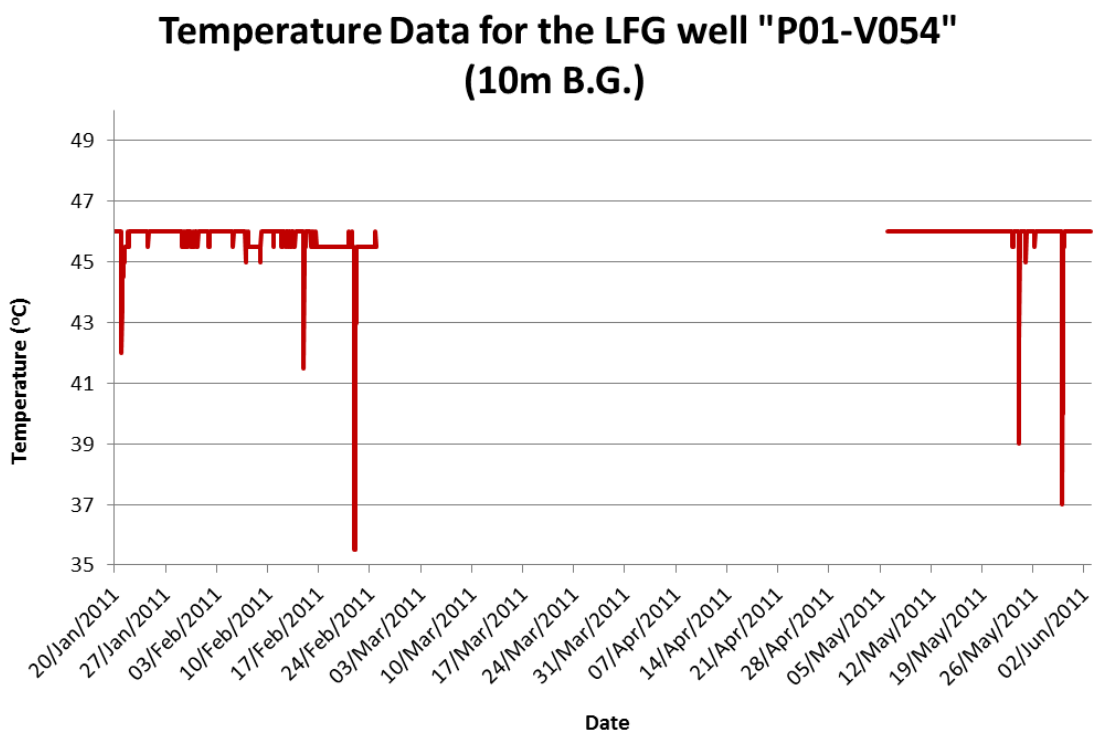
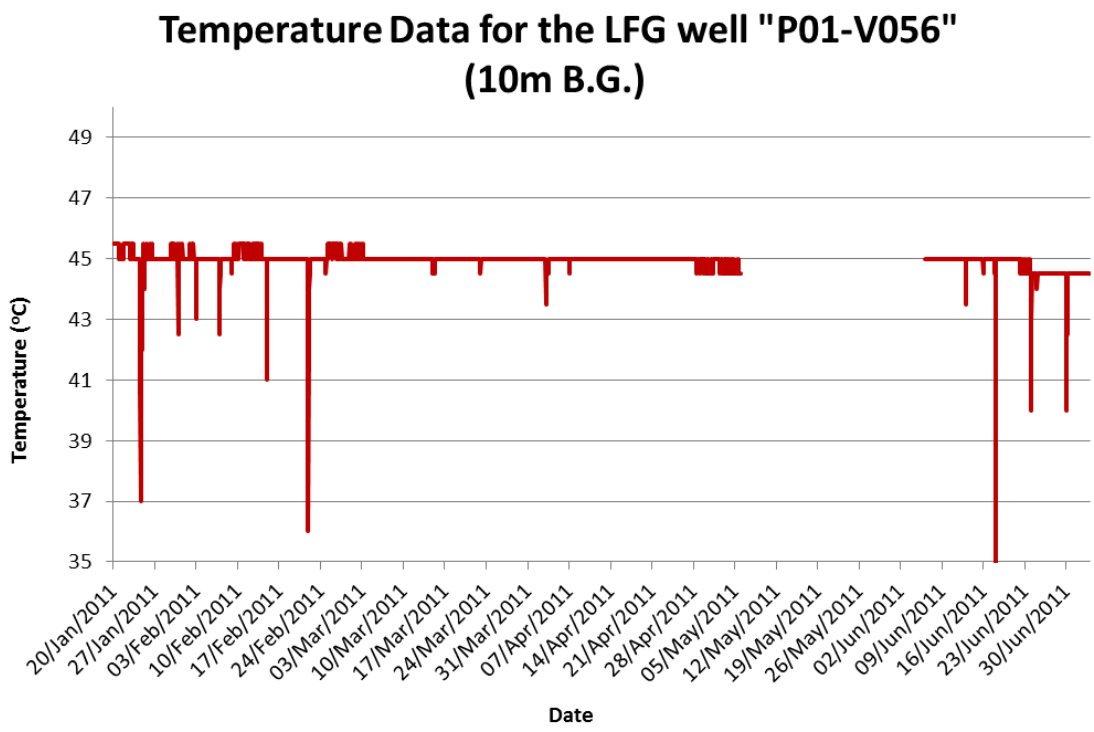
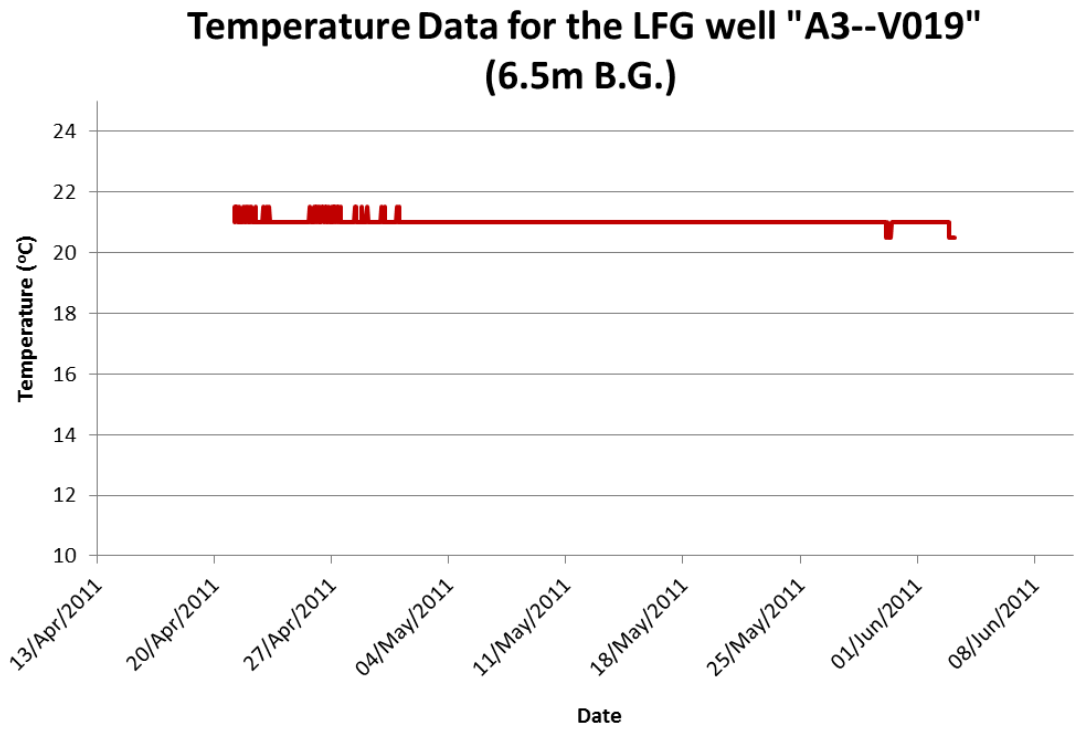
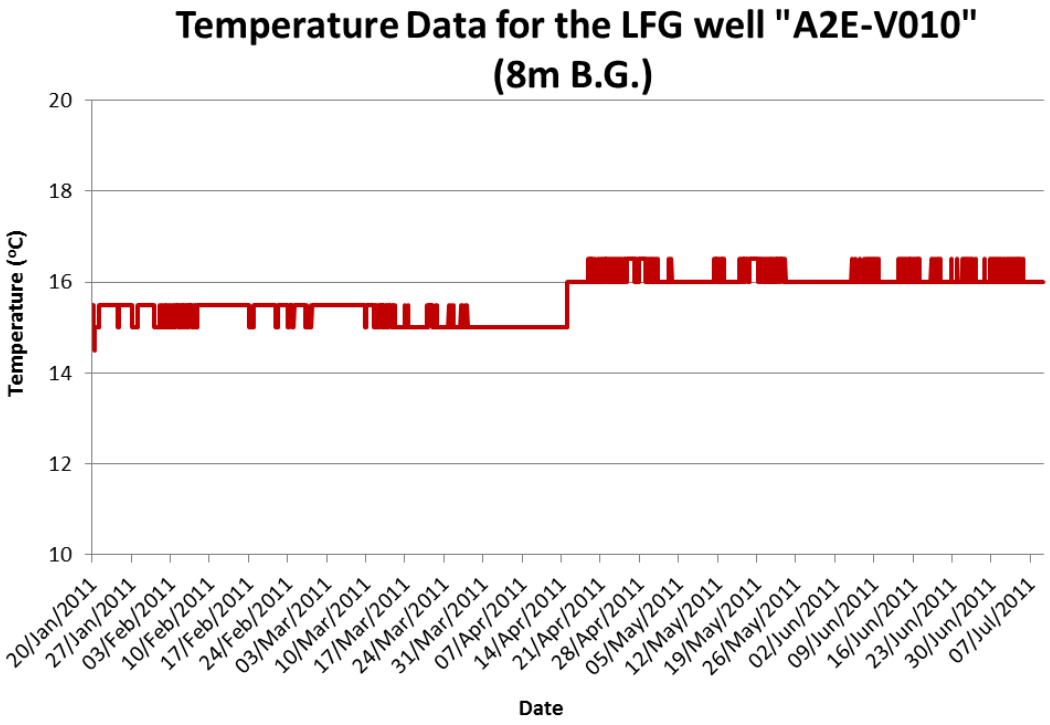
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
Date

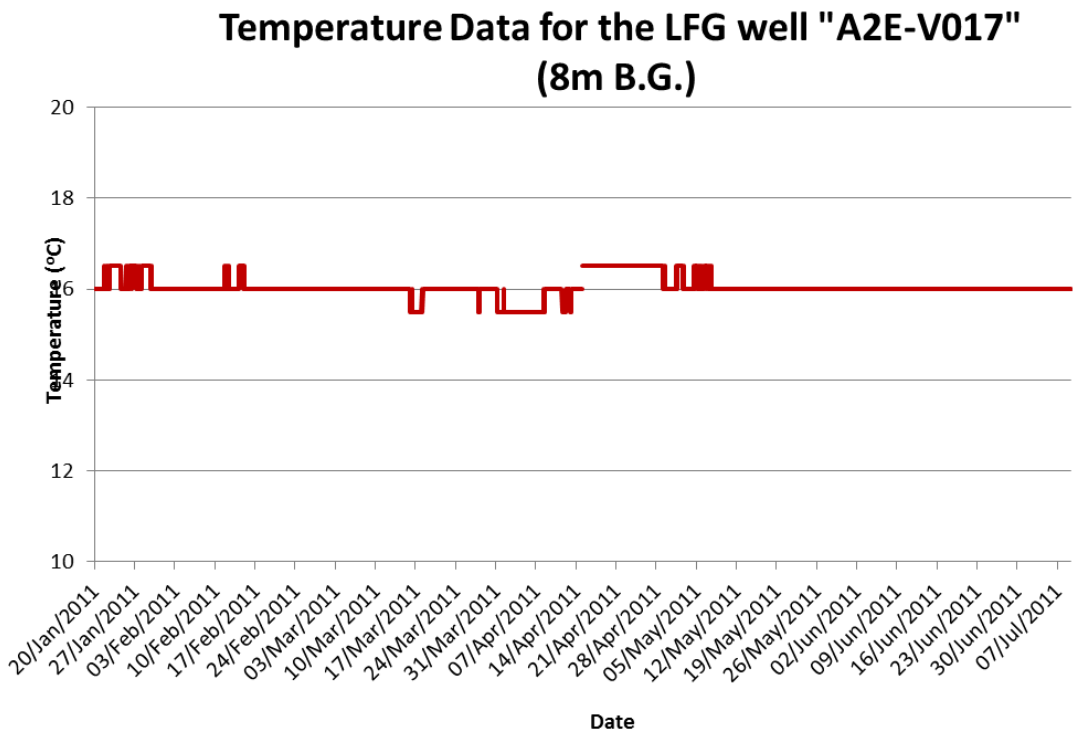

Temperature Data for the LFG well "P01-V054"
(5m B.G.)
Temperature (ºC)
49
47
45
43
41
39
37
35
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
Date

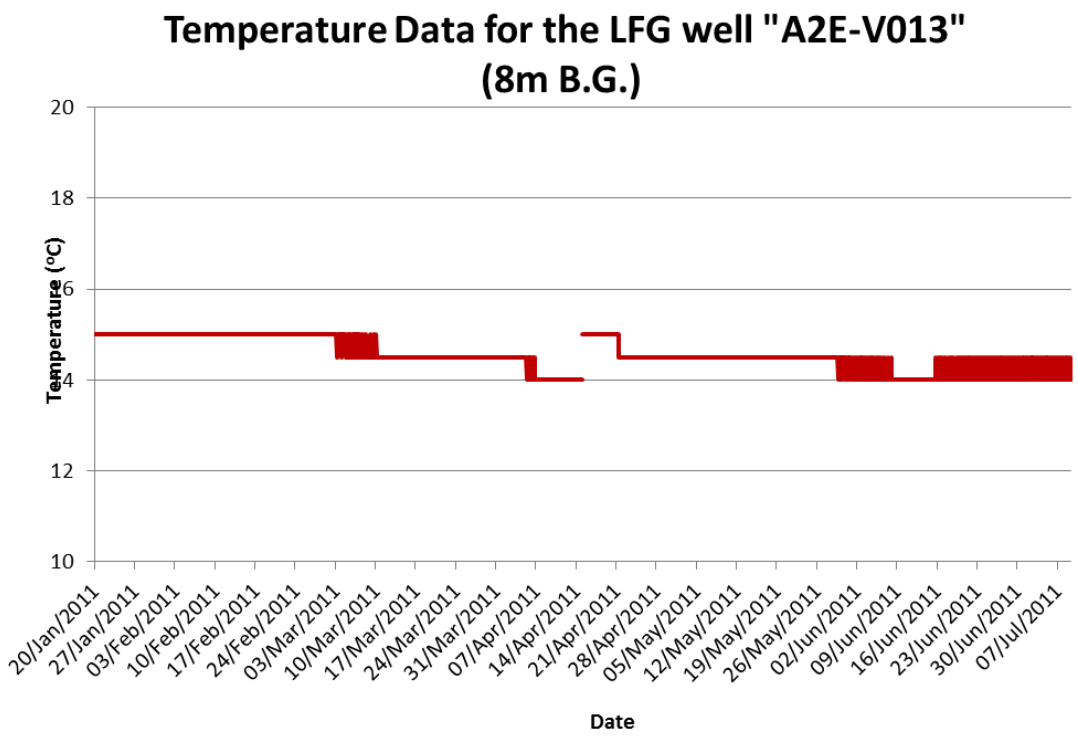

Temperature Data for the LFG well "P01-V054"
(10m B.G.)
Temperature (ºC)
49
47
45
43
41
39
37
35
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
Date

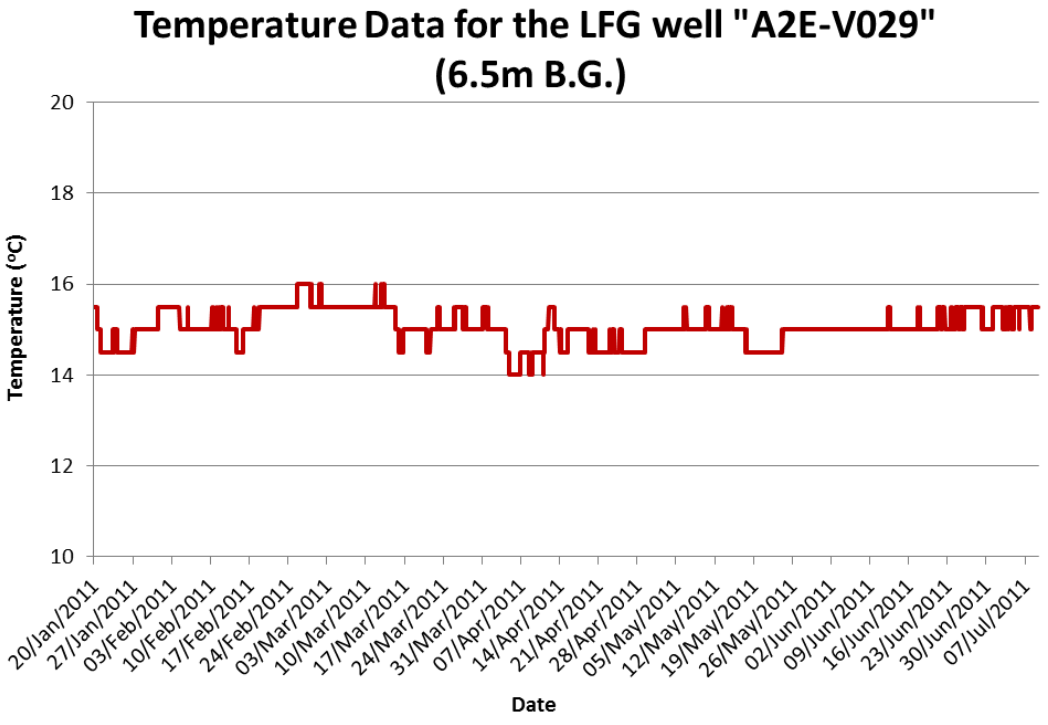

Temperature Data for the LFG well "P01-V056"
(10m B.G.)
Temperature (°C)
49
47
45
43
41
39
37
35
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
Date

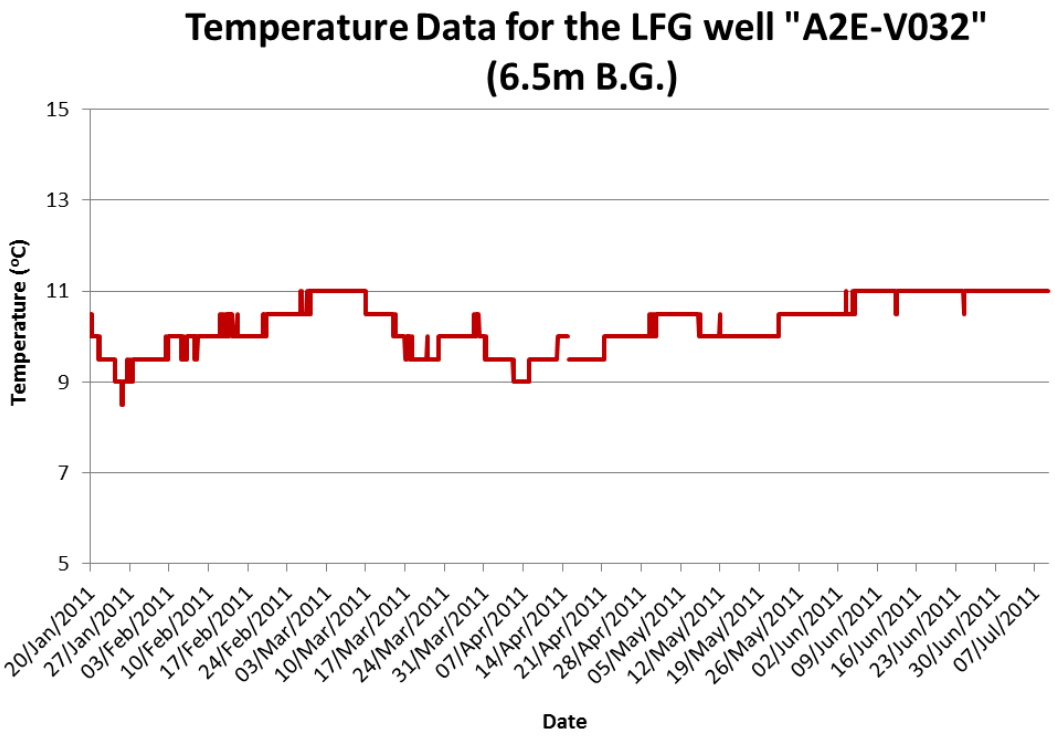

Temperature Data for the LFG well "A3--V019"
(6.5m B.G.)
Temperature (°C)
24
22
20
18
16
14
12
10
13/Apr/2011
20/Apr/2011
27/Apr/2011
04/May/2011
11/May/2011
18/May/2011
25/May/2011
01/Jun/2011
08/Jun/2011
Date

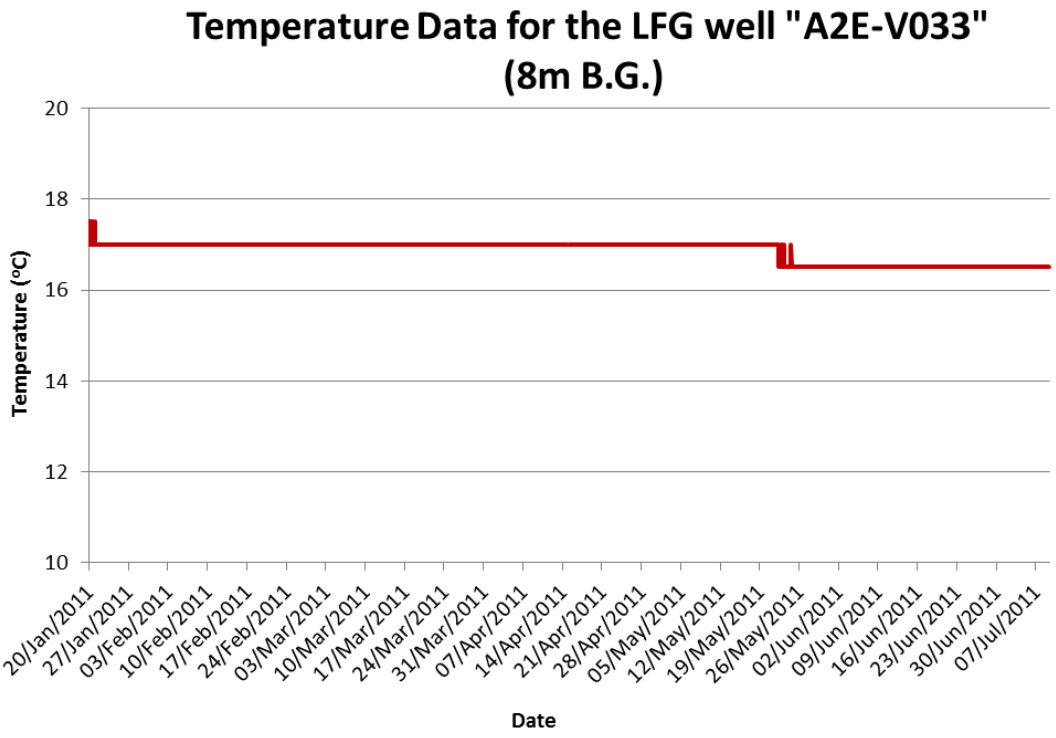

Temperature Data for the LFG well "A2E-V010"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

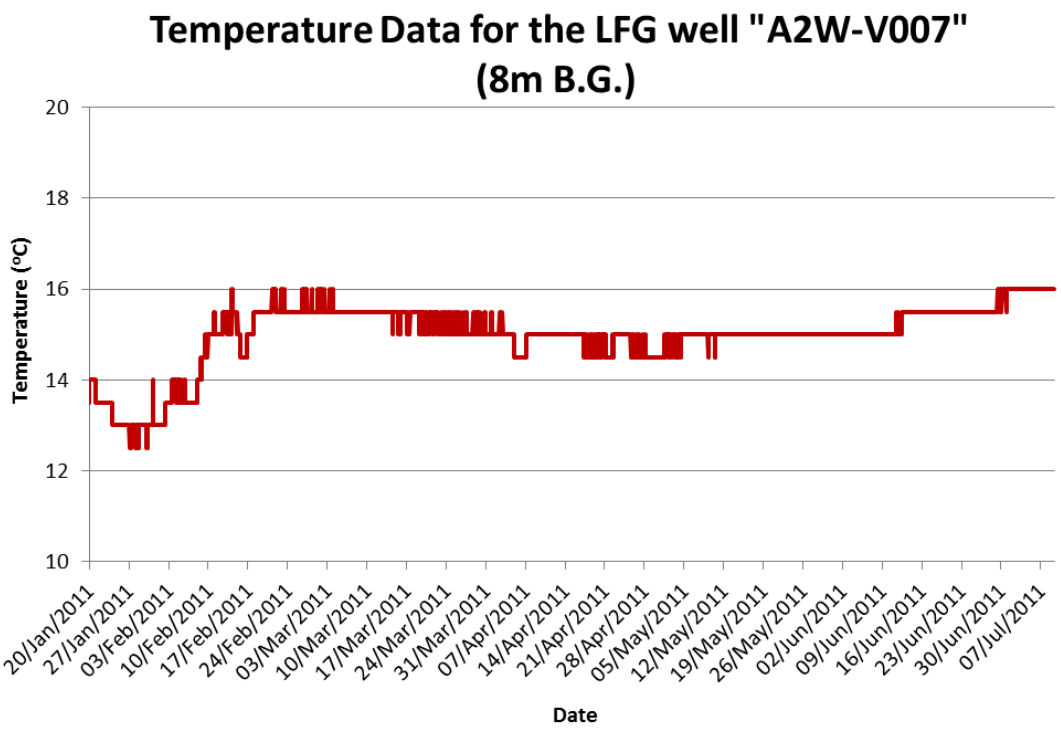

Temperature Data for the LFG well "A2E-V017"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

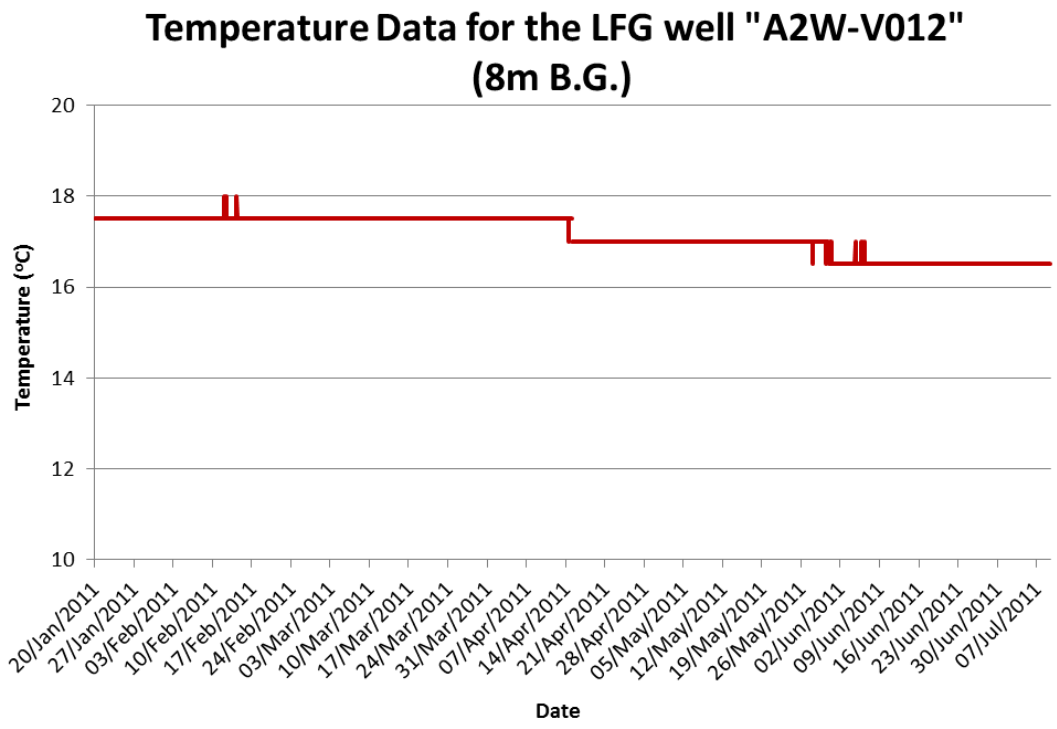

Temperature Data for the LFG well "A2E-V013"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

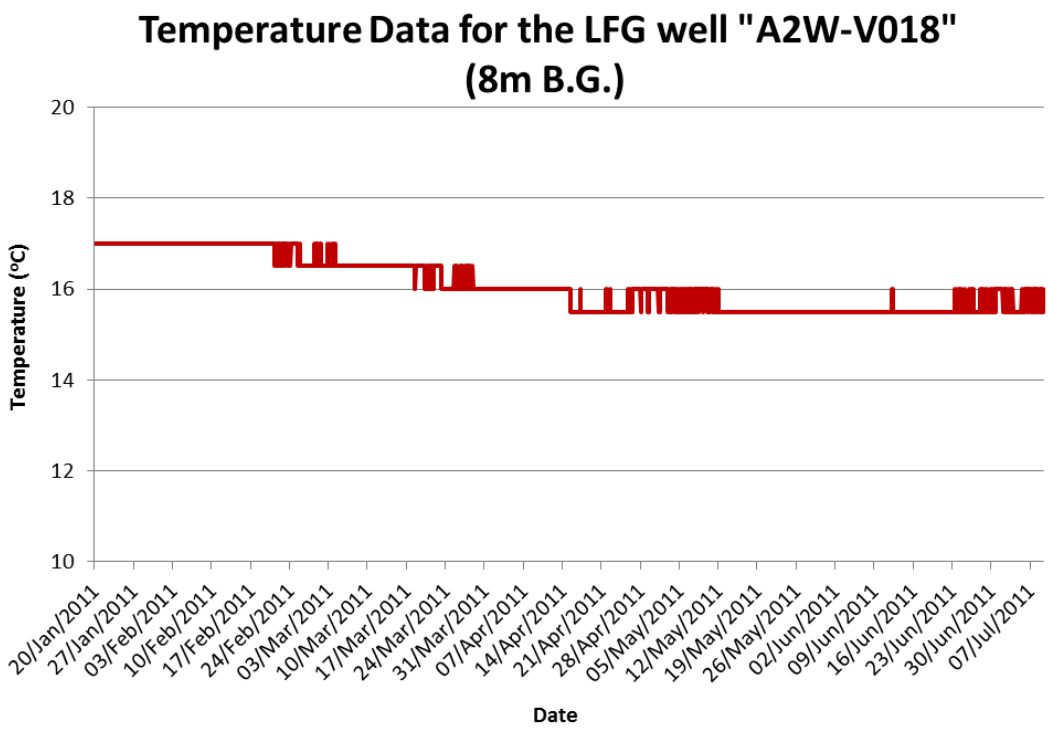

Temperature Data for the LFG well "A2E-V029"
(6.5m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

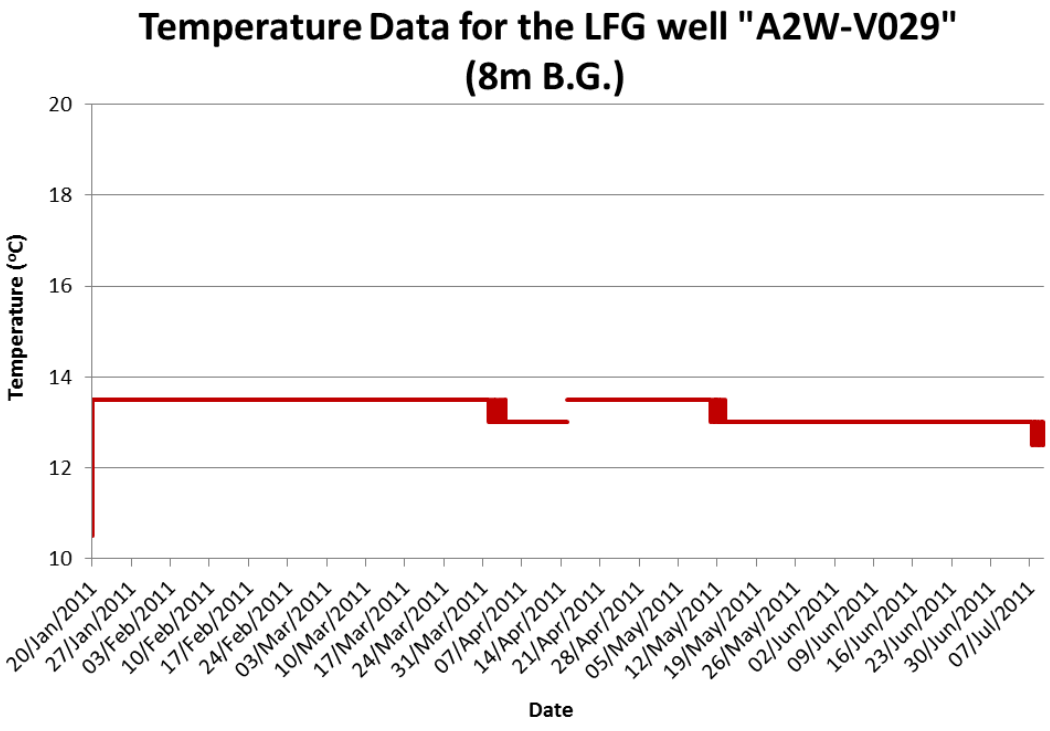

Temperature Data for the LFG well "A2E-V032"
(6.5m B.G.)
Temperature (°C)
15
13
11
9
7
5
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

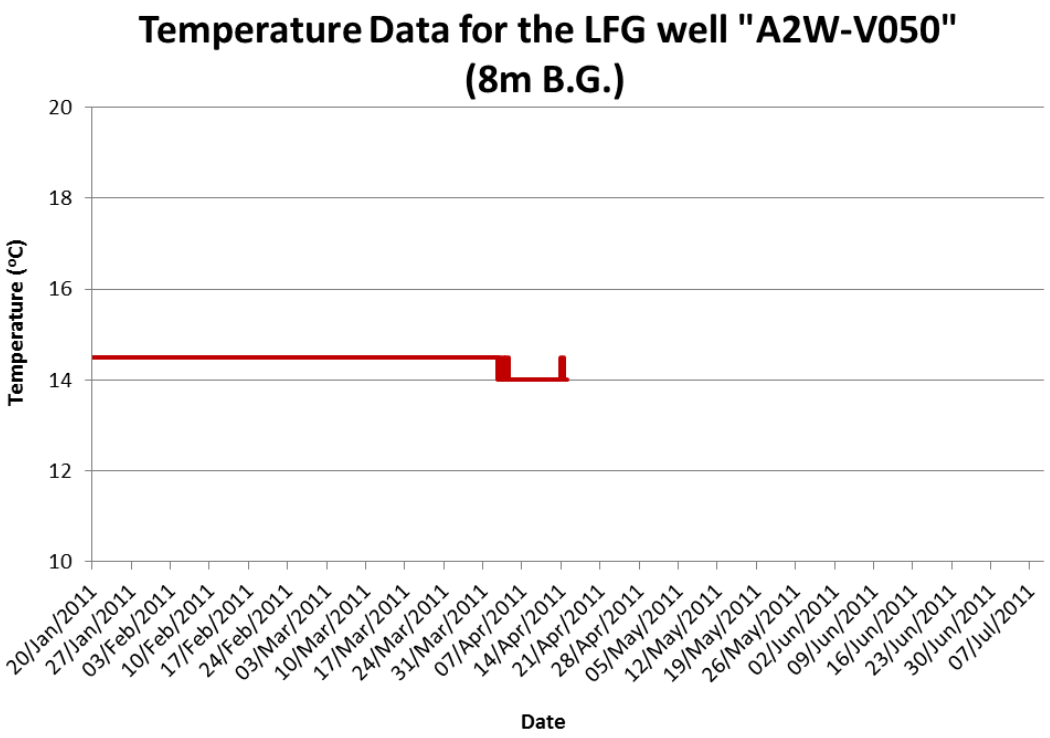

Temperature Data for the LFG well "A2E-V033"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

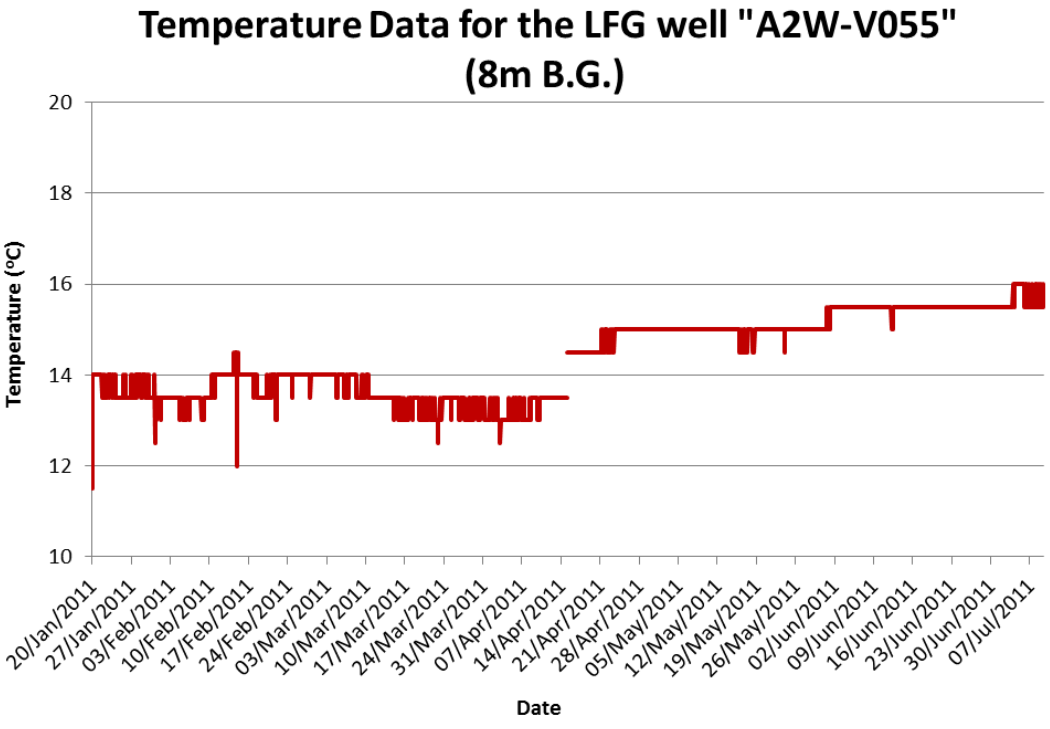

Temperature Data for the LFG well "A2W-V007"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

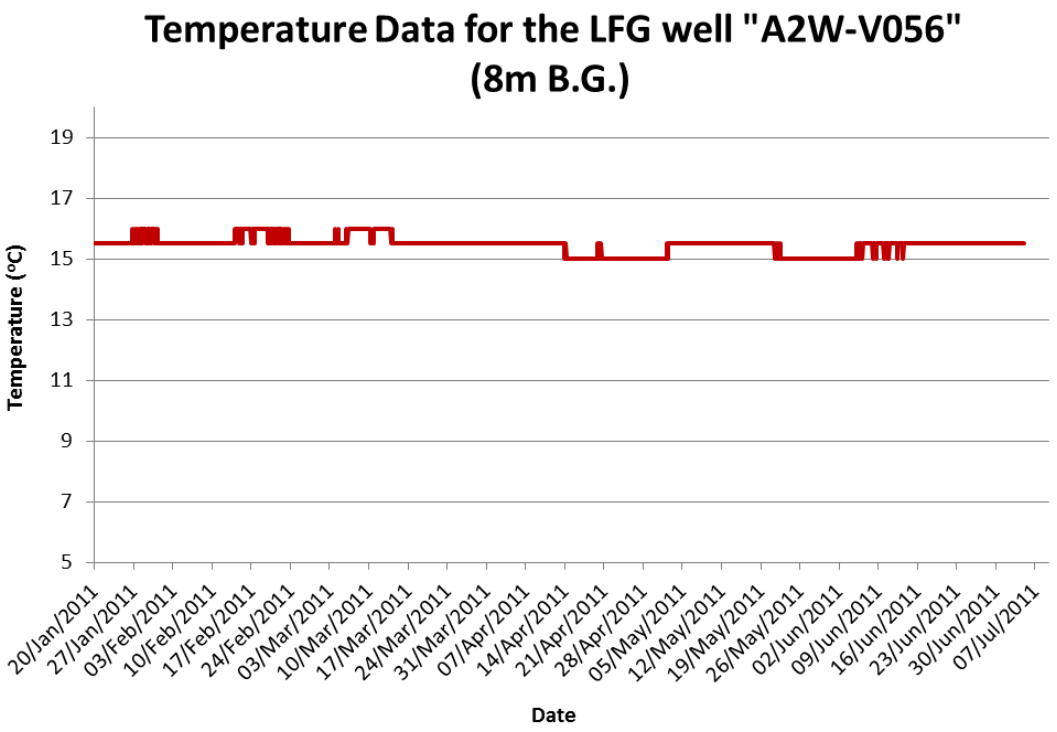

Temperature Data for the LFG well "A2W-V012"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

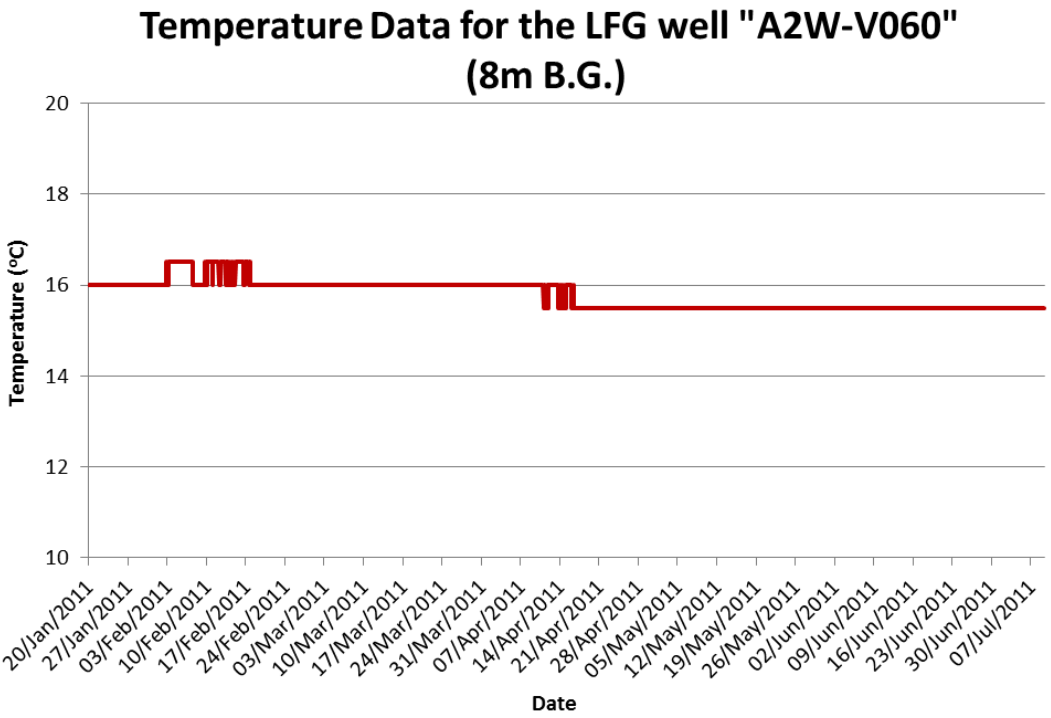

Temperature Data for the LFG well "A2W-V018"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

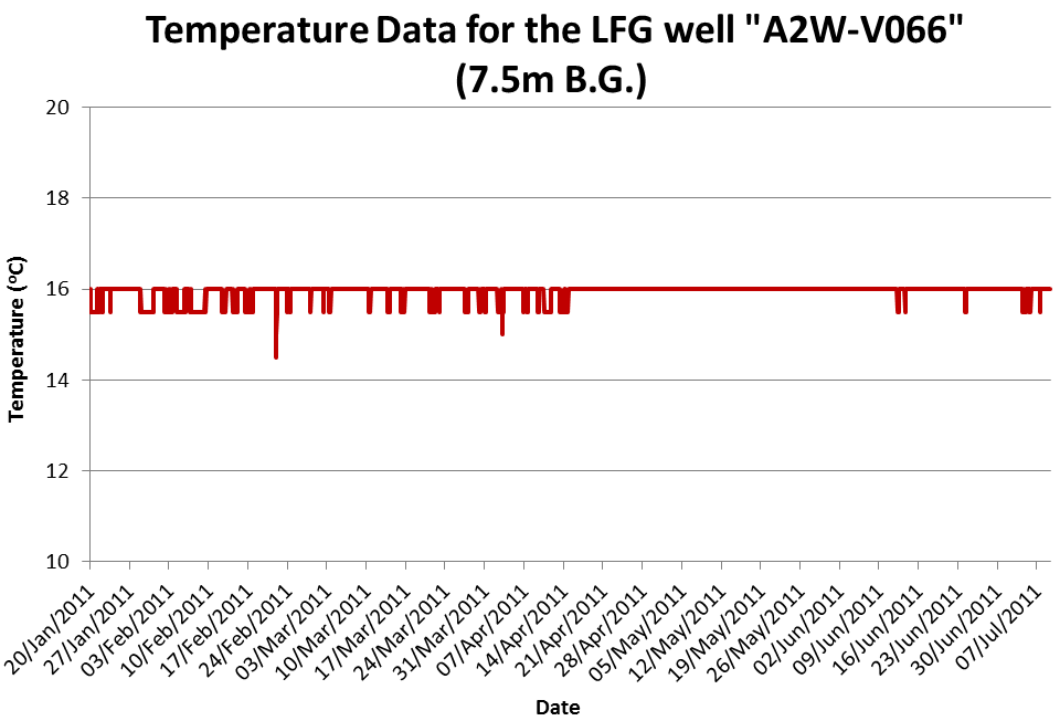

Temperature Data for the LFG well "A2W-V029"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date


Temperature Data for the LFG well "A2W-V050"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date


Temperature Data for the LFG well "A2W-V055"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

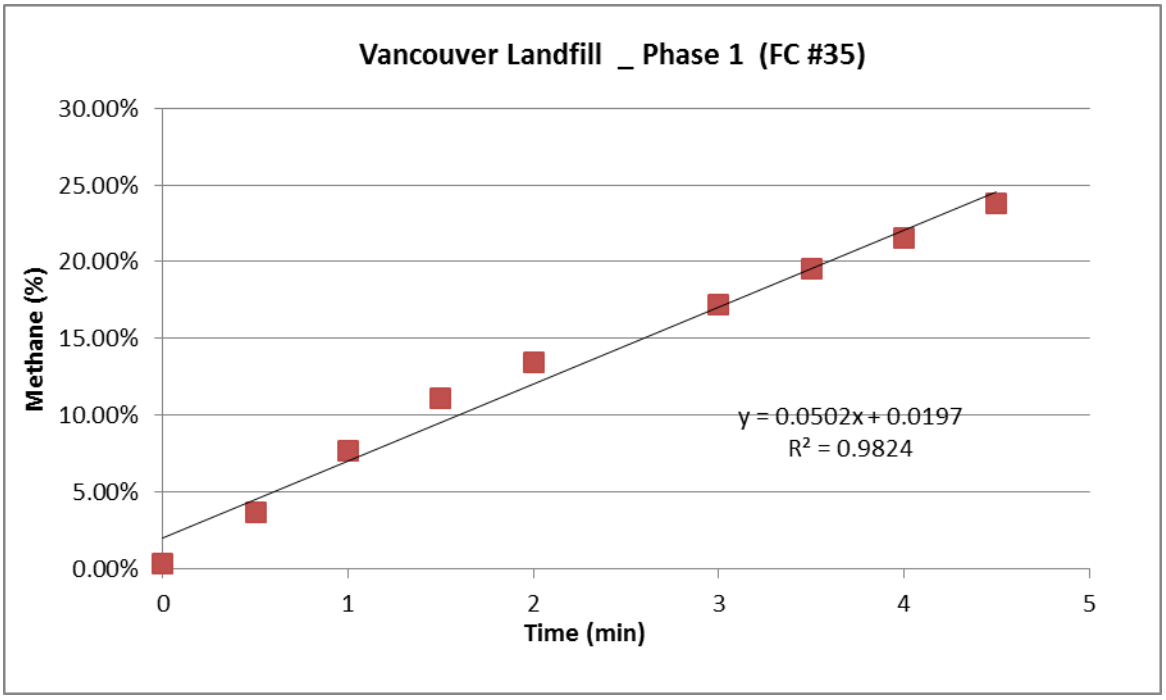

Temperature Data for the LFG well "A2W-V056"
(8m B.G.)
Temperature (°C)
19
17
15
13
11
9
7
5
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

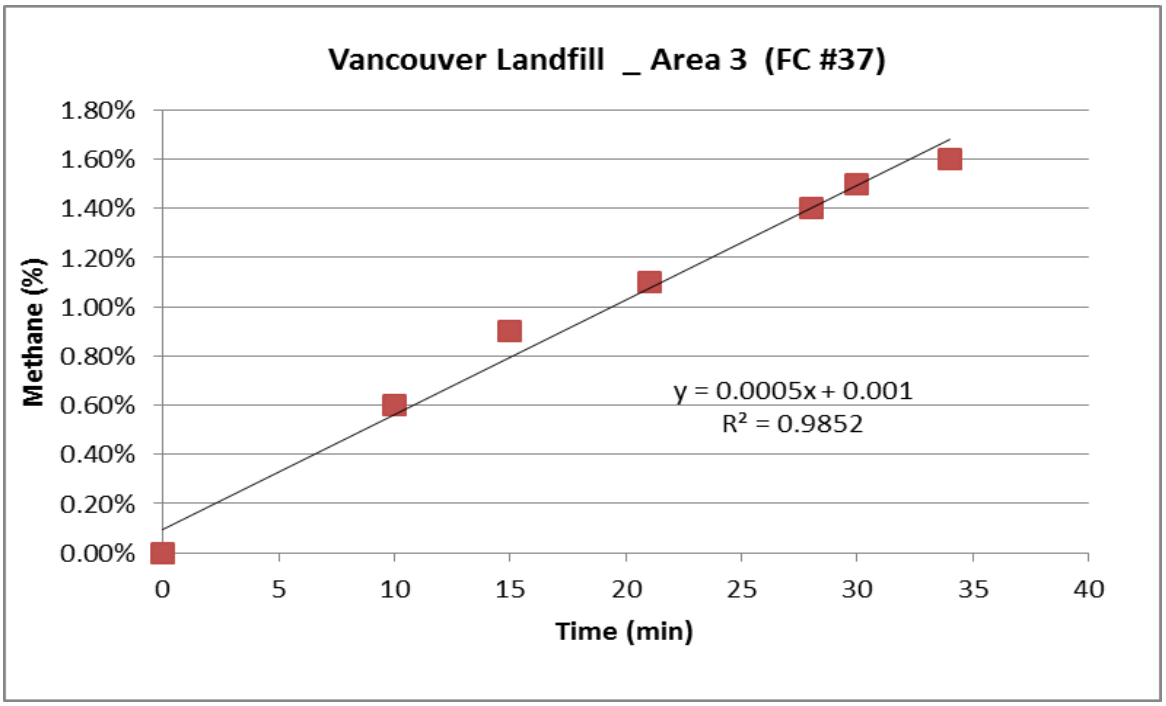

Temperature Data for the LFG well "A2W-V060"
(8m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

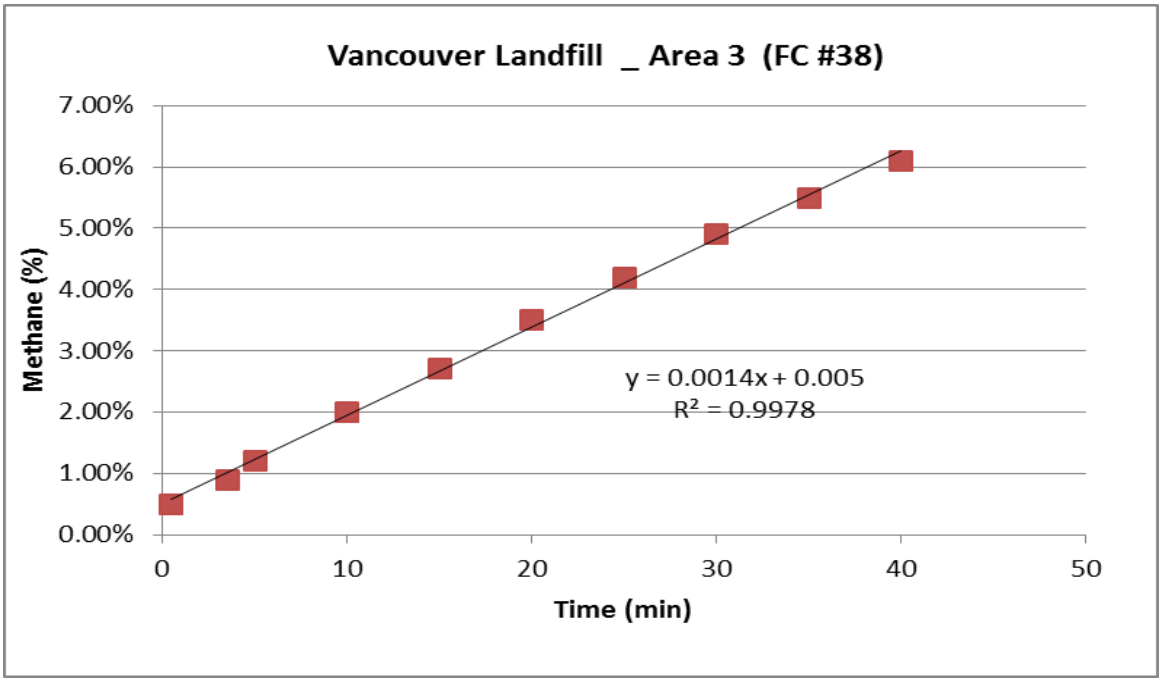

Temperature Data for the LFG well "A2W-V066"
(7.5m B.G.)
Temperature (°C)
20
18
16
14
12
10
20/Jan/2011
27/Jan/2011
03/Feb/2011
10/Feb/2011
17/Feb/2011
24/Feb/2011
03/Mar/2011
10/Mar/2011
17/Mar/2011
24/Mar/2011
31/Mar/2011
07/Apr/2011
14/Apr/2011
21/Apr/2011
28/Apr/2011
05/May/2011
12/May/2011
19/May/2011
26/May/2011
02/Jun/2011
09/Jun/2011
16/Jun/2011
23/Jun/2011
30/Jun/2011
07/Jul/2011
Date

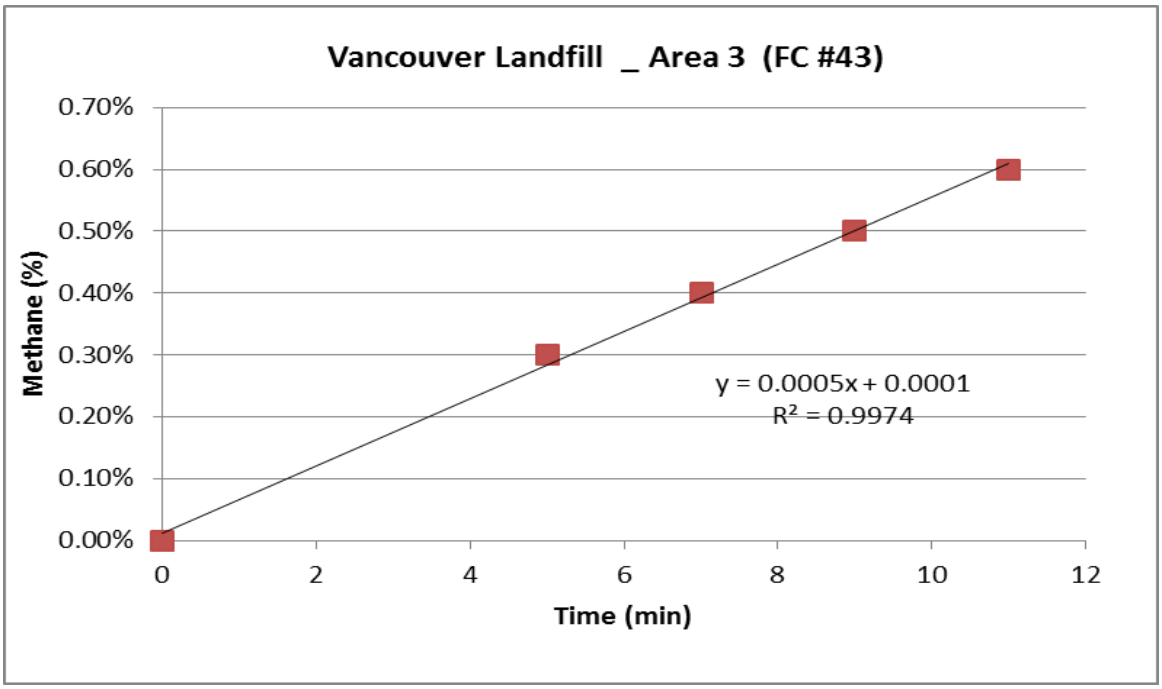
Appendix D LFG Emission Investigations

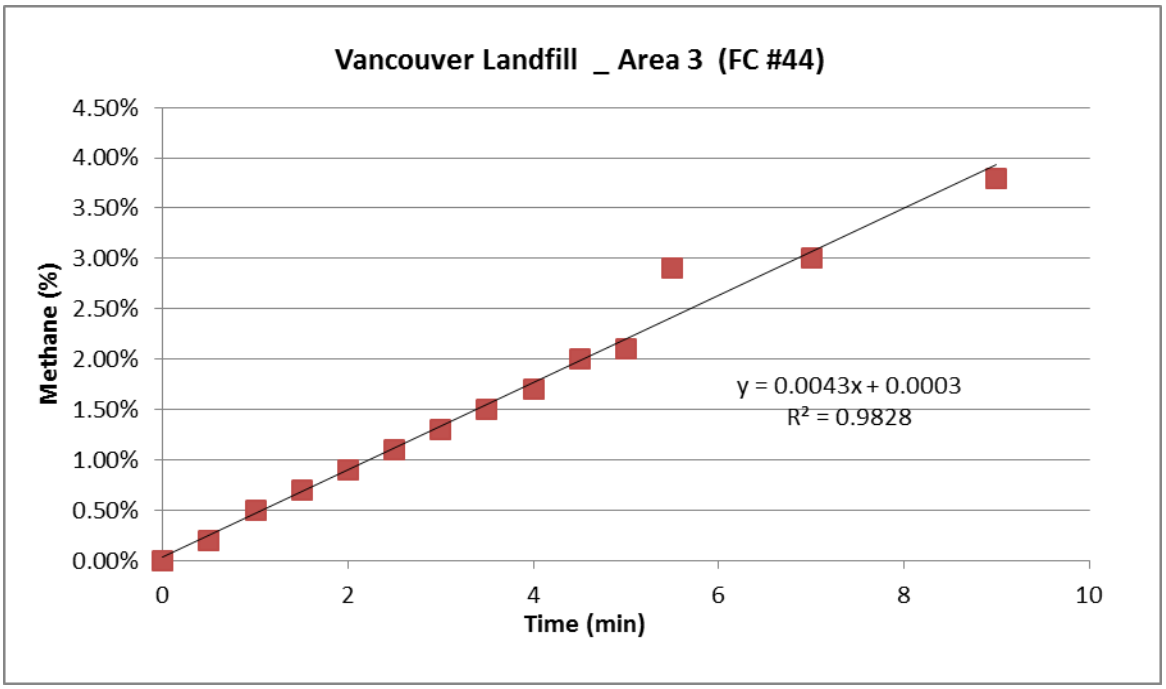
D.1 Flux Chamber Survey Data - Vancouver Landfill (June - July 2012)

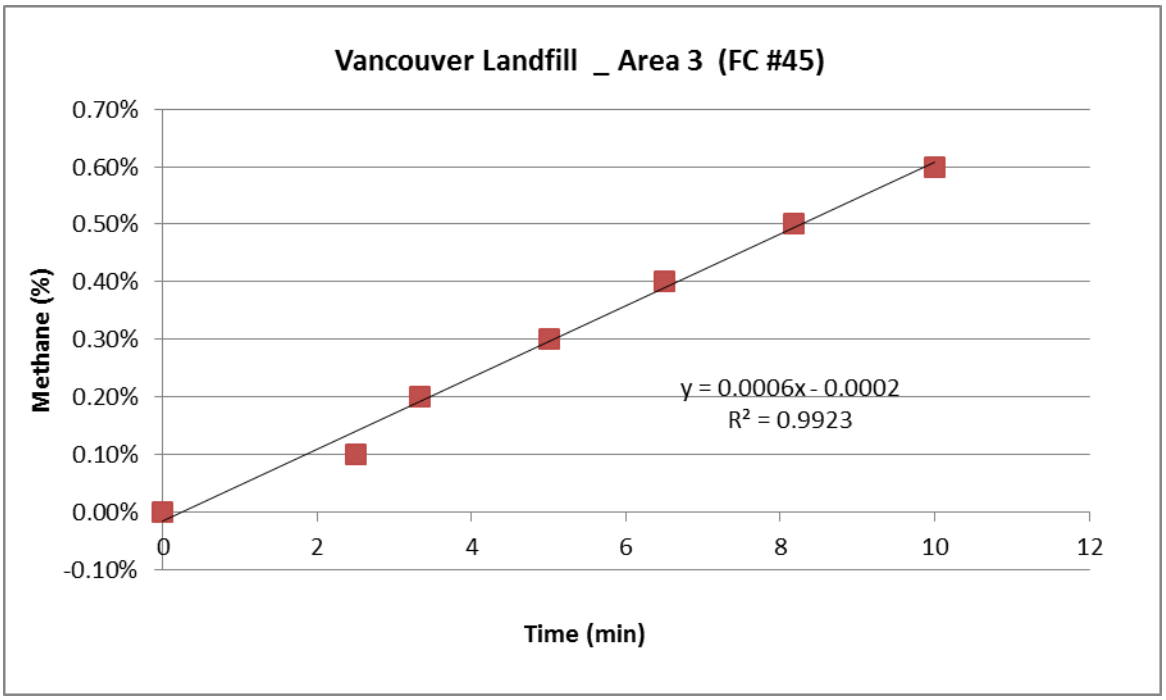


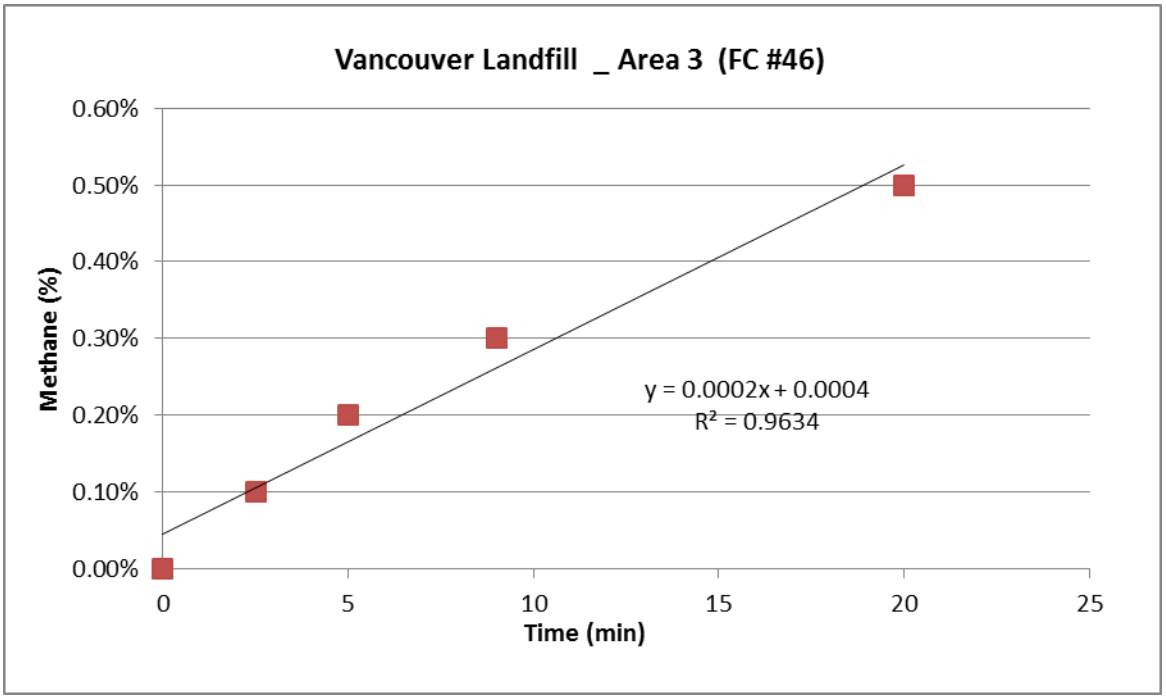


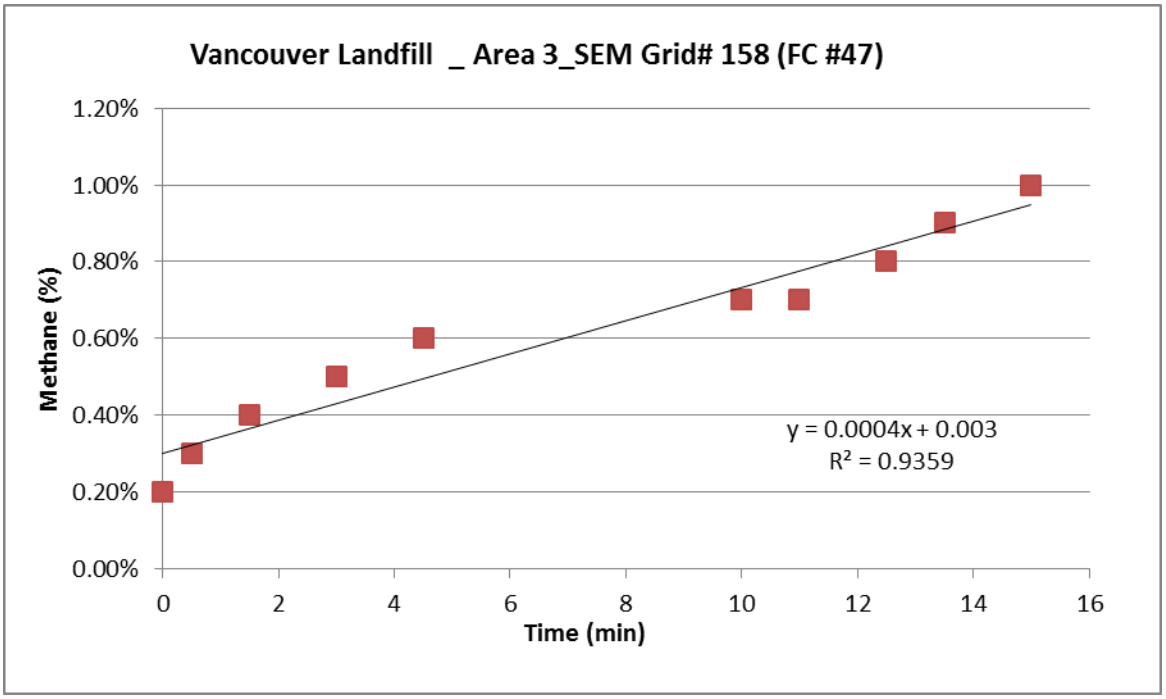

Vancouver Landfill _ Area 3 (FC #38)
Methane (%)
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
0
10
20
30
40
50
Time (min)
y = 0.0014x + 0.005
R² = 0.9978

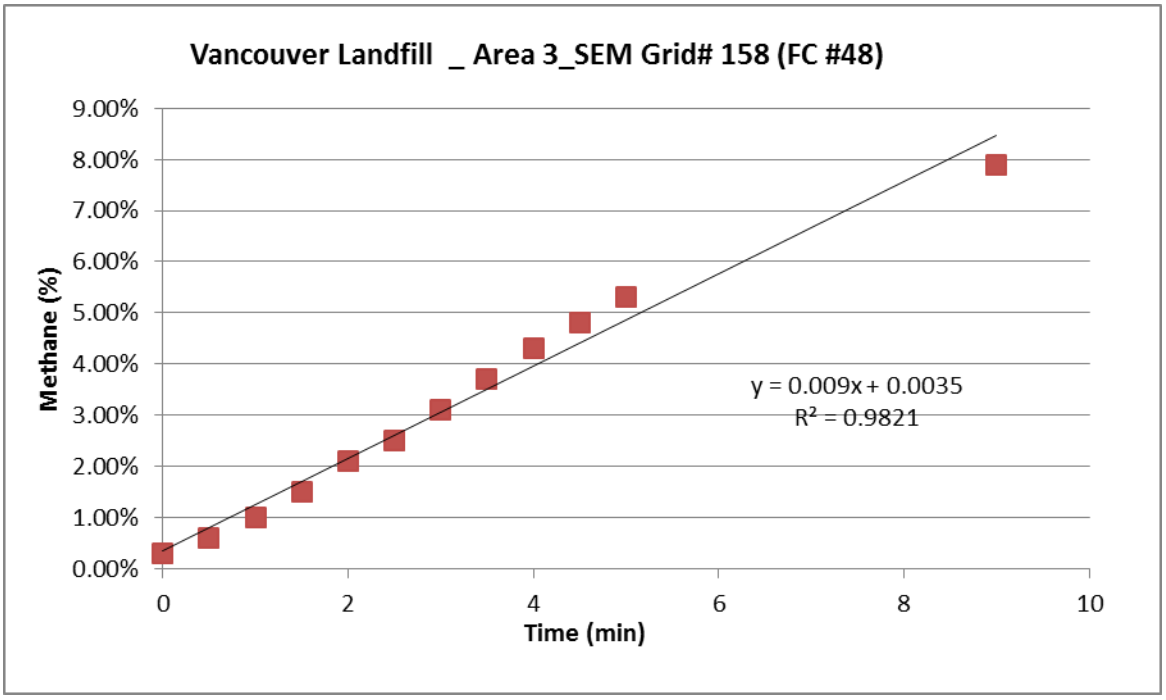

Vancouver Landfill _ Area 3 (FC #43)
Methane (%)
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
2
4
6
8
10
12
Time (min)
y = 0.0005x + 0.0001
R² = 0.9974

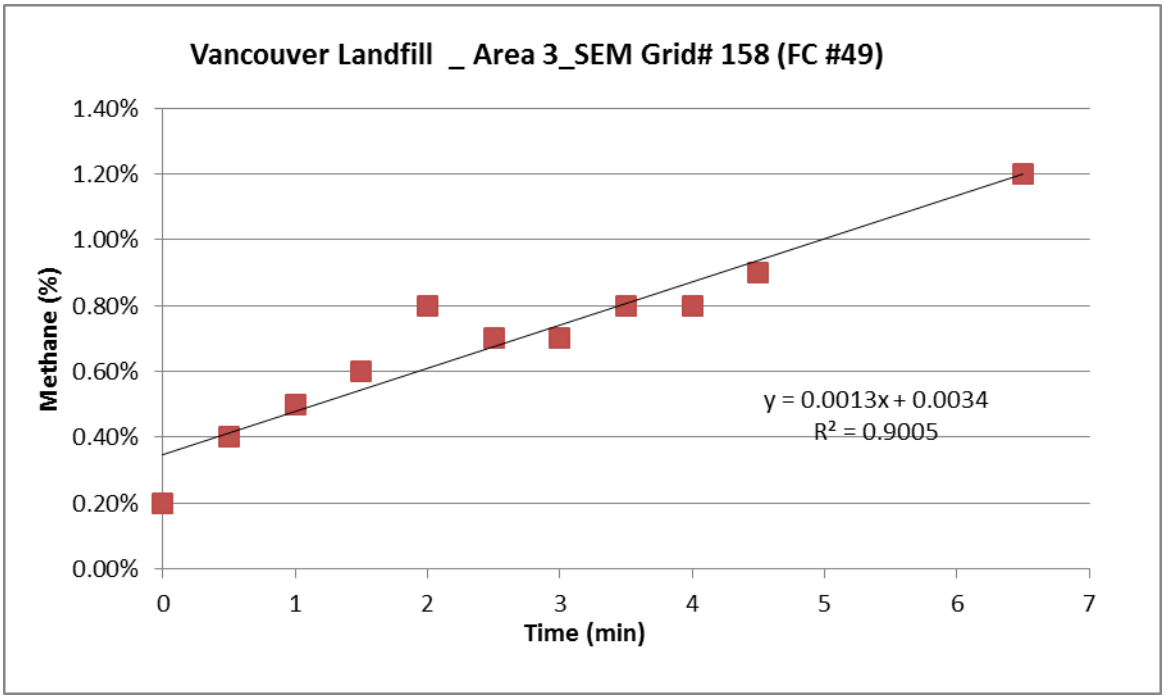

Vancouver Landfill _ Area 3 (FC #44)
Methane (%)
4.50%
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
2
4
6
8
10
Time (min)
y = 0.0043x + 0.0003
R² = 0.9828

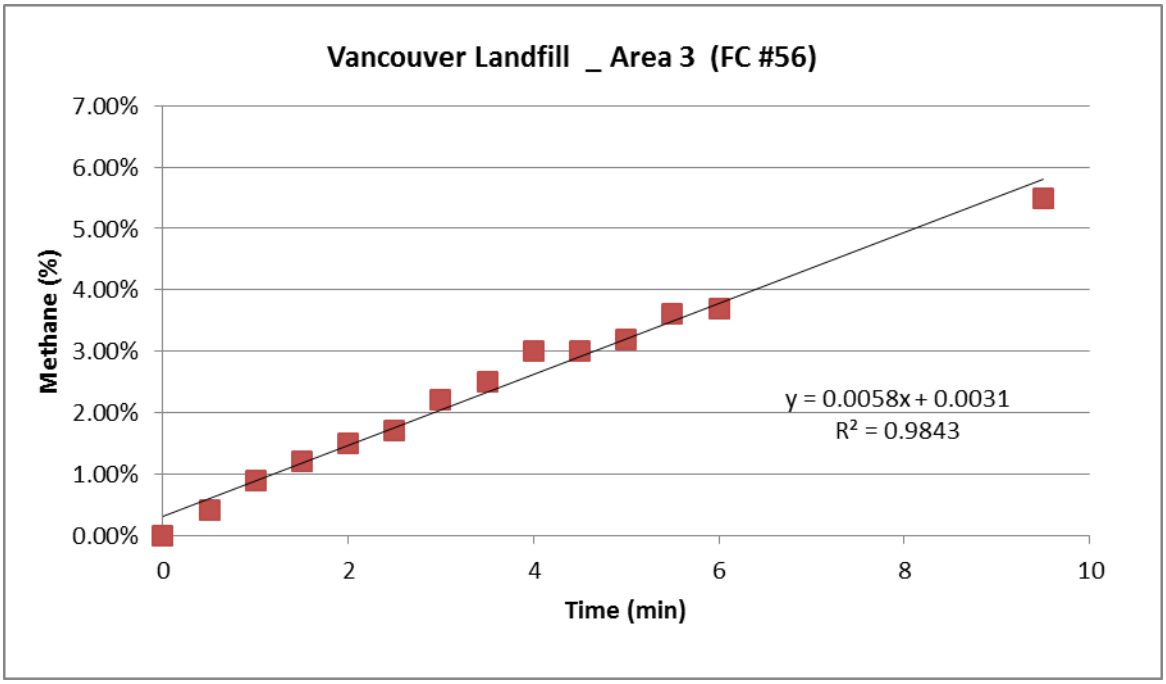

Vancouver Landfill _ Area 3 (FC #45)
Methane (%)
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
-0.10%
0
2
4
6
8
10
12
Time (min)
y = 0.0006x - 0.0002
R² = 0.9923

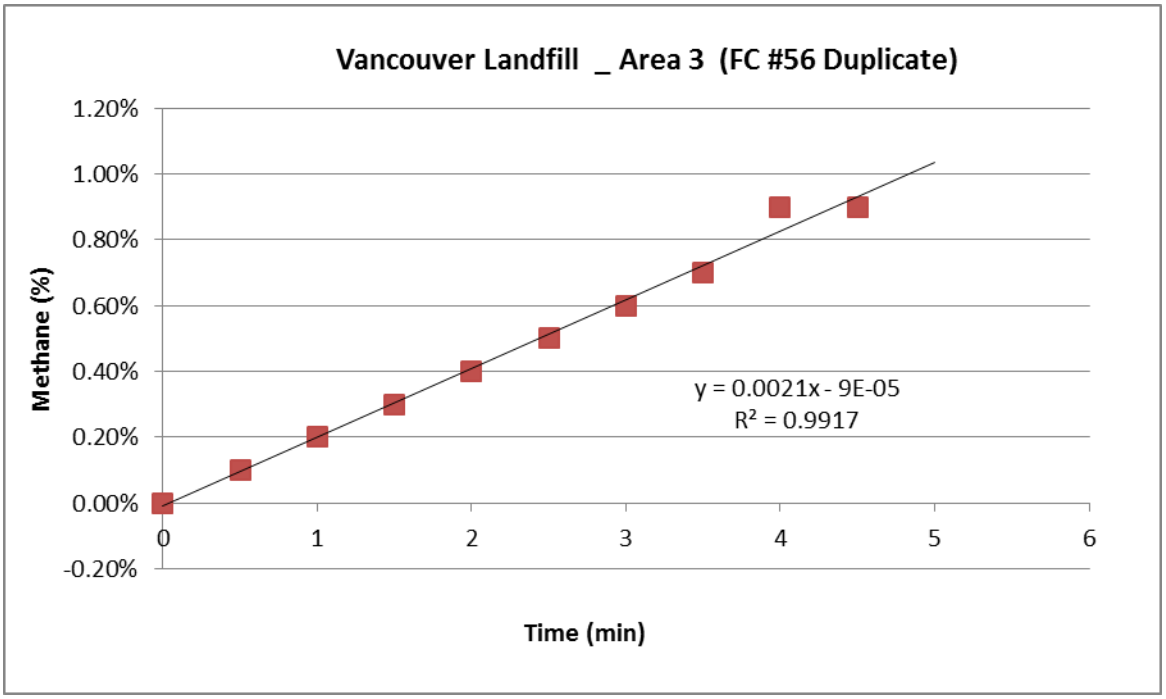

Vancouver Landfill _ Area 3 (FC #46)
Methane (%)
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
y = 0.0002x + 0.0004
R² = 0.9634
0
5
10
15
20
25
Time (min)

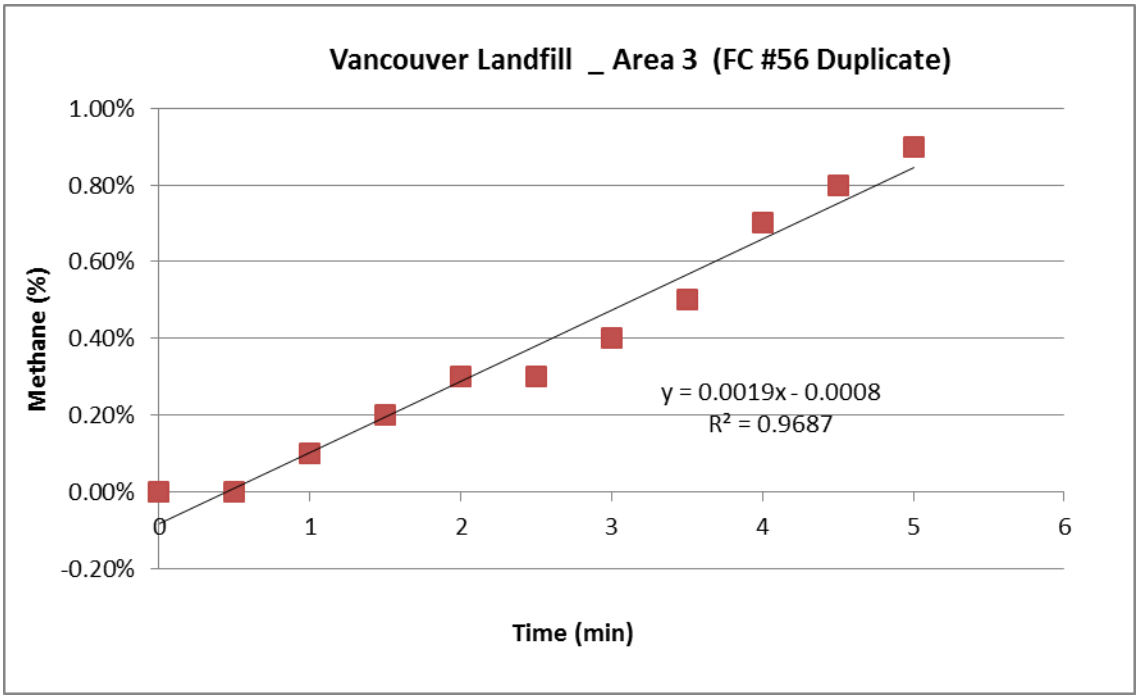

Vancouver Landfill _ Area 3_SEM Grid# 158 (FC #47)
Methane (%)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
y = 0.0004x + 0.003
R² = 0.9359
0
2
4
6
8
10
12
14
16
Time (min)

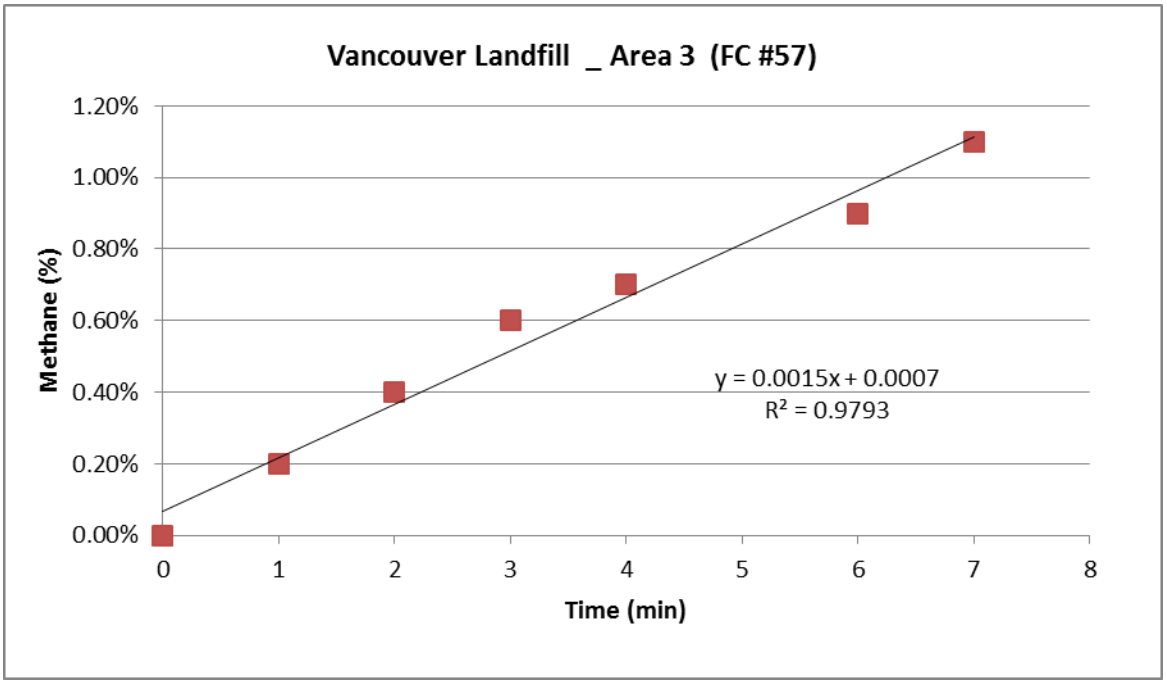

Vancouver Landfill _ Area 3_SEM Grid# 158 (FC #48)
9.00%
8.00%
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
Methane (%)
0
2
4
6
8
10
Time (min)
y = 0.009x + 0.0035
R² = 0.9821

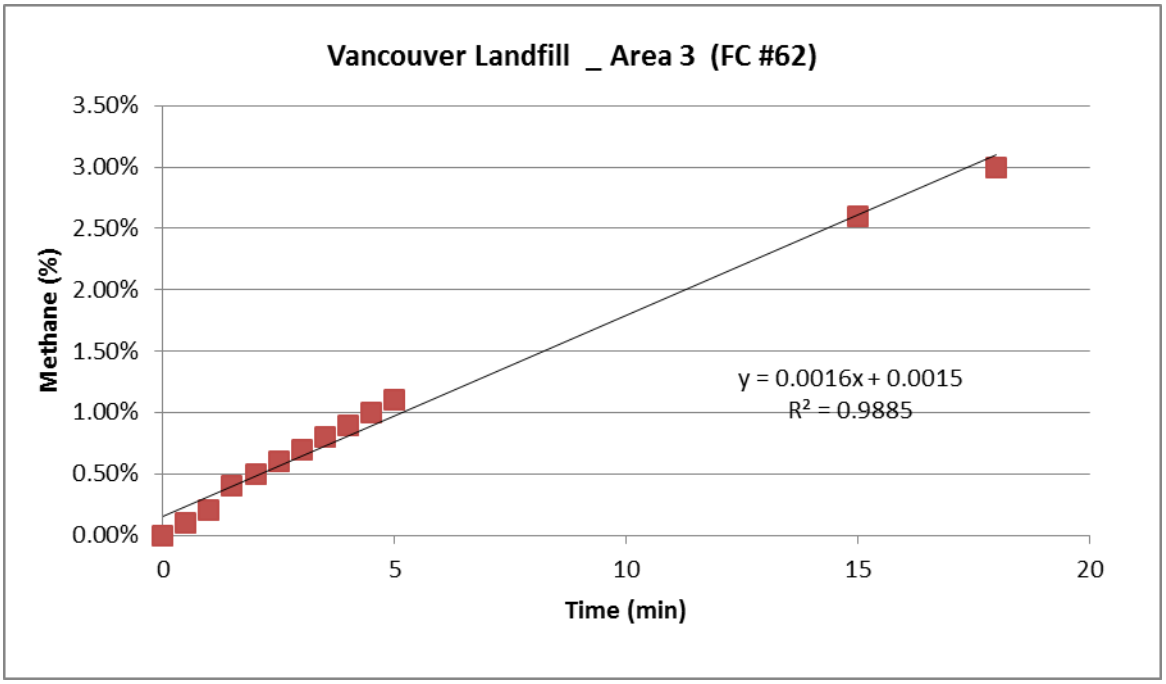

Vancouver Landfill _ Area 3_SEM Grid# 158 (FC #49)
1.40%
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
Methane (%)
0
1
2
3
4
5
6
7
Time (min)
y = 0.0013x + 0.0034
R² = 0.9005

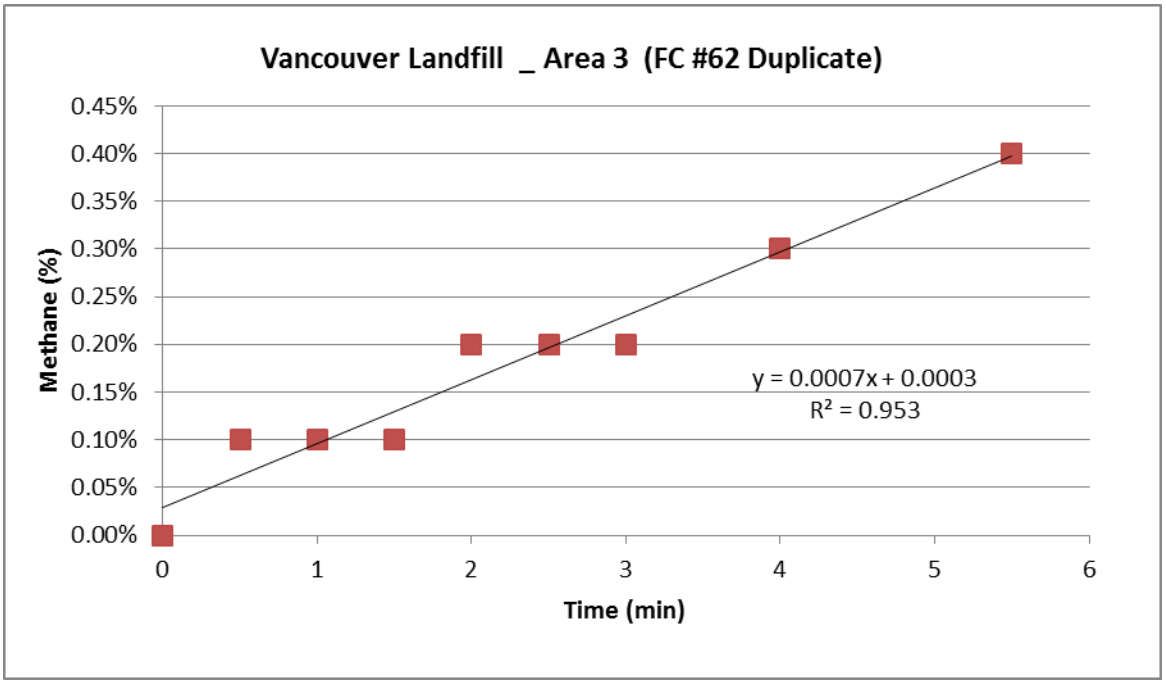

Vancouver Landfill _ Area 3 (FC #56)
Methane (%)
7.00%
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
0
2
4
6
8
10
Time (min)
y = 0.0058x + 0.0031
R² = 0.9843

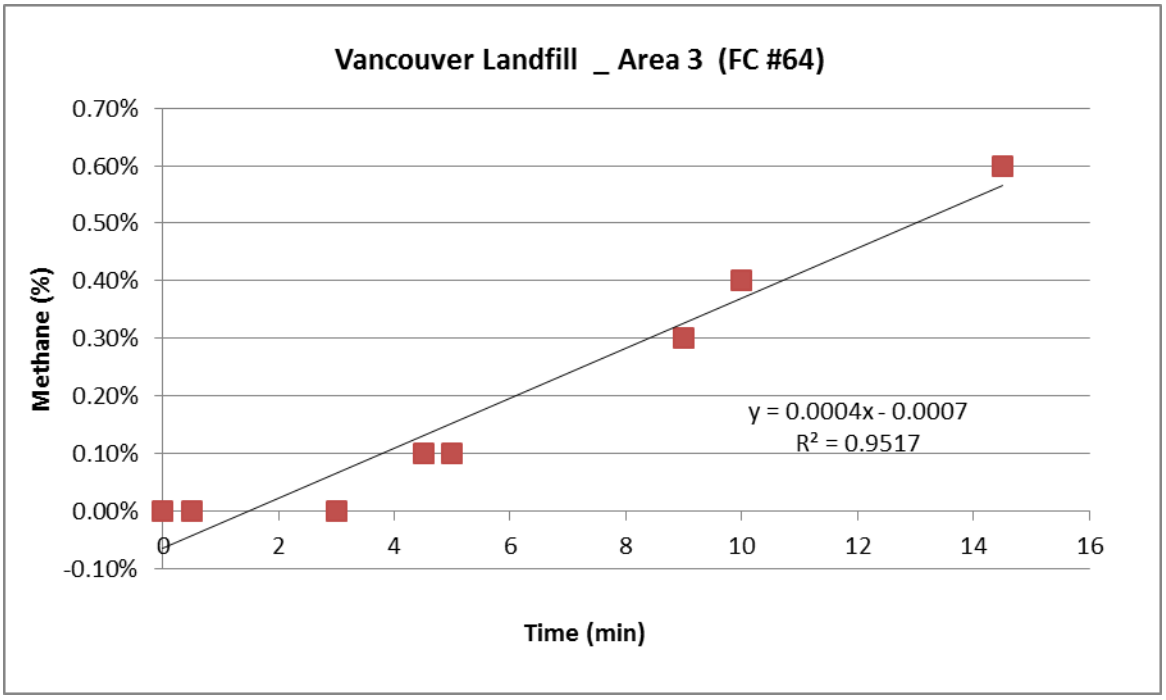

Vancouver Landfill _ Area 3 (FC #56 Duplicate)
Methane (%)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
0
1
2
3
4
5
6
Time (min)
y = 0.0021x - 9E-05
R² = 0.9917

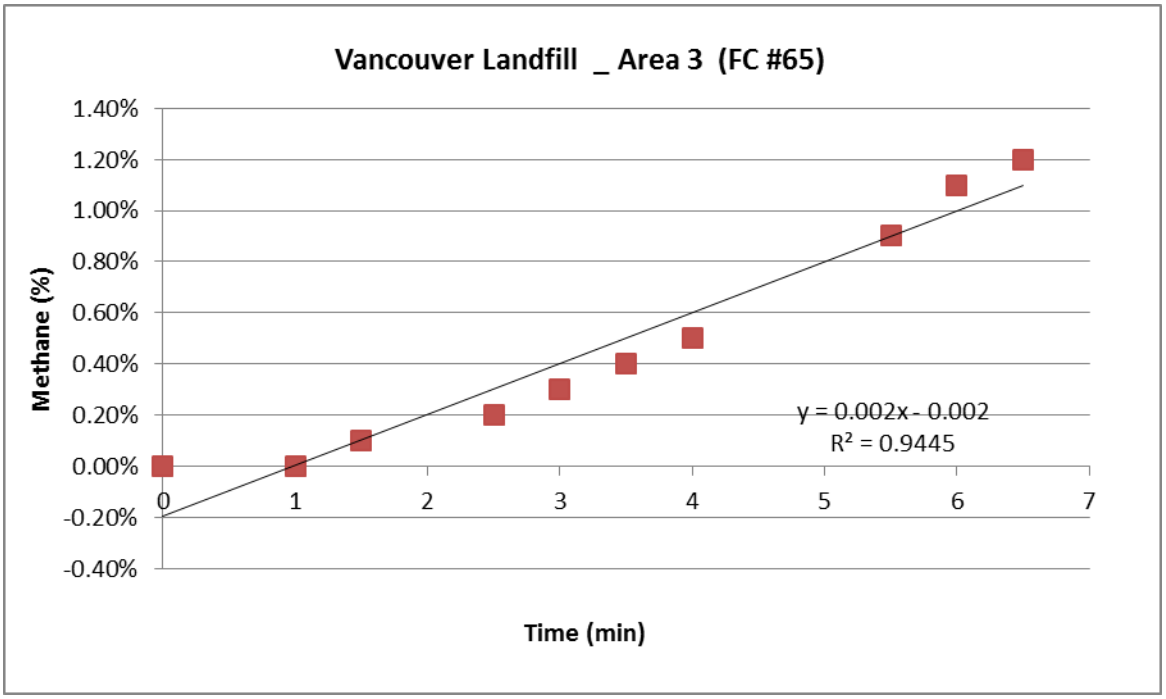

Vancouver Landfill _ Area 3 (FC #56 Duplicate)
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
Methane (%)
0
1
2
3
4
5
6
Time (min)
y = 0.0019x - 0.0008
R² = 0.9687

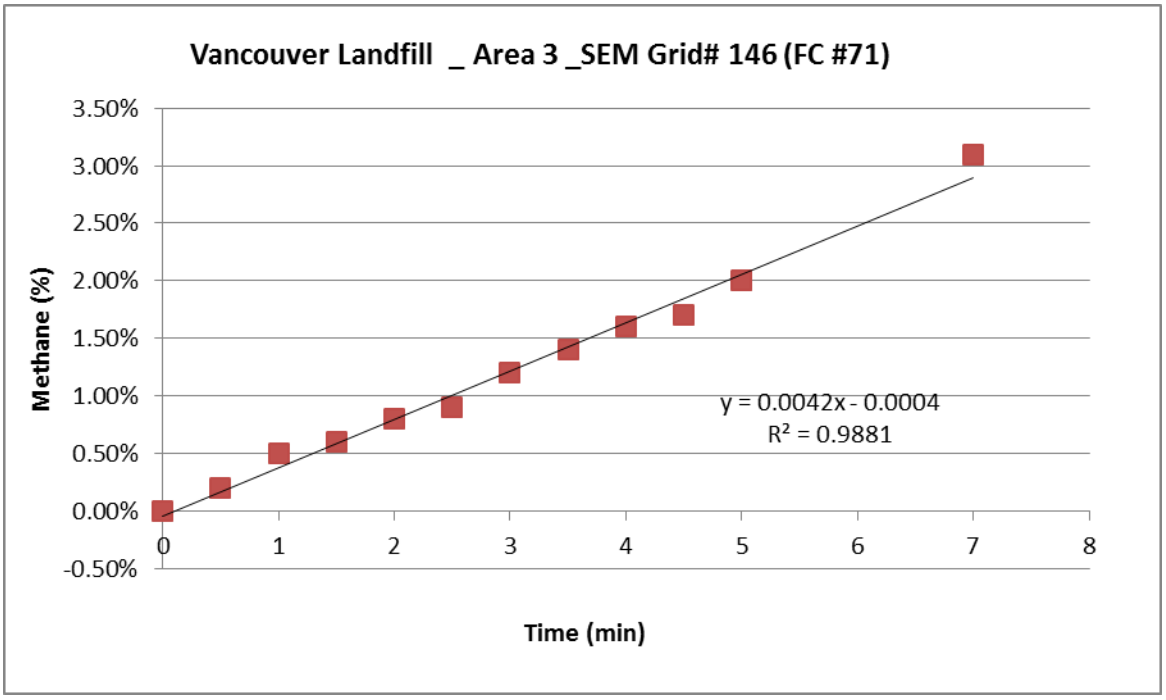

Vancouver Landfill _ Area 3 (FC #57)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
Methane (%)
0
1
2
3
4
5
6
7
8
Time (min)
y = 0.0015x + 0.0007
R² = 0.9793

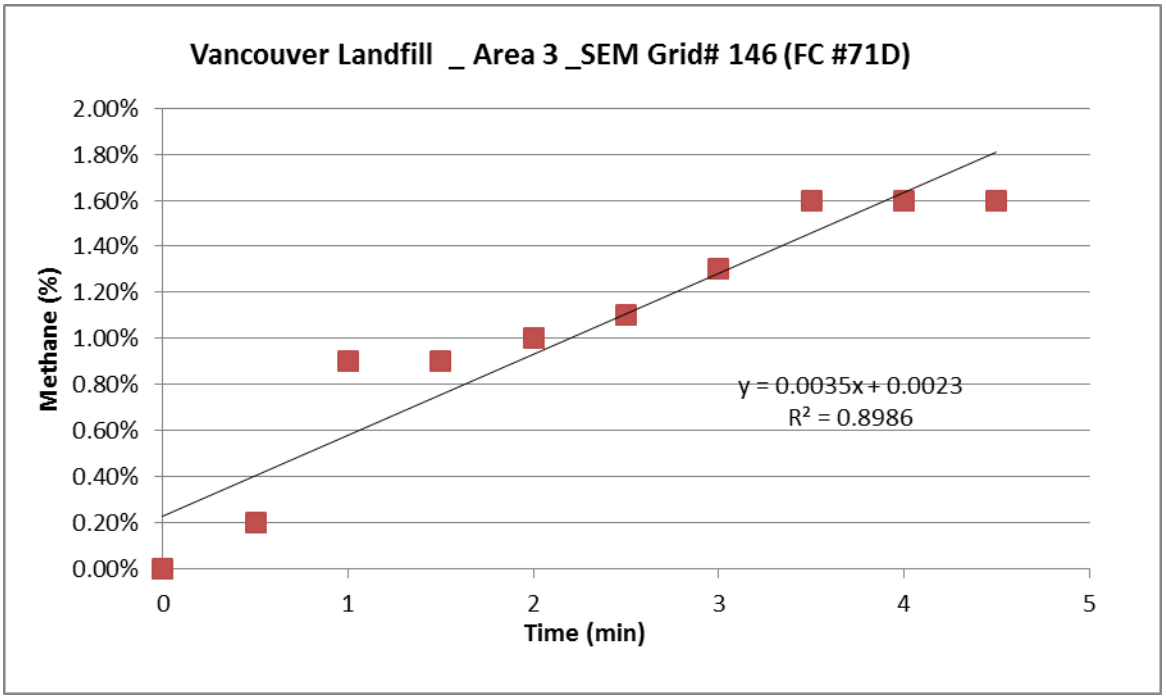

Vancouver Landfill _ Area 3 (FC #62)
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Methane (%)
0
5
10
15
20
Time (min)
y = 0.0016x + 0.0015
R² = 0.9885

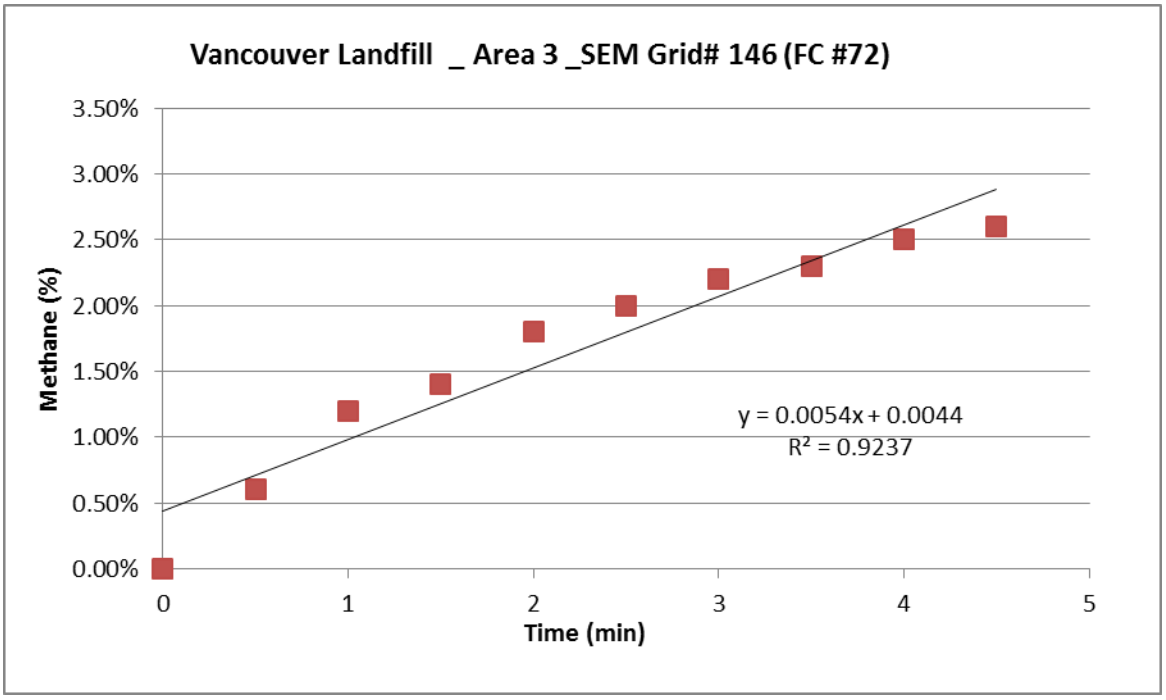

Vancouver Landfill _ Area 3 (FC #62 Duplicate)
0.45%
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
Methane (%)
0
1
2
3
4
5
6
Time (min)
y = 0.0007x + 0.0003
R² = 0.953

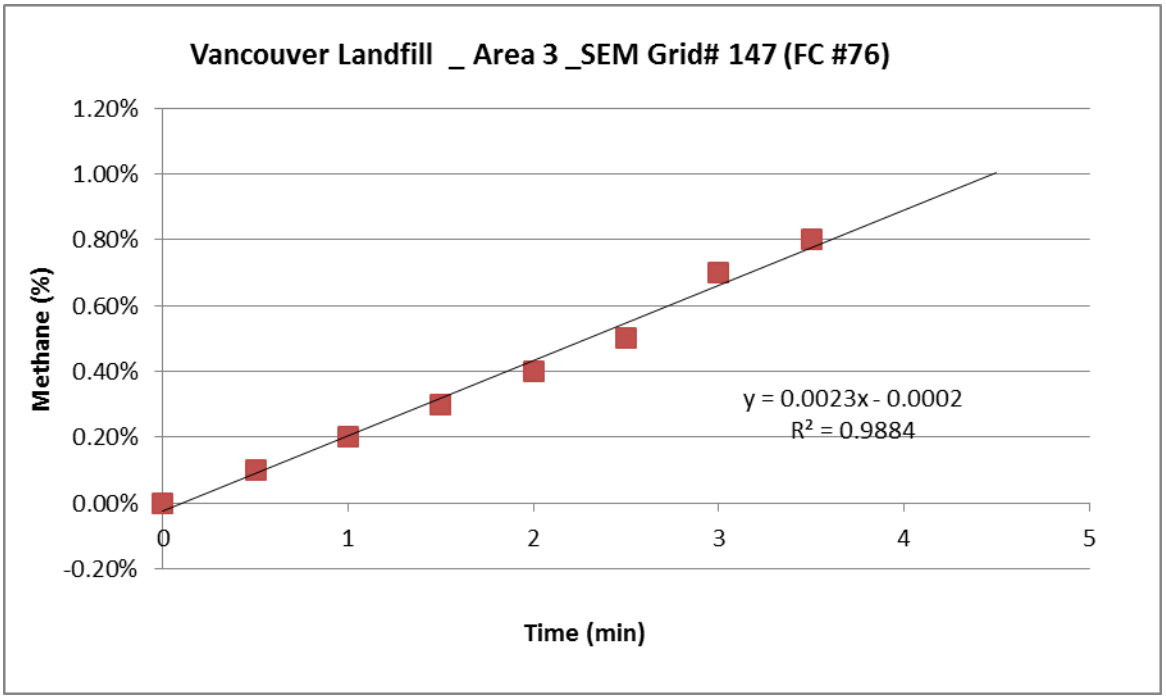

Vancouver Landfill _ Area 3 (FC #64)
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
-0.10%
Methane (%)
0
2
4
6
8
10
12
14
16
y = 0.0004x - 0.0007
R² = 0.9517
Time (min)

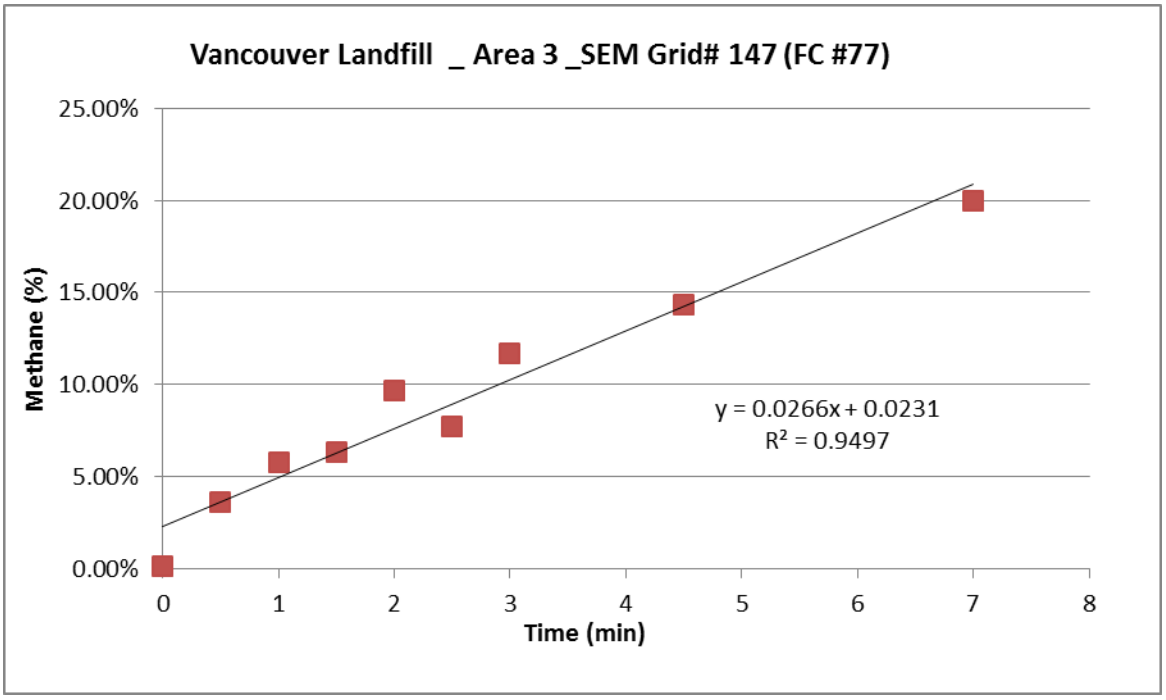

Vancouver Landfill _ Area 3 (FC #65)
1.40%
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Methane (%)
0
1
2
3
4
5
6
7
y = 0.002x - 0.002
R² = 0.9445
Time (min)

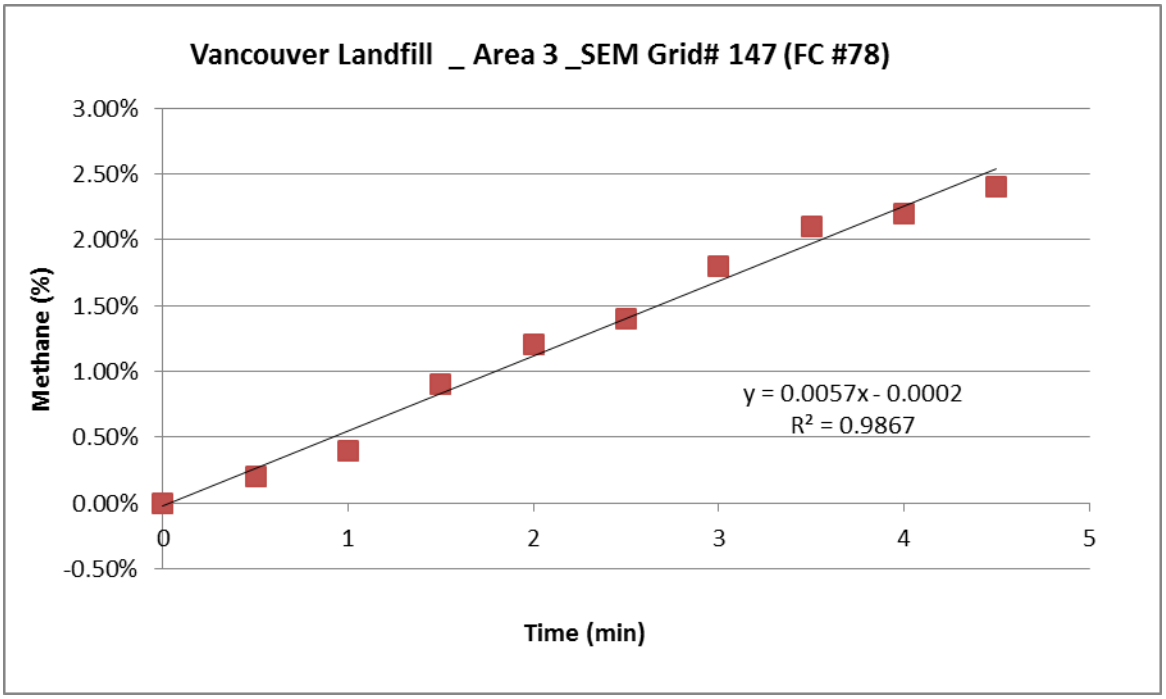

Vancouver Landfill _ Area 3 _SEM Grid# 146 (FC #71)
Methane (%)
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
0
1
2
3
4
5
6
7
8
y = 0.0042x - 0.0004
R² = 0.9881
Time (min)

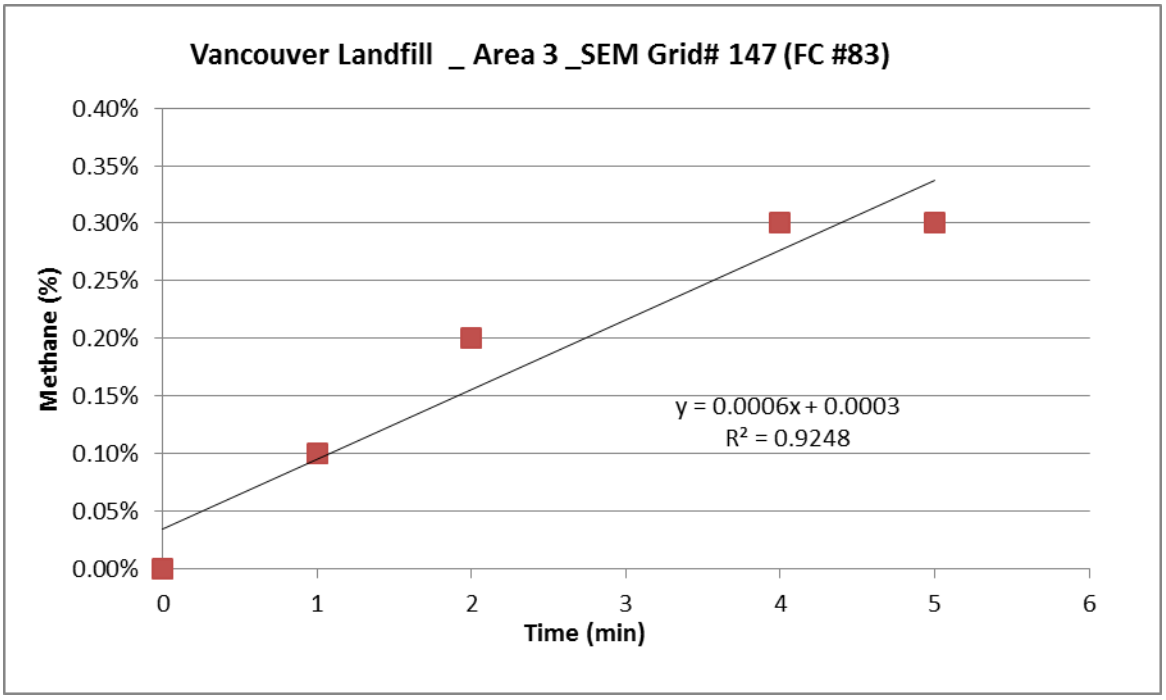

Vancouver Landfill _ Area 3 _SEM Grid# 146 (FC #71D)
Methane (%)
2.00%
1.80%
1.60%
1.40%
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
1
2
3
4
5
y = 0.0035x + 0.0023
R² = 0.8986
Time (min)

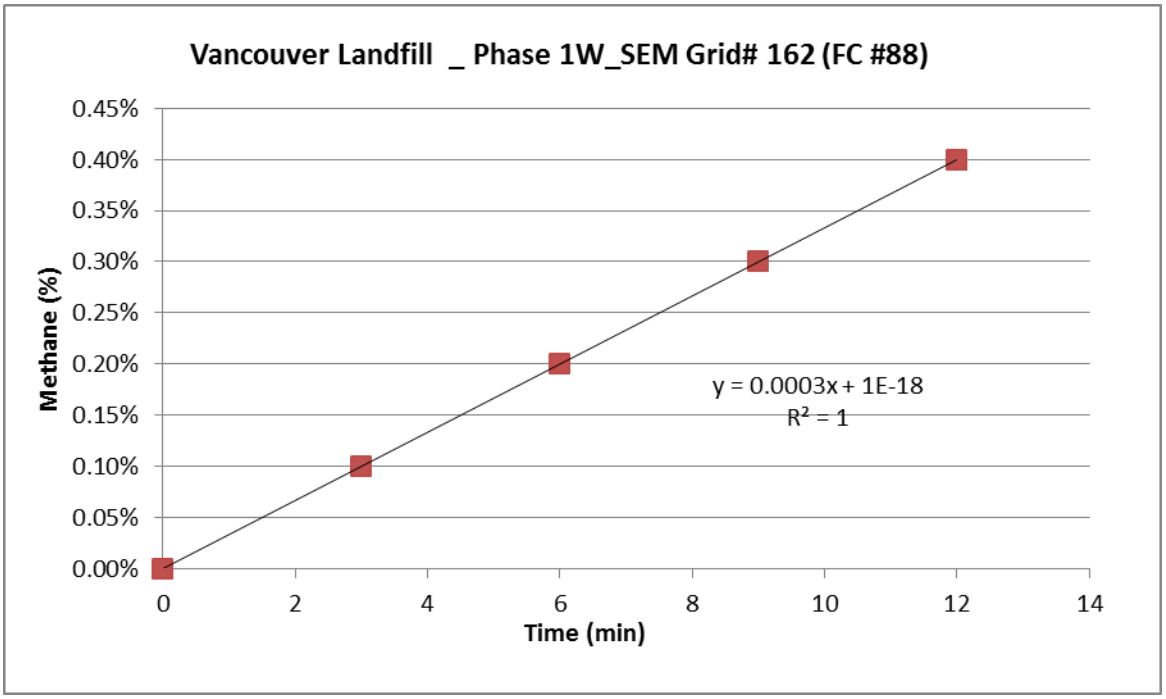

Vancouver Landfill _ Area 3 _SEM Grid# 146 (FC #72)
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Methane (%)
0
1
2
3
4
5
Time (min)
y = 0.0054x + 0.0044
R² = 0.9237

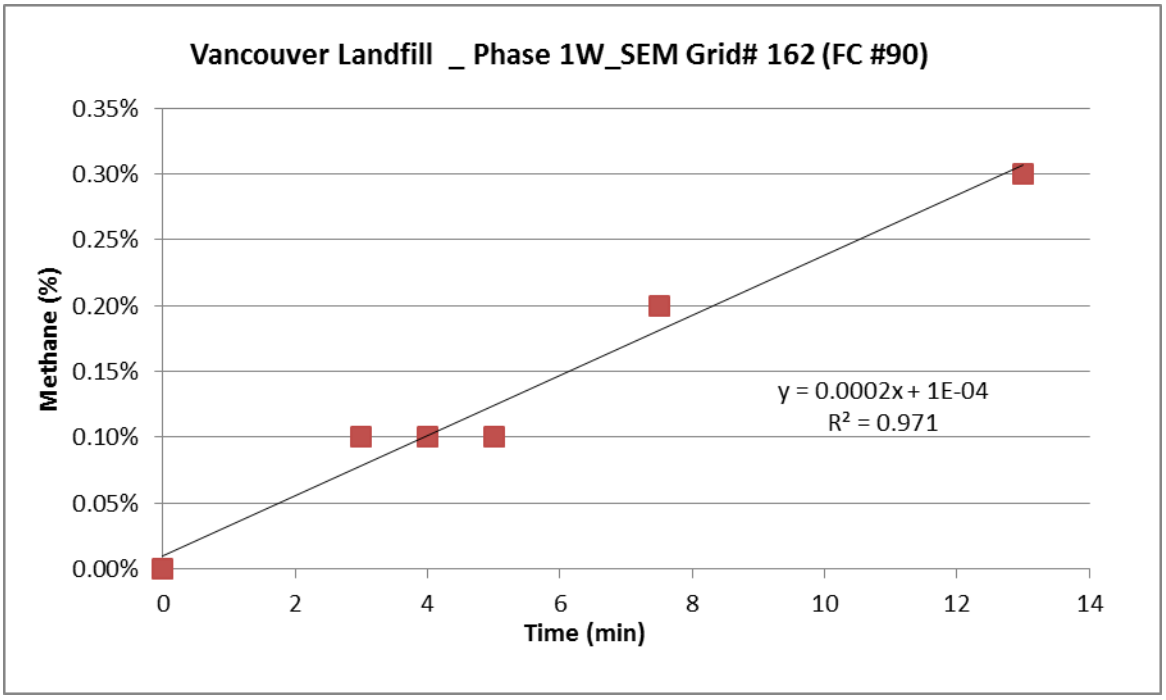

Vancouver Landfill _ Area 3 _SEM Grid# 147 (FC #76)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
Methane (%)
0
1
2
3
4
5
Time (min)
y = 0.0023x - 0.0002
R² = 0.9884

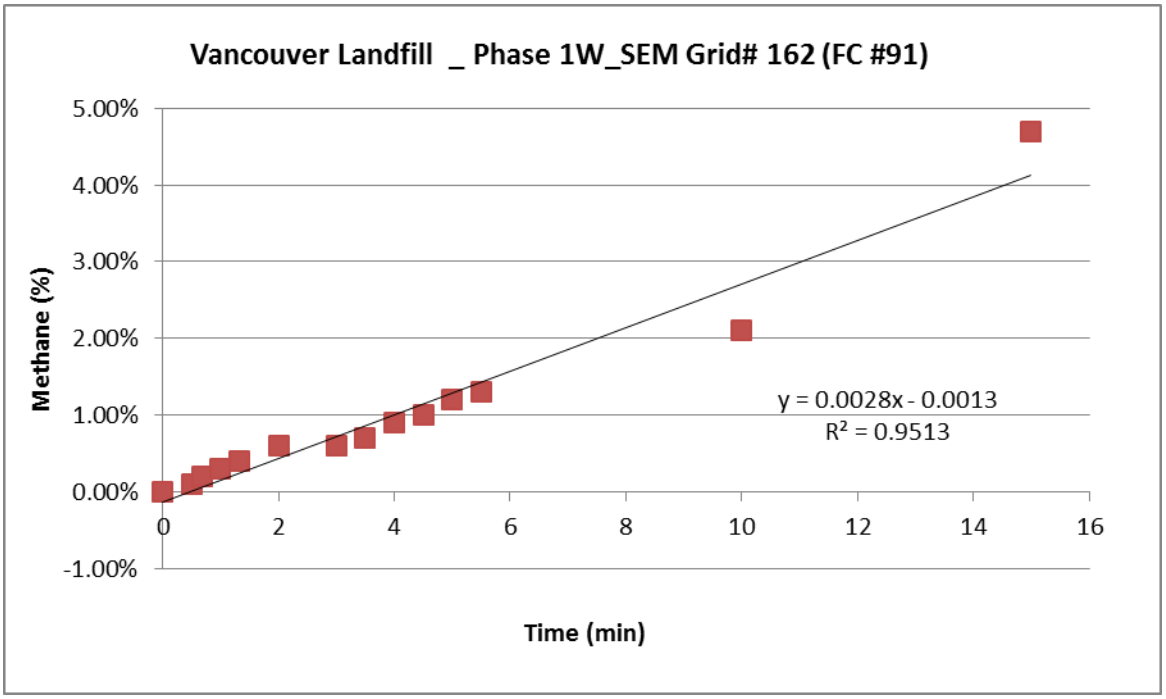

Vancouver Landfill _ Area 3 _SEM Grid# 147 (FC #77)
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Methane (%)
0
1
2
3
4
5
6
7
8
Time (min)
y = 0.0266x + 0.0231
R² = 0.9497

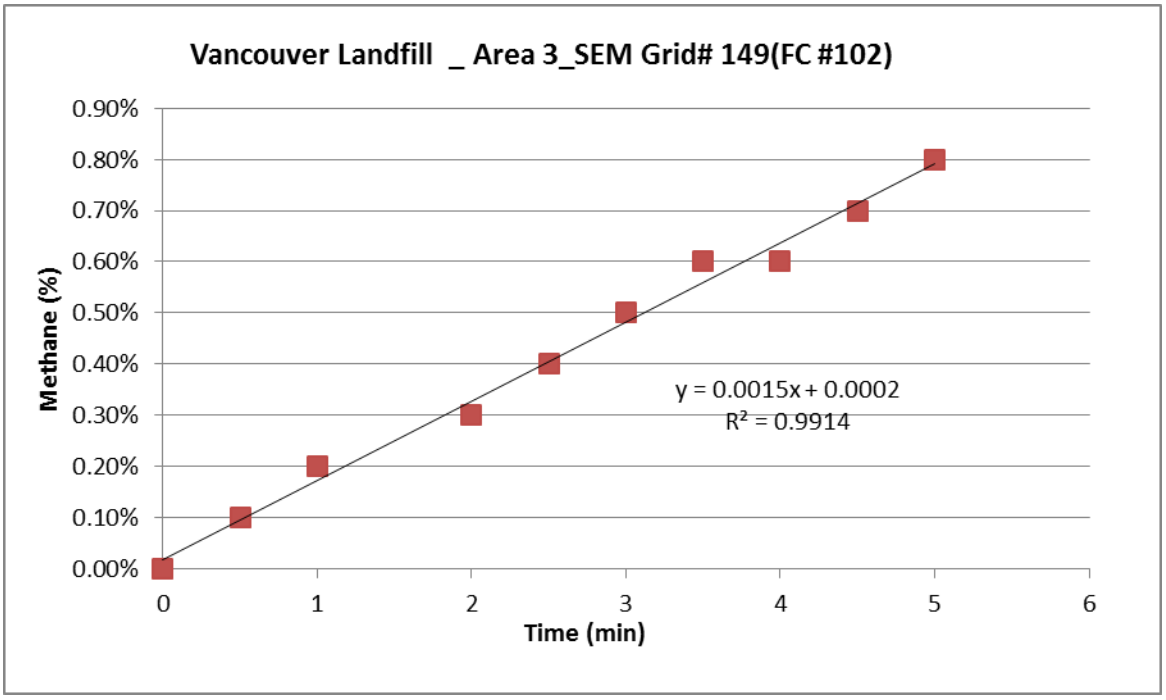

Vancouver Landfill _ Area 3 _SEM Grid# 147 (FC #78)
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
-0.50%
Methane (%)
0
1
2
3
4
5
Time (min)
y = 0.0057x - 0.0002
R² = 0.9867

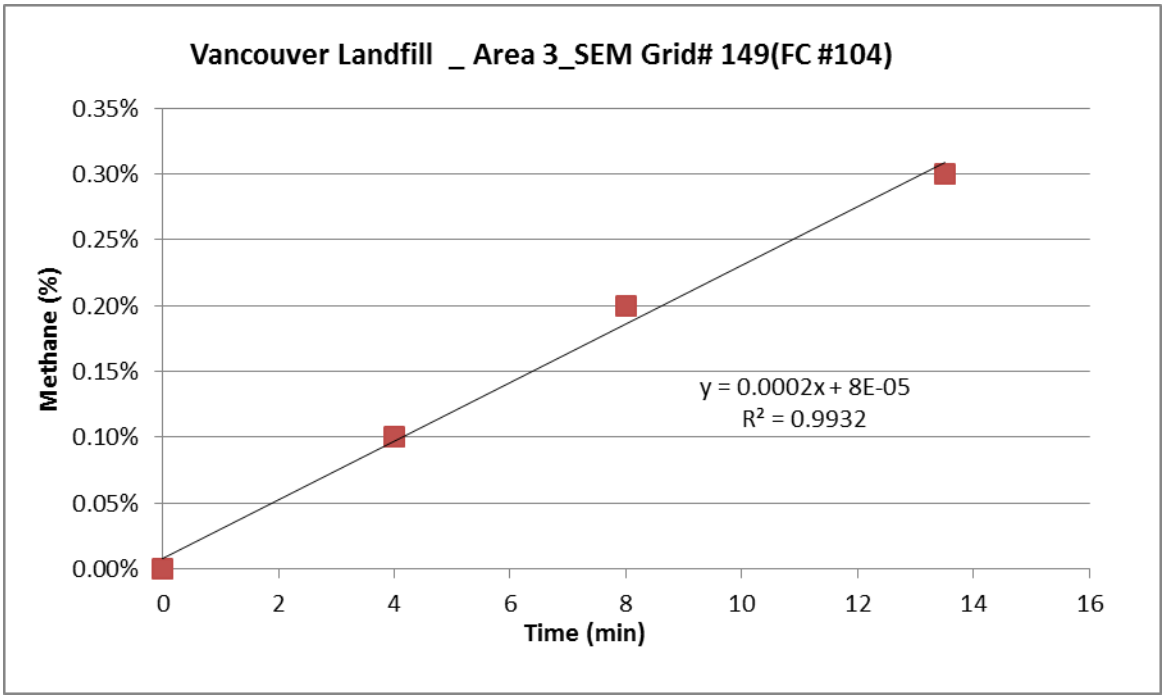

Vancouver Landfill _ Area 3 _SEM Grid# 147 (FC #83)
Methane (%)
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
1
2
3
4
5
6
Time (min)
y = 0.0006x + 0.0003
R² = 0.9248

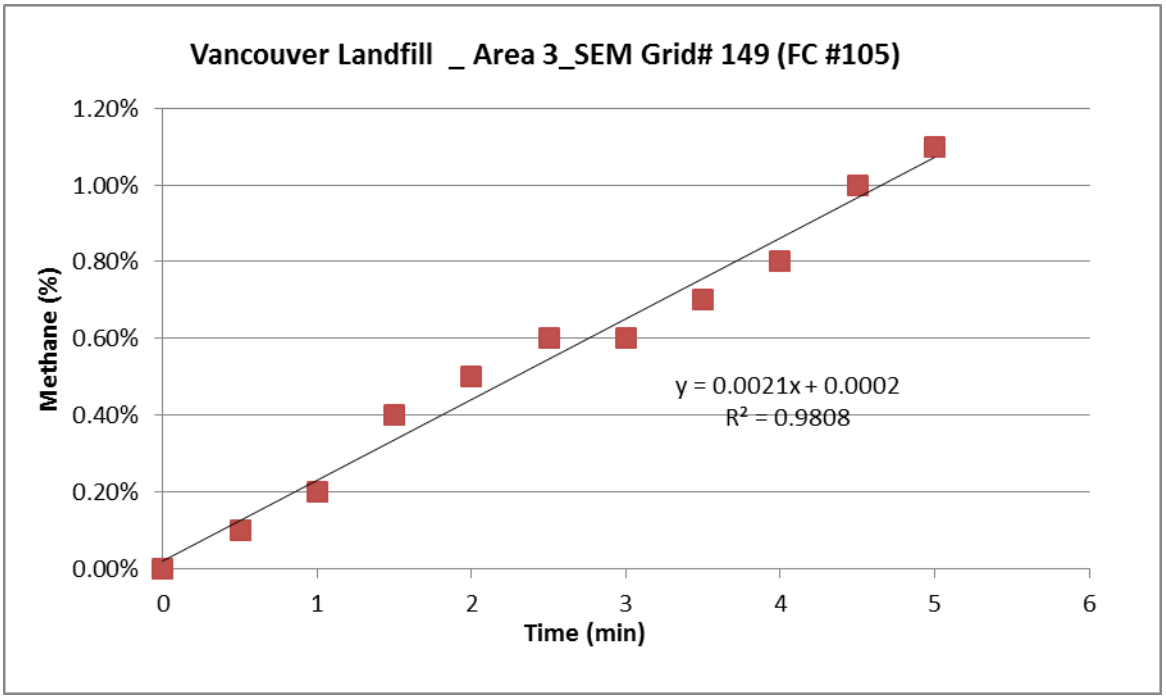

Vancouver Landfill _ Phase 1W_SEM Grid# 162 (FC #88)
Methane (%)
0.45%
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
2
4
6
8
10
12
14
Time (min)
y = 0.0003x + 1E-18
R² = 1

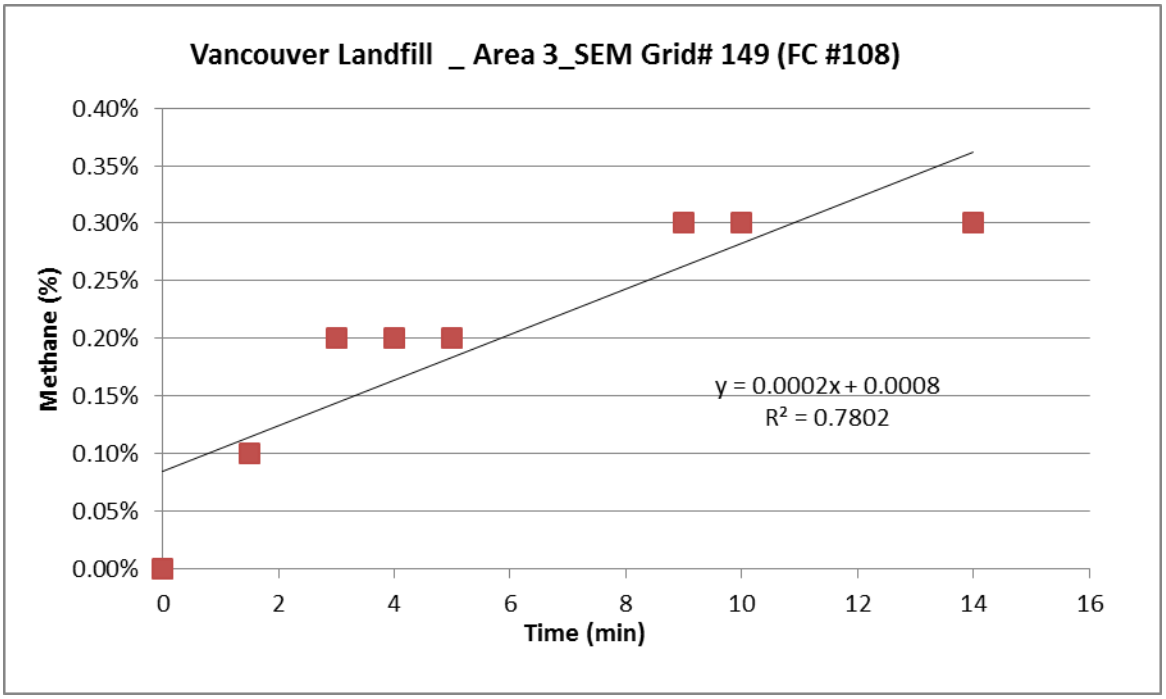

Vancouver Landfill _ Phase 1W_SEM Grid# 162 (FC #90)
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
Methane (%)
y = 0.0002x + 1E-04
R² = 0.971
0
2
4
6
8
10
12
14
Time (min)

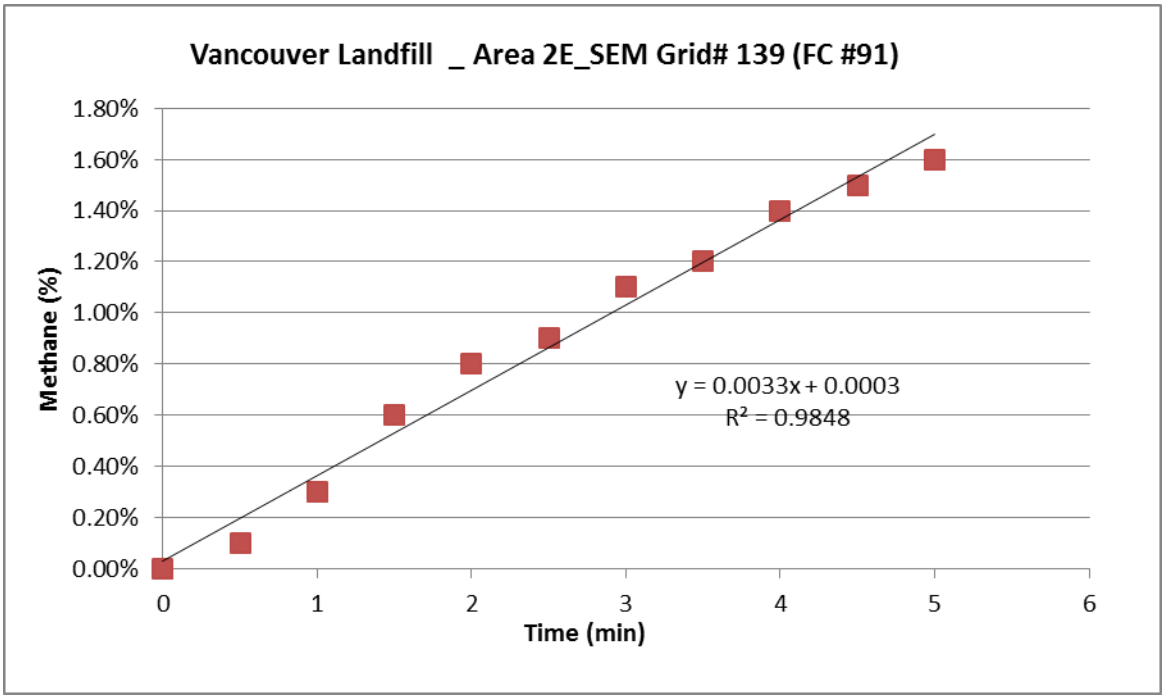

Vancouver Landfill _ Phase 1W_SEM Grid# 162 (FC #91)
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
-1.00%
Methane (%)
y = 0.0028x - 0.0013
R² = 0.9513
0
2
4
6
8
10
12
14
16
Time (min)

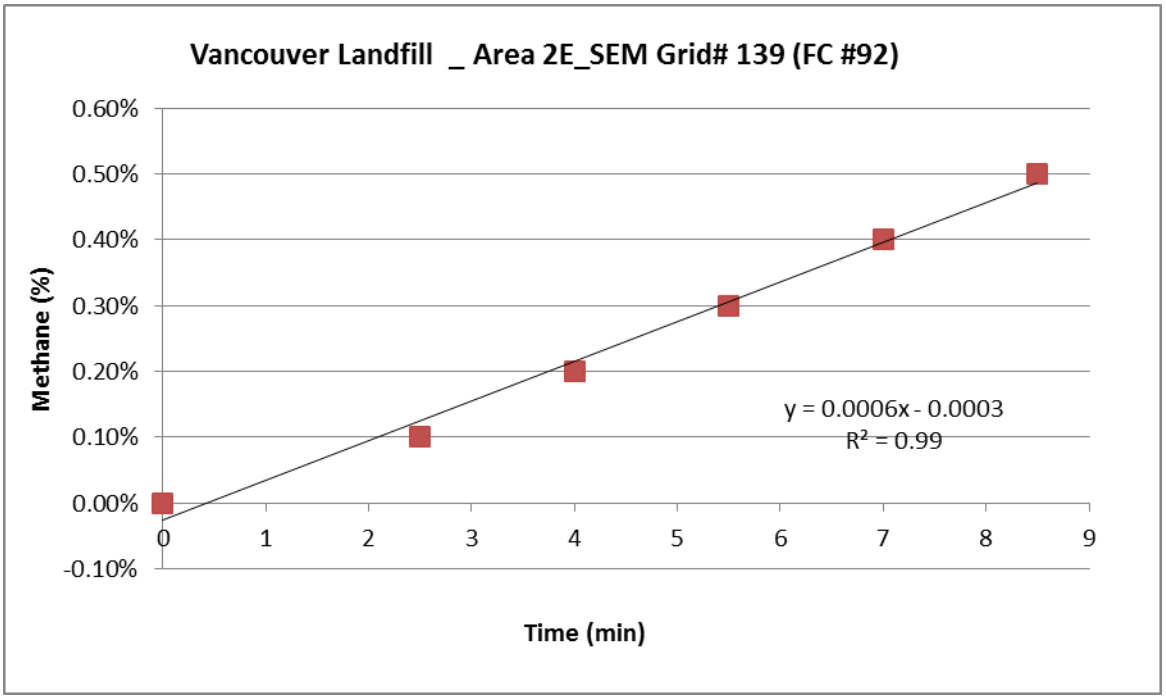

Vancouver Landfill _ Area 3_SEM Grid# 149(FC #102)
Methane (%)
0.90%
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
6
Time (min)
y = 0.0015x + 0.0002
R² = 0.9914

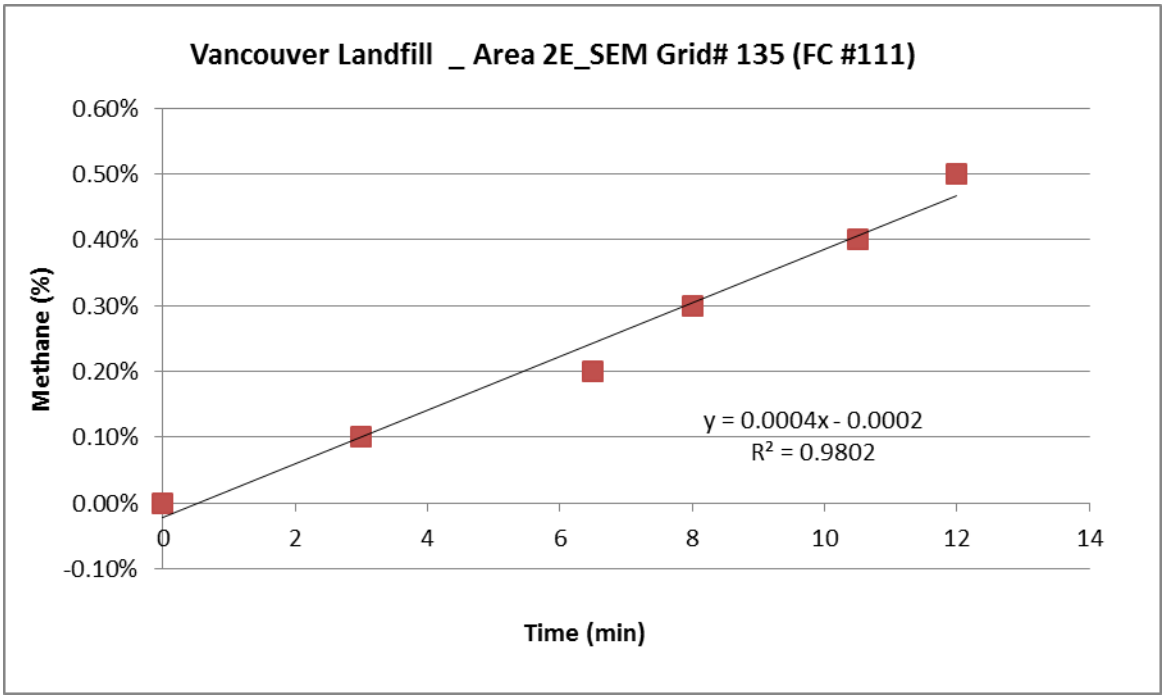

Vancouver Landfill _ Area 3_SEM Grid# 149(FC #104)
Methane (%)
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
2
4
6
8
10
12
14
16
Time (min)
y = 0.0002x + 8E-05
R² = 0.9932

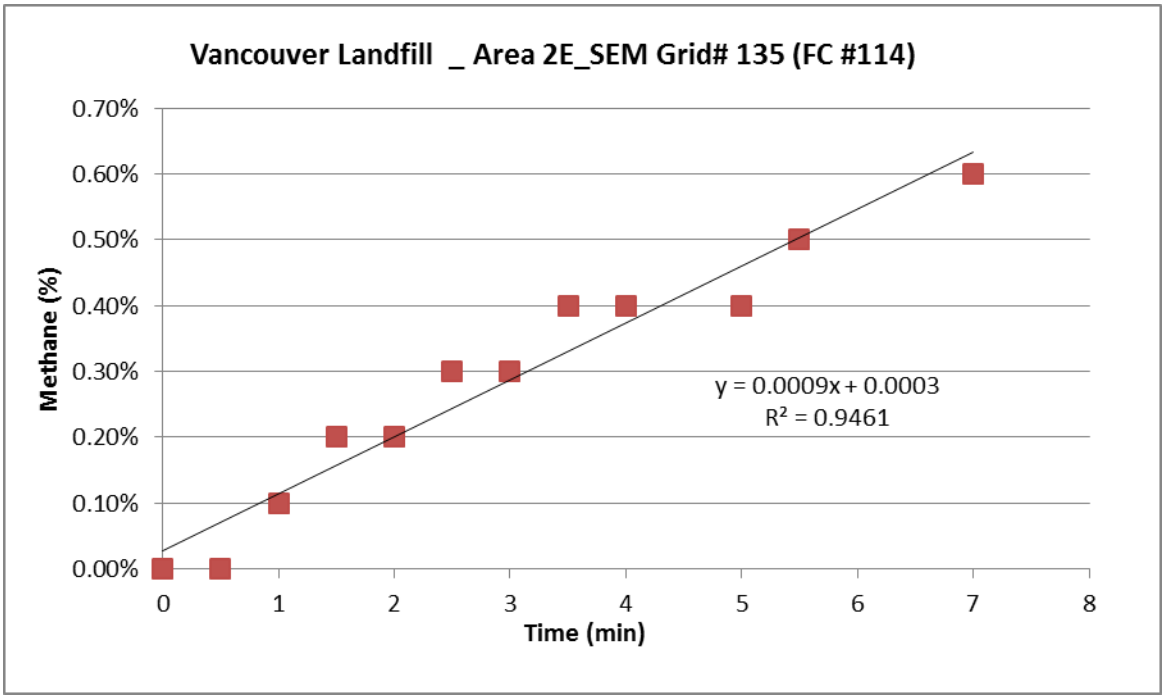

Vancouver Landfill _ Area 3_SEM Grid# 149 (FC #105)
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
Methane (%)
0
1
2
3
4
5
6
Time (min)
y = 0.0021x + 0.0002
R² = 0.9808

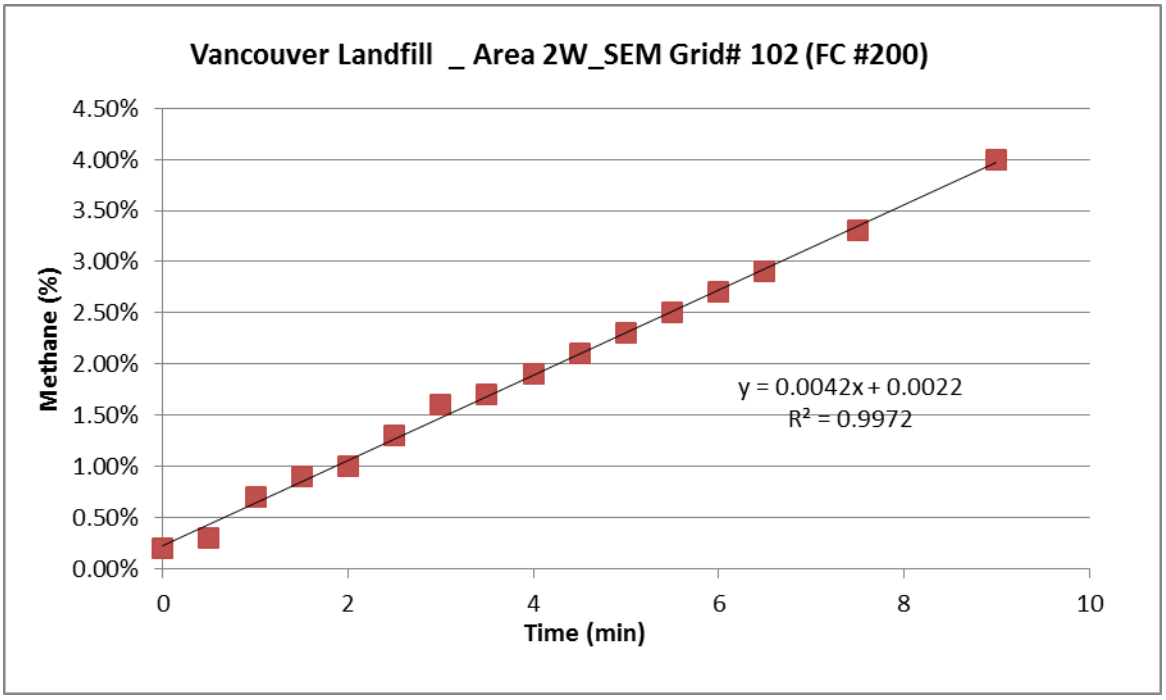

Vancouver Landfill _ Area 3_SEM Grid# 149 (FC #108)
0.40%
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
Methane (%)
0
2
4
6
8
10
12
14
16
Time (min)
y = 0.0002x + 0.0008
R² = 0.7802

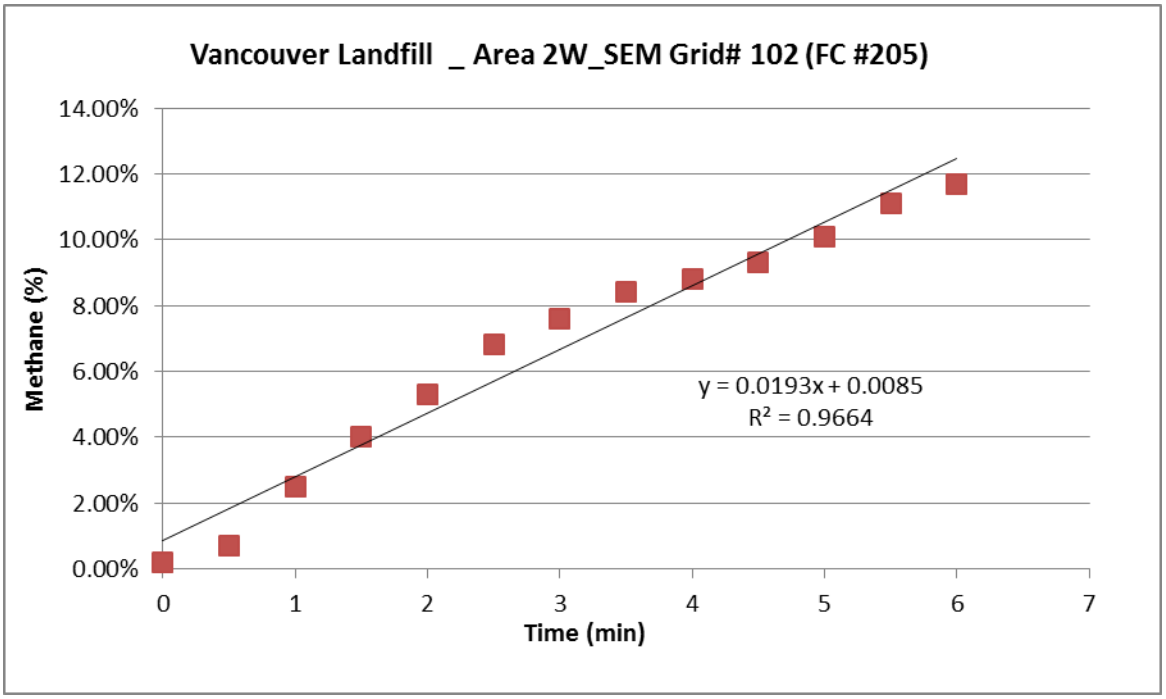

Vancouver Landfill _ Area 2E_SEM Grid# 139 (FC #91)
Methane (%)
1.80%
1.60%
1.40%
1.20%
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
1
2
3
4
5
6
Time (min)
y = 0.0033x + 0.0003
R² = 0.9848

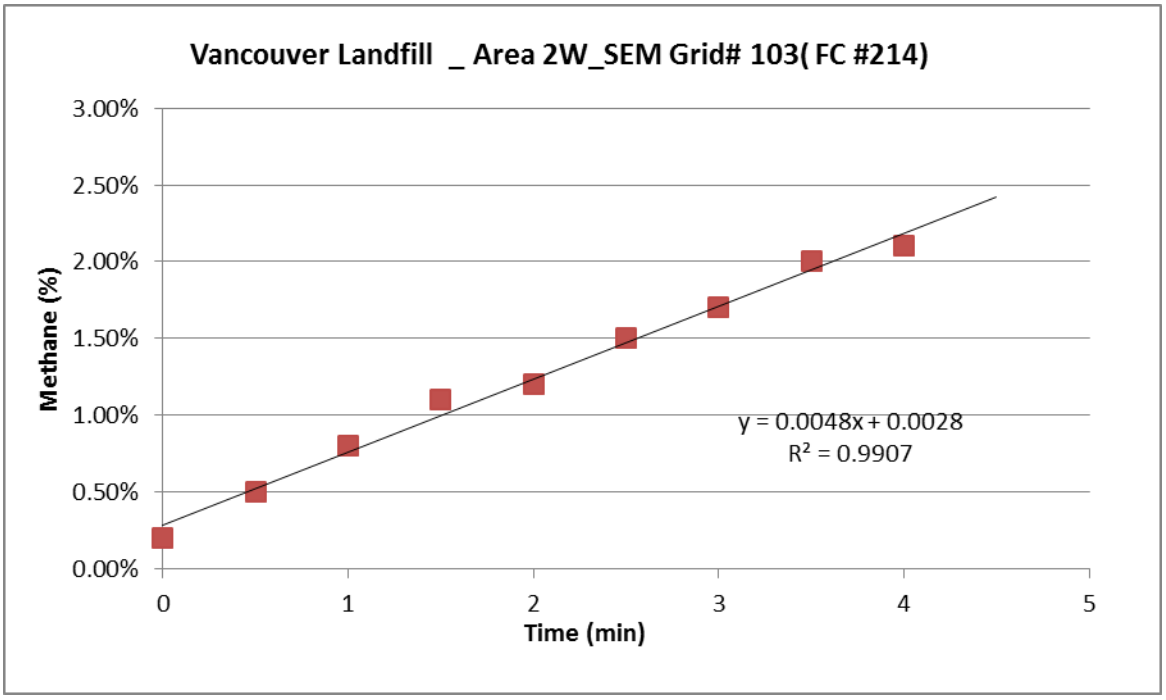

Vancouver Landfill _ Area 2E_SEM Grid# 139 (FC #92)
Methane (%)
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
-0.10%
0
1
2
3
4
5
6
7
8
9
Time (min)
y = 0.0006x - 0.0003
R² = 0.99

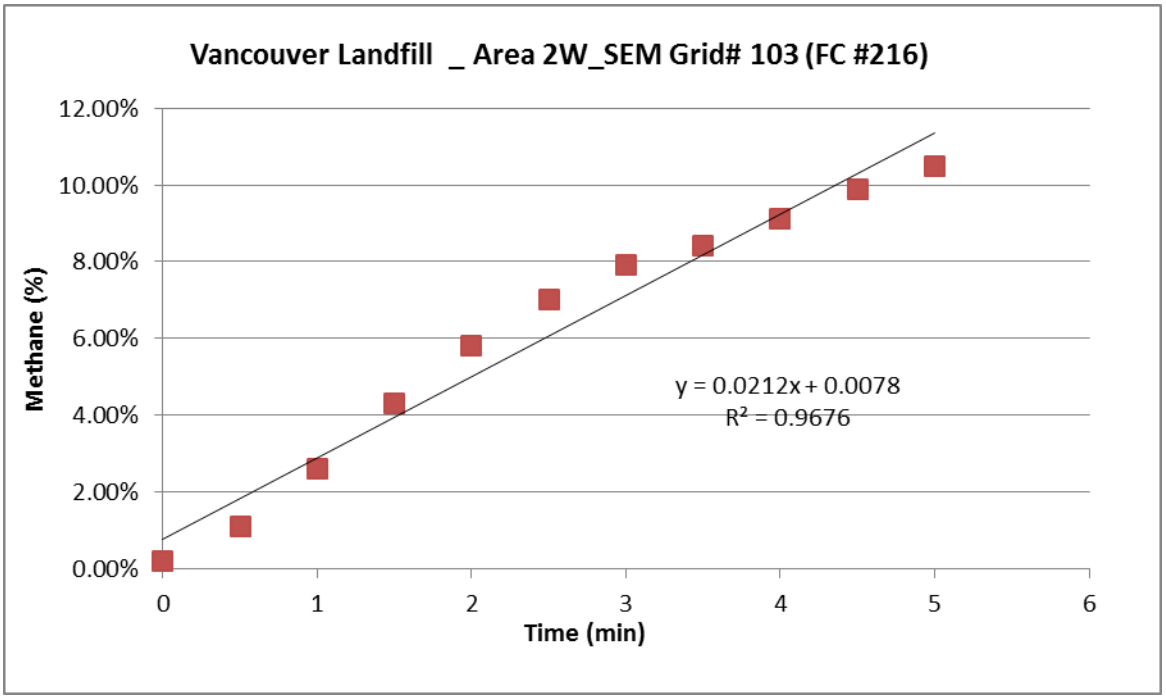

Vancouver Landfill _ Area 2E_SEM Grid# 135 (FC #111)
Methane (%)
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
-0.10%
0
2
4
6
8
10
12
14
Time (min)
y = 0.0004x - 0.0002
R² = 0.9802

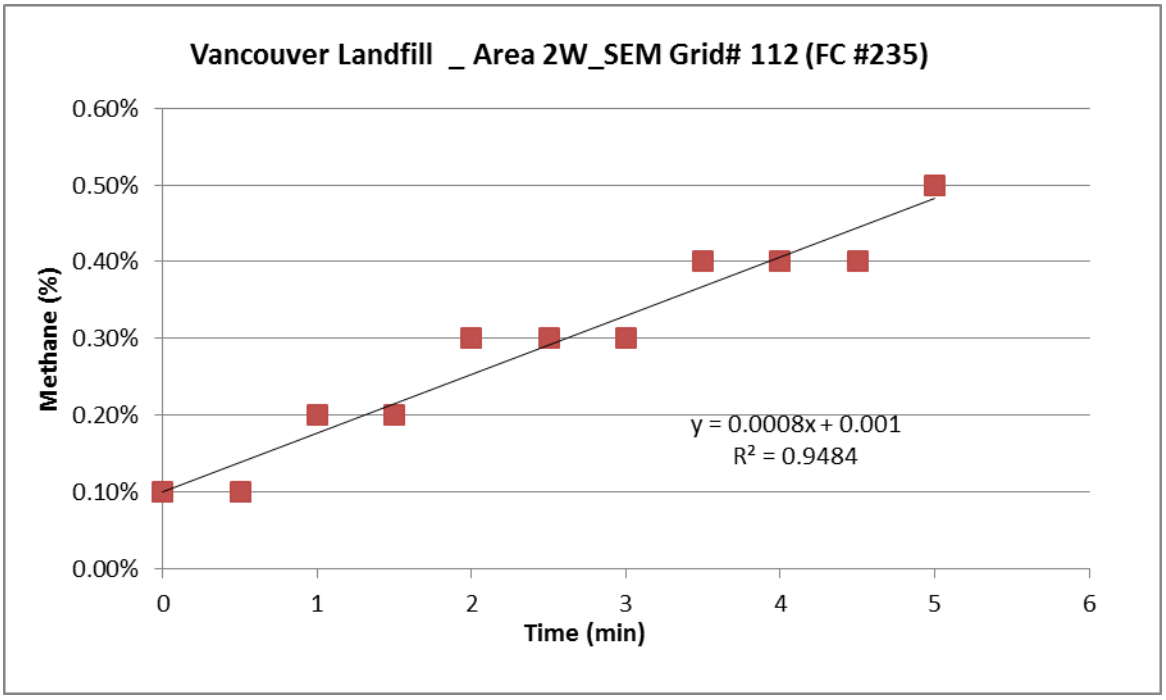

Vancouver Landfill _ Area 2E_SEM Grid# 135 (FC #114)
Methane (%)
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
6
7
8
Time (min)
y = 0.0009x + 0.0003
R² = 0.9461

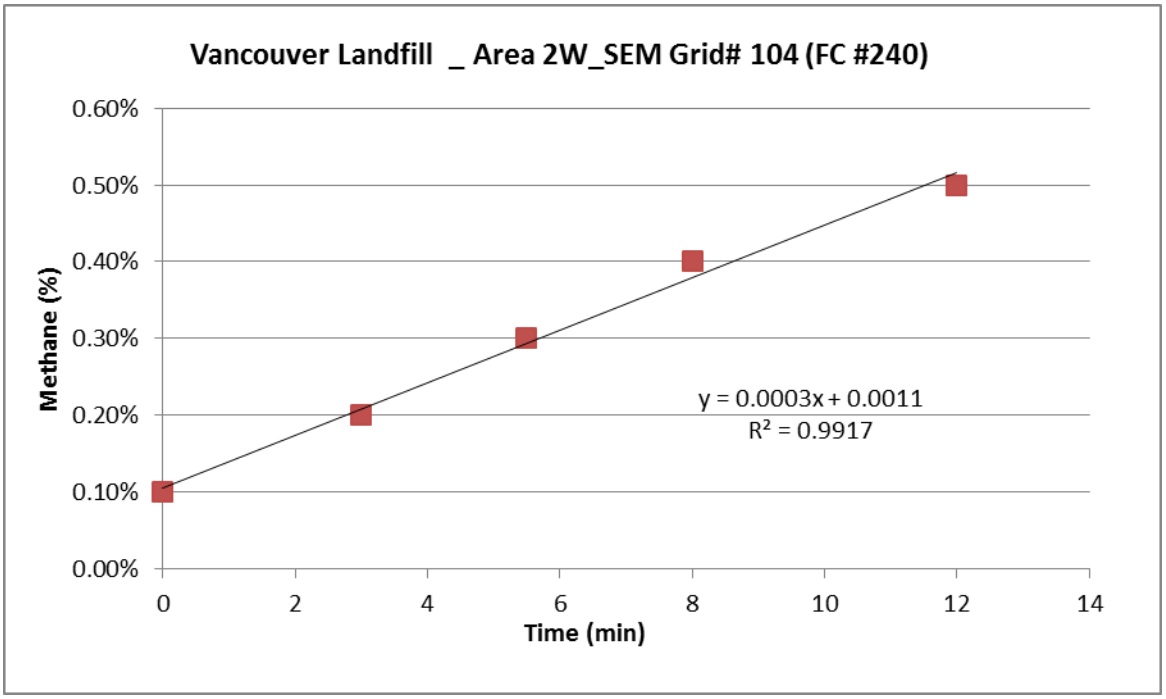

Vancouver Landfill _ Area 2W_SEM Grid# 102 (FC #200)
Methane (%)
4.50%
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
2
4
6
8
10
Time (min)
y = 0.0042x + 0.0022
R² = 0.9972

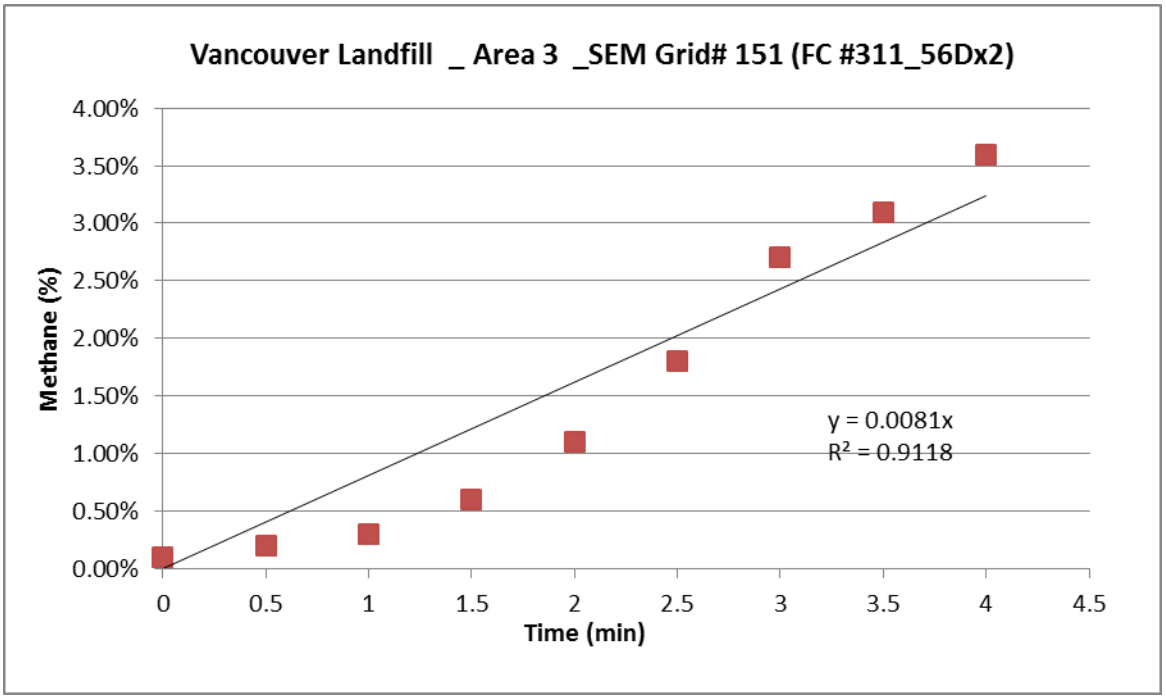

Vancouver Landfill _ Area 2W_SEM Grid# 102 (FC #205)
Methane (%)
14.00%
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
0
1
2
3
4
5
6
7
Time (min)
y = 0.0193x + 0.0085
R² = 0.9664

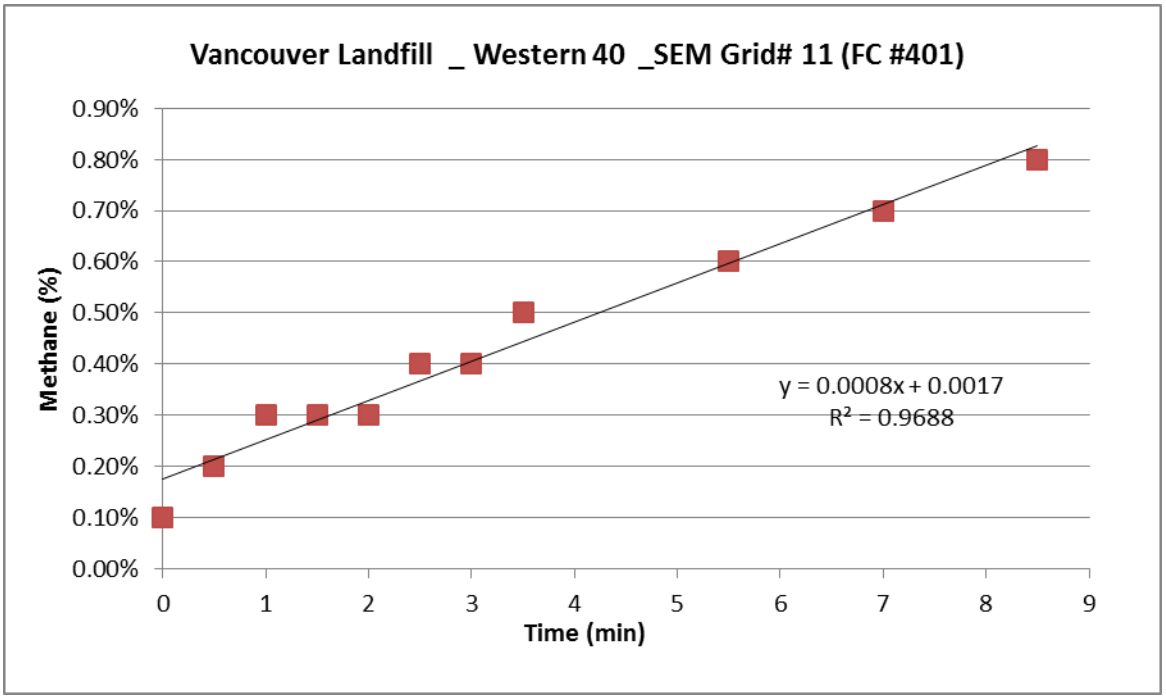

Vancouver Landfill _ Area 2W_SEM Grid# 103(FC #214)
Methane (%)
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
1
2
3
4
5
Time (min)
y = 0.0048x + 0.0028
R² = 0.9907

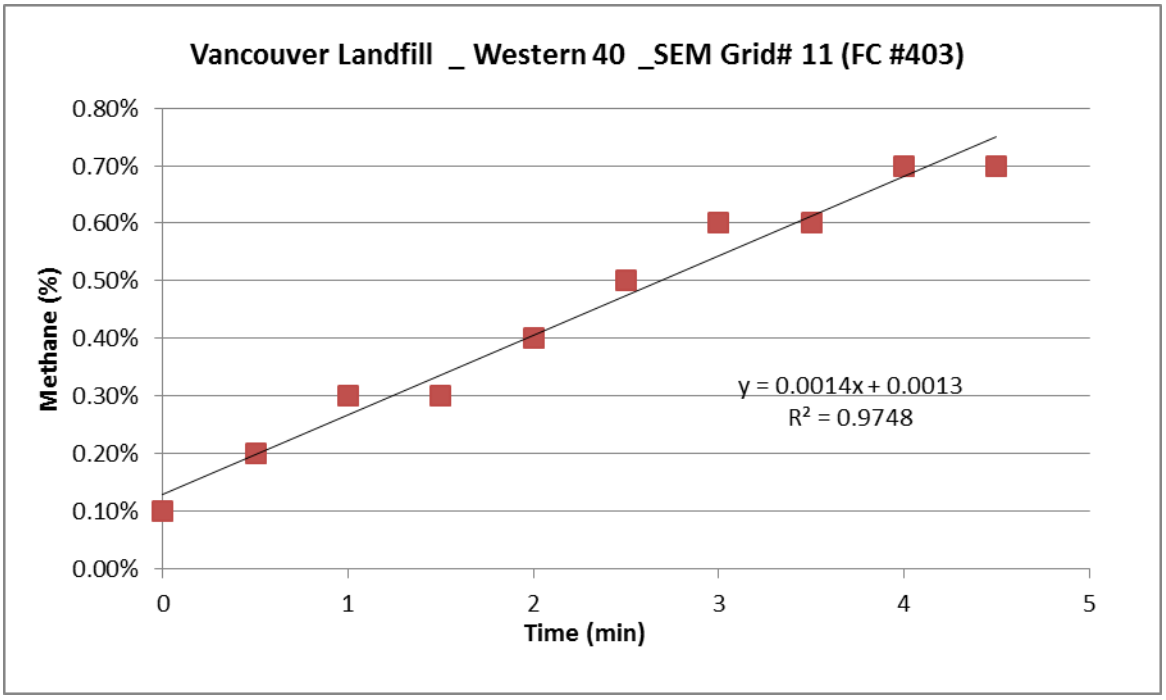

Vancouver Landfill _ Area 2W_SEM Grid# 103 (FC #216)
Methane (%)
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
0
1
2
3
4
5
6
Time (min)
y = 0.0212x + 0.0078
R² = 0.9676

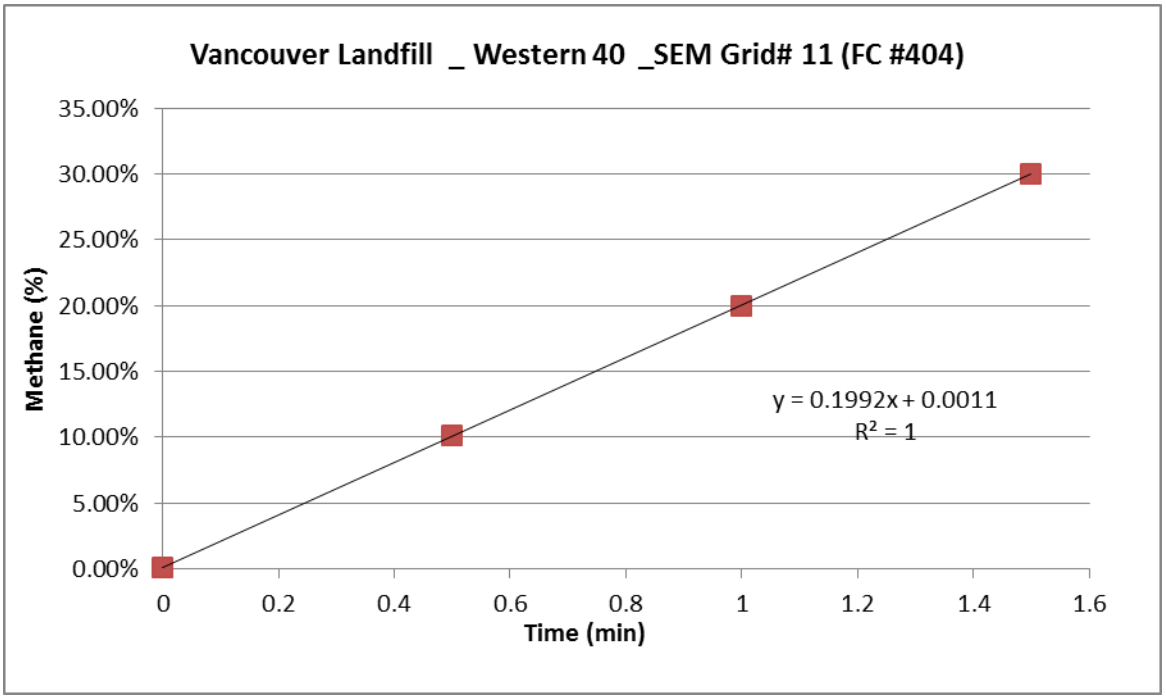

Vancouver Landfill _ Area 2W_SEM Grid# 112 (FC #235)
Methane (%)
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
6
Time (min)
y = 0.0008x + 0.001
R² = 0.9484

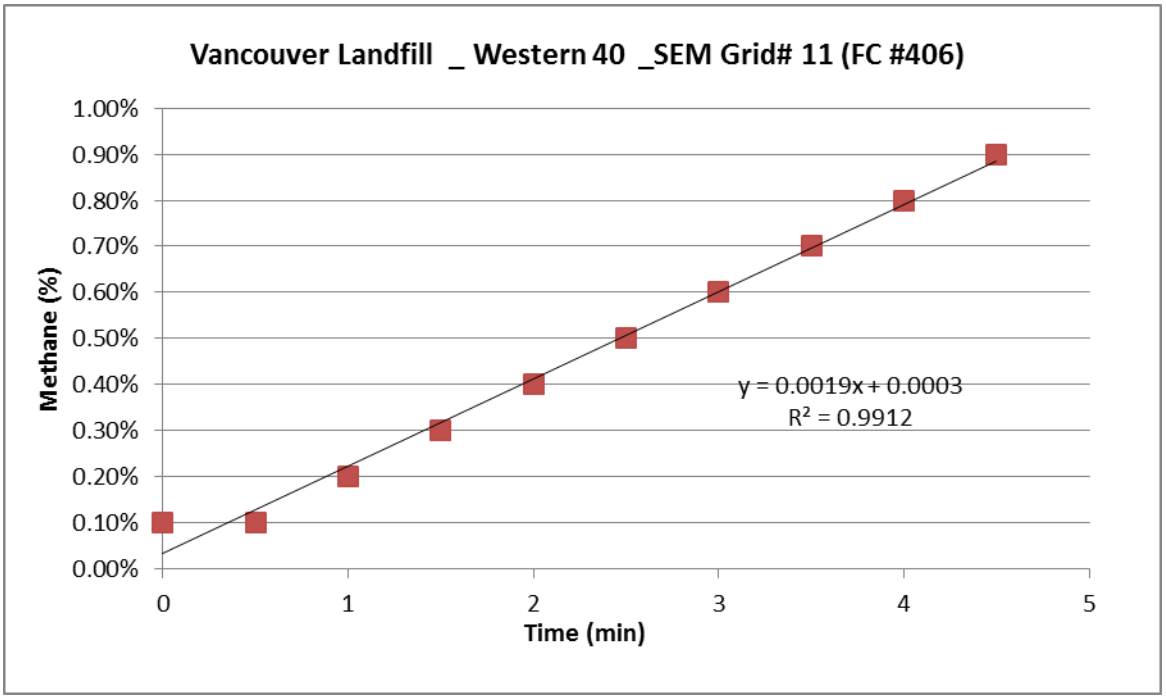

Vancouver Landfill _ Area 2W_SEM Grid# 104 (FC #240)
Methane (%)
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
2
4
6
8
10
12
14
Time (min)
y = 0.0003x + 0.0011
R² = 0.9917

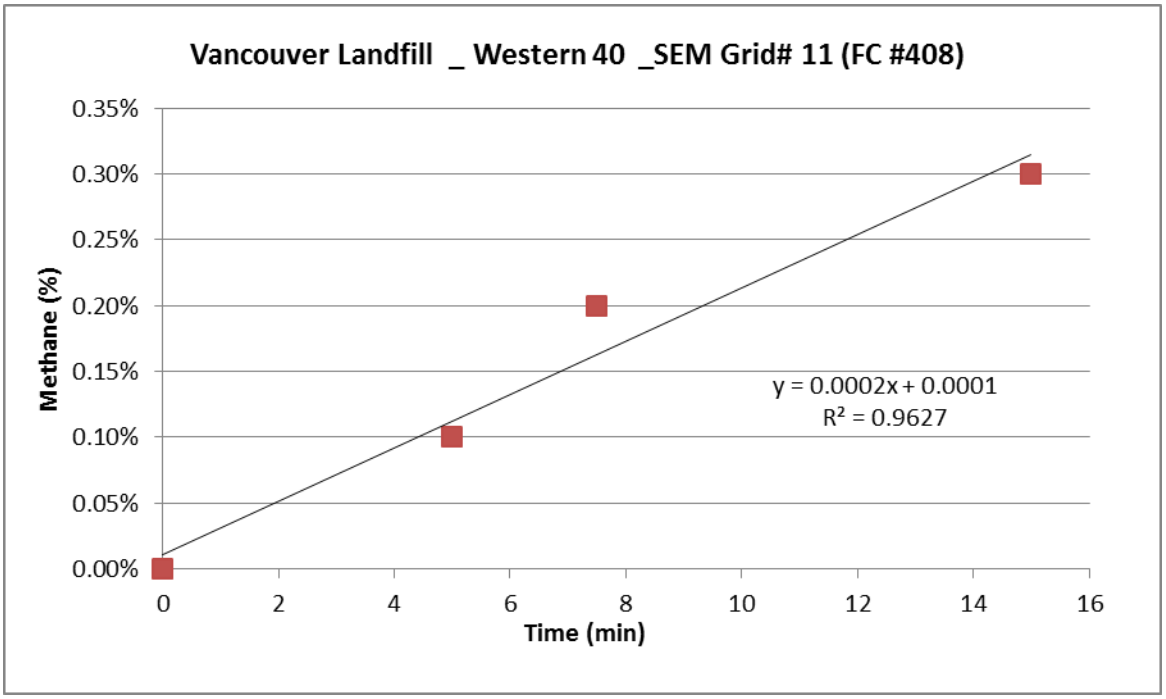

Vancouver Landfill _ Area 3 _SEM Grid# 151 (FC #311_56Dx2)
Methane (%)
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Time (min)
y = 0.0081x
R² = 0.9118


Vancouver Landfill _ Western 40 _SEM Grid# 11 (FC #401)
Methane (%)
0.90%
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
6
7
8
9
Time (min)
y = 0.0008x + 0.0017
R² = 0.9688


Vancouver Landfill _ Western 40 _SEM Grid# 11 (FC #403)
Methane (%)
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
Time (min)
y = 0.0014x + 0.0013
R² = 0.9748


Vancouver Landfill _ Western 40 _SEM Grid# 11 (FC #404)
Methane (%)
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Time (min)
y = 0.1992x + 0.0011
R² = 1


Vancouver Landfill _ Western 40 _SEM Grid# 11 (FC #406)
Methane (%)
1.00%
0.90%
0.80%
0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
0
1
2
3
4
5
Time (min)
y = 0.0019x + 0.0003
R² = 0.9912

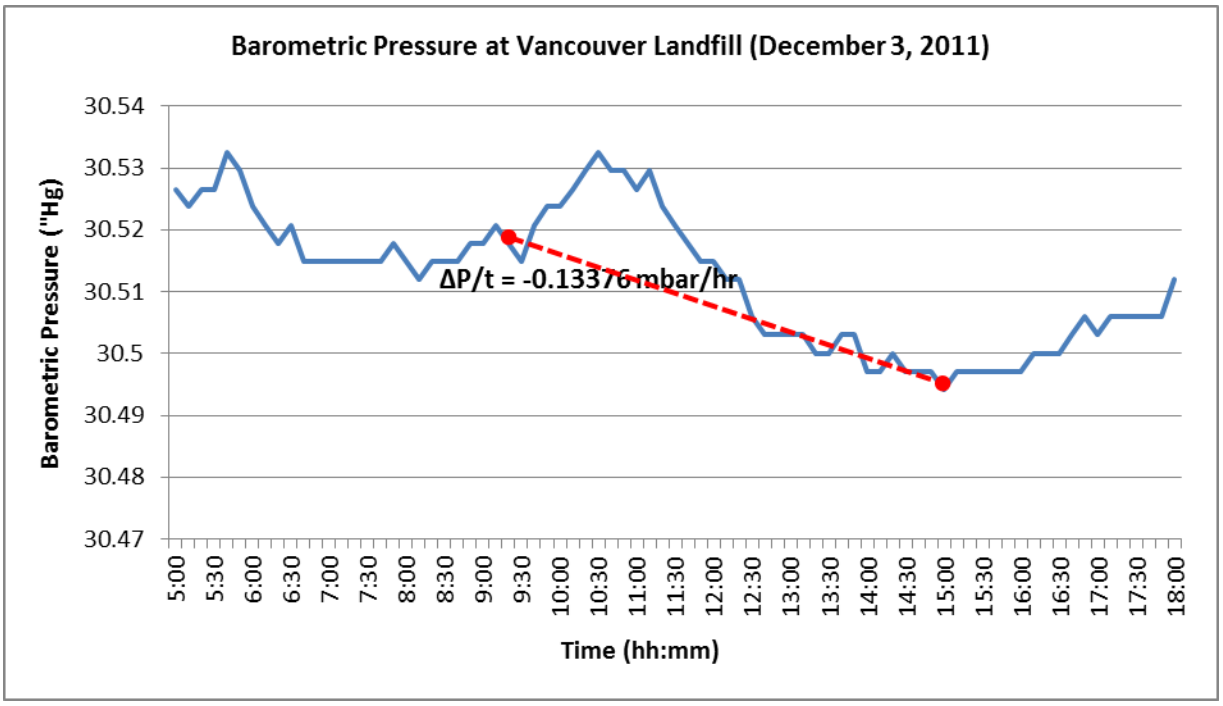

Vancouver Landfill _ Western 40 _SEM Grid# 11 (FC #408)
Methane (%)
0.35%
0.30%
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
0
2
4
6
8
10
12
14
16
Time (min)
y = 0.0002x + 0.0001
R² = 0.9627

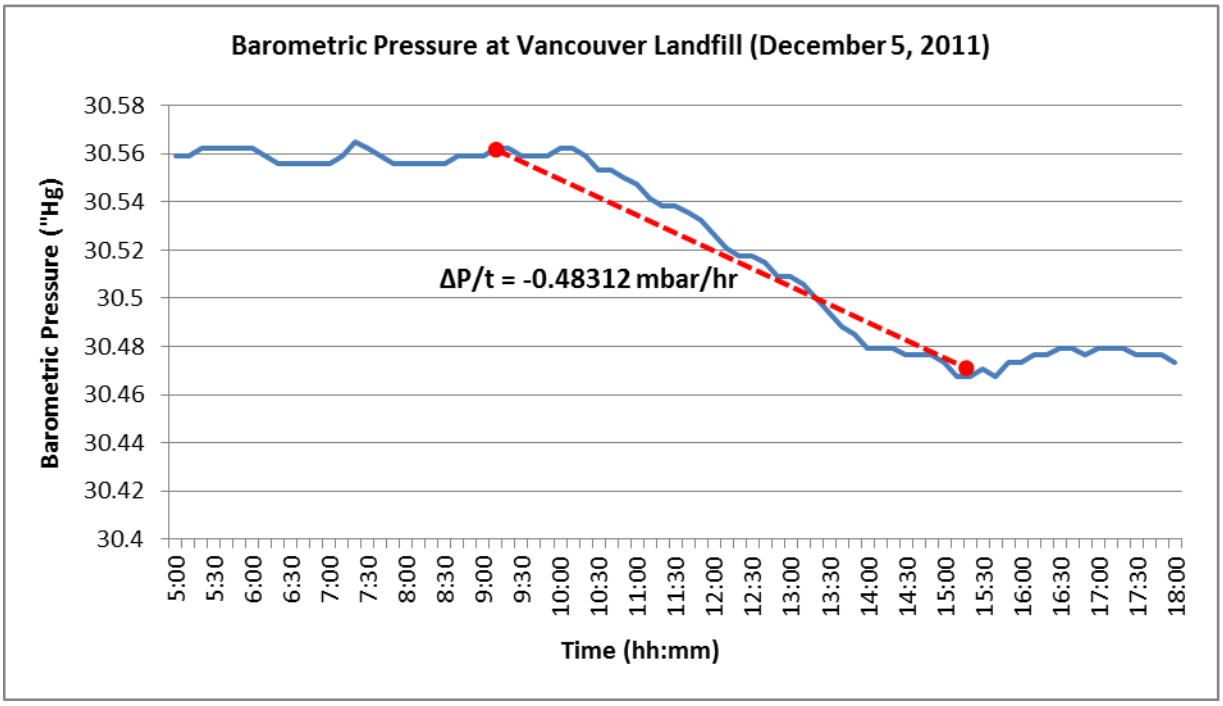
D.2 Full Results of The Flux Chamber Survey and Measured Methane Emission Rates (MER) at the Vancouver Landfill

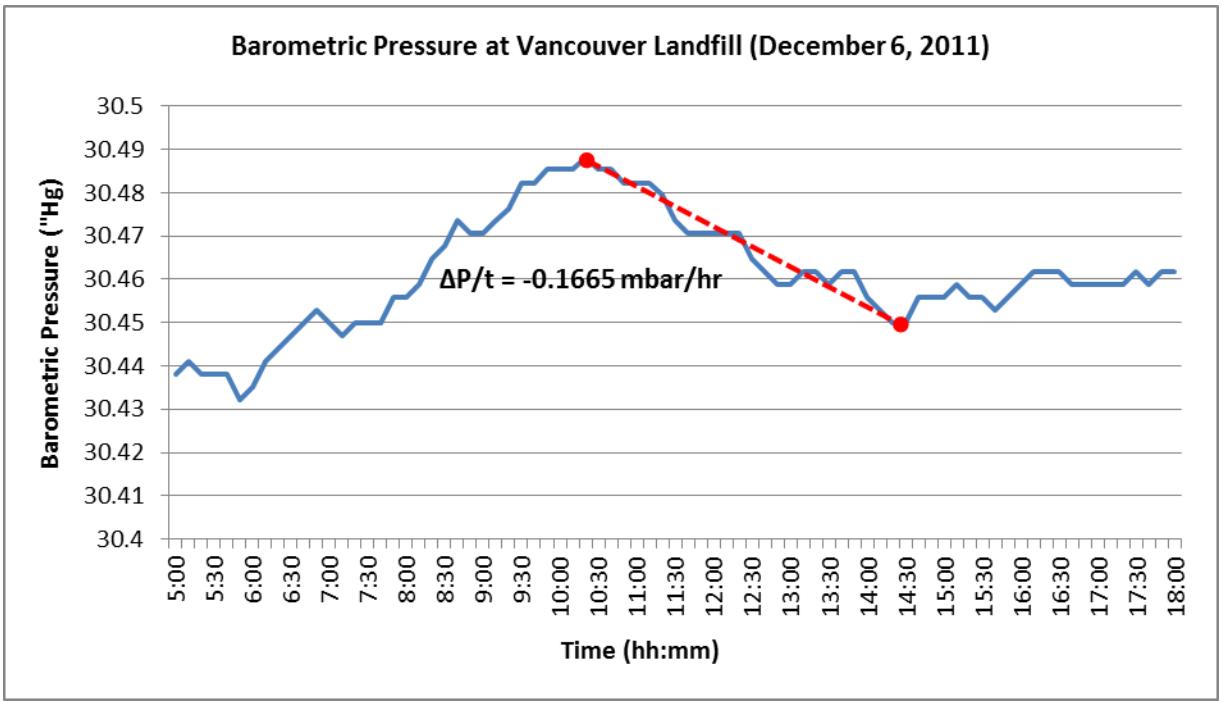
Date	Area	Grid#	FC#	$R_{\Delta P}$	CH_4 Emission (MER)			LFG Emission at 50%CH_4		R^2
					Measured	Adjusted		Measured	Adjusted	
				mbar/hr	gr/m^2/d	gr/m^2/d	kg/area/d	scfm/ha	scfm/ha	
15-Jun-12	Phase 1	163	35	-0.138	4709	3704	370	3546	2789	0.9824
15-Jun-12	Phase 1	163	35D	-0.138	4699	3695	0	3601	2832	0.9831
15-Jun-12	Phase 1	163	37	-0.138	46	36	36	35	27	0.9852
15-Jun-12	Phase 1	163	38	-0.138	135	106	21	104	81	0.9978
15-Jun-12	Phase 1	163	39	-0.138	434	341	34	333	262	0.9998
19-Jul-12	Phase 1	163	39D	-0.538	760	369	0	582	283	0.9985
15-Jun-12	Area 3	158	43	-0.138	48	38	1	37	29	0.9974
26-Jun-12	Area 3	158	44	0.350	419	708	13	304	513	0.9828
26-Jun-12	Area 3	158	45	0.350	58	99	2	42	72	0.9925
26-Jun-12	Area 3	158	46	0.350	29	49	1	21	36	0.9654
17-Jul-12	Area 3	158	46D	-0.067	60	53	0	46	41	0.9583
17-Jul-12	Area 3	158	47	-0.067	37	33	1	28	25	0.9359
17-Jul-12	Area 3	158	48	-0.067	797	704	13	604	533	0.9957
17-Jul-12	Area 3	158	48D	-0.067	890	786	0	672	593	0.9995
17-Jul-12	Area 3	158	49	-0.067	121	107	53	92	81	0.9005
17-Jul-12	Area 3	149	102	-0.067	139	123	2	106	94	0.9914
17-Jul-12	Area 3	149	104	-0.067	19	16	0	14	12	0.9932
17-Jul-12	Area 3	149	105	-0.067	193	171	34	148	131	0.9808
17-Jul-12	Area 3	149	108	-0.067	18	16	2	14	12	0.7802
17-Jul-12	Area 2E	139	91	-0.240	302	205	20	233	158	0.9848
17-Jul-12	Area 2E	139	92	-0.240	55	37	4	42	29	0.9900
17-Jul-12	Area 2E	135	111	-0.240	37	25	1	28	19	0.9802
17-Jul-12	Area 2E	135	114	-0.240	82	56	6	64	43	0.9461
18-Jul-12	Area 2W	102	200	0.013	402	412	10	297	304	0.9972
18-Jul-12	Area 2W	102	205	0.013	1817	559	56	1363	1397	0.9628
19-Jul-12	Area 2W	102	205D	-0.538	3724	542	0	2854	1385	0.9534
18-Jul-12	Area 2W	103	214	0.013	444	455	15	339	348	0.9907
18-Jul-12	Area 2W	103	216	0.013	1963	1006	34	1497	1535	0.9676
18-Jul-12	Area 2W	112	235	0.013	74	76	8	57	58	0.9880
18-Jul-12	Area 2W	104	240	0.013	28	28	10	21	22	0.9917
21-Jun-12	Area 3	151	56	-0.488	510	260	2	389	198	0.9854
26-Jun-12	Area 3	151	56D	0.601	205	447	0	148	324	0.9917
26-Jun-12	Area 3	151	56D2	0.601	185	404	0	134	293	0.9687
19-Jul-12	Area 3	151	56D3	-0.538	750	364	0	572	278	0.9118
21-Jun-12	Area 3	151	57	-0.488	132	67	1	101	51	0.9878
21-Jun-12	Area 3	151	62	-0.488	148	75	2	113	58	0.9936
26-Jun-12	Area 3	151	62D	0.601	68	149	0	49	108	0.9530
26-Jun-12	Area 3	151	64	0.601	37	81	2	27	59	0.9517
26-Jun-12	Area 3	151	65	0.601	195	426	43	141	309	0.9445

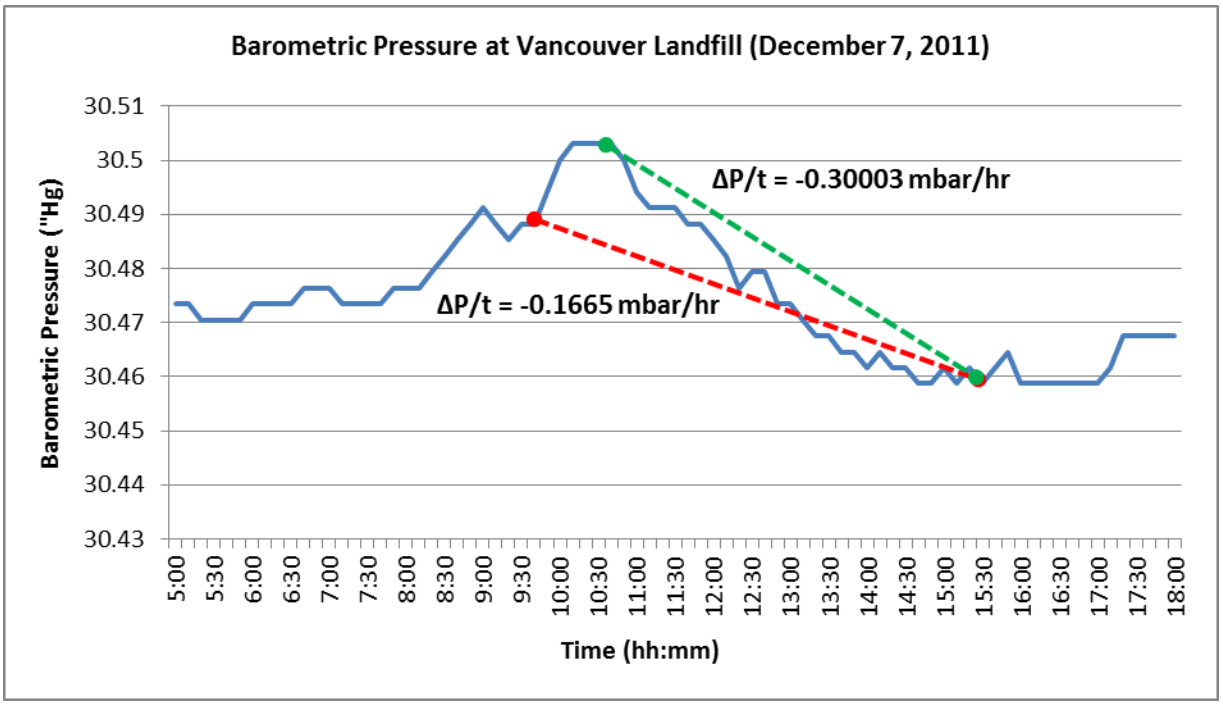
Date	Area	Grid#	FC#	$R_{\Delta P}$	CH_4 Emission (MER)			LFG Emission at 50%CH_4		R^2
					Measured	Adjusted		Measured	Adjusted	
				mbar/hr	$gr/m^2/d$	$gr/m^2/d$	kg/area/d	scfm/ha	scfm/ha	
16-Jul-12	Area 3	146	71D	-0.300	326	205	0	247	155	0.8986
16-Jul-12	Area 3	146	71	-0.300	389	244	12	297	186	0.9881
16-Jul-12	Area 3	146	72	-0.300	500	314	16	381	240	0.9237
16-Jul-12	Area 3	147	76	-0.300	202	127	4	154	97	0.9884
16-Jul-12	Area 3	147	77	-0.300	2462	1546	52	1879	1180	0.9497
16-Jul-12	Area 3	147	78	-0.300	528	331	11	403	253	0.9867
16-Jul-12	Area 3	147	83	-0.300	92	58	58	71	44	0.9248
16-Jul-12	Phase 1	162	88	-0.600	26	12	3	20	9	1.0000
16-Jul-12	Phase 1	162	90	-0.600	17	8	1	13	6	0.9710
16-Jul-12	Phase 1	162	91	-0.600	256	117	6	198	91	0.9513
19-Jul-12	West 40	11	401	-0.538	74	36	36	57	27	0.9688
19-Jul-12	West 40	11	403	-0.538	130	63	63	99	48	0.9748
19-Jul-12	West 40	11	406	-0.538	175	85	85	134	65	0.9912
19-Jul-12	West 40	11	408	-0.538	18	9	9	14	7	0.9627

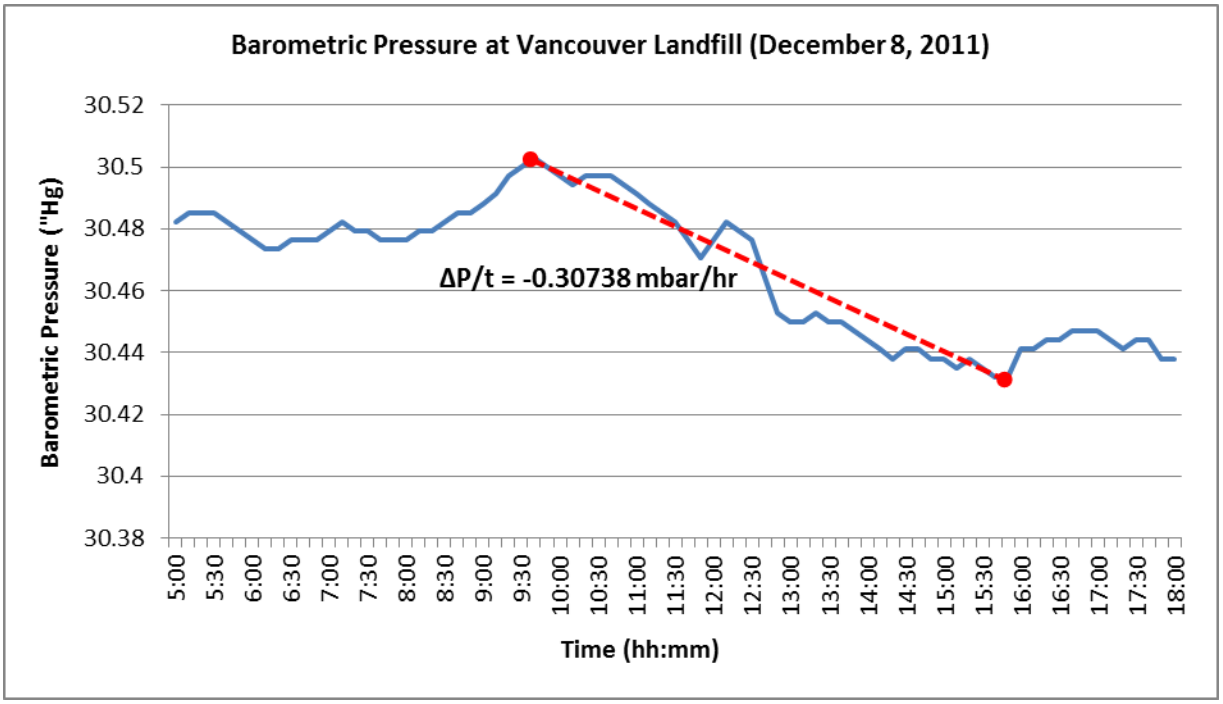
D.3 Graphical Presentation of the Recorded Barometric Pressure During Preliminary Surface Scan and Flux Measurement Test at the Vancouver Landfill

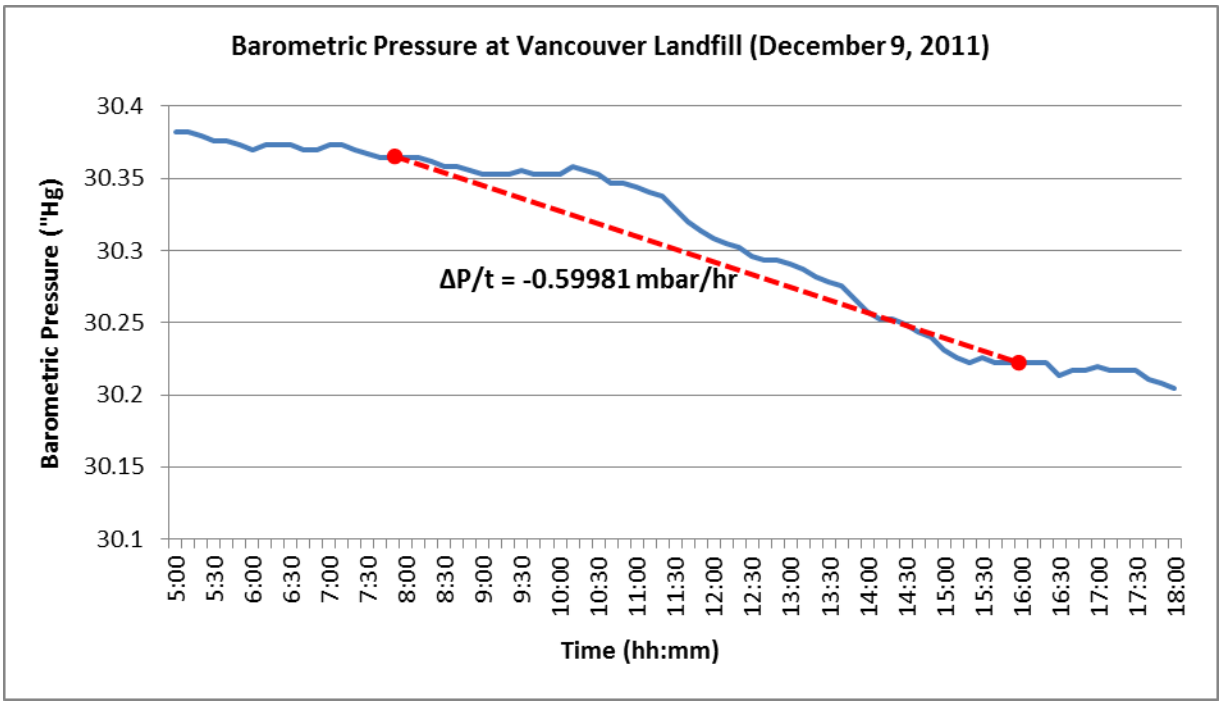


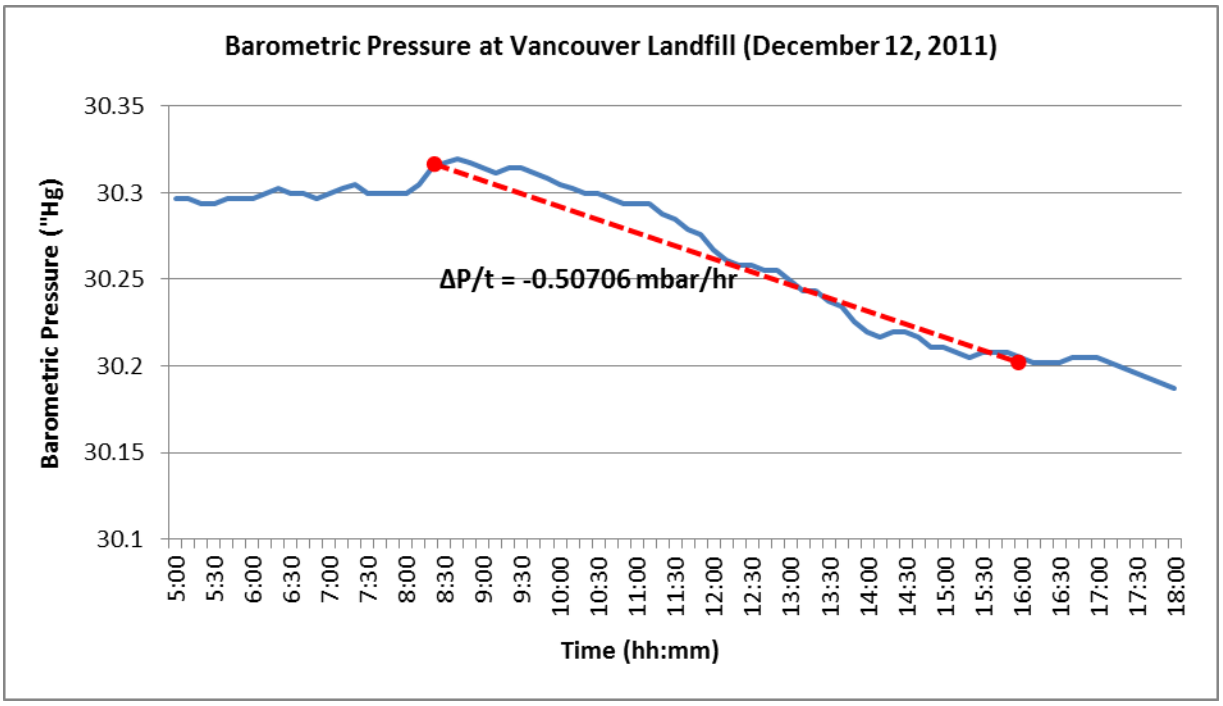


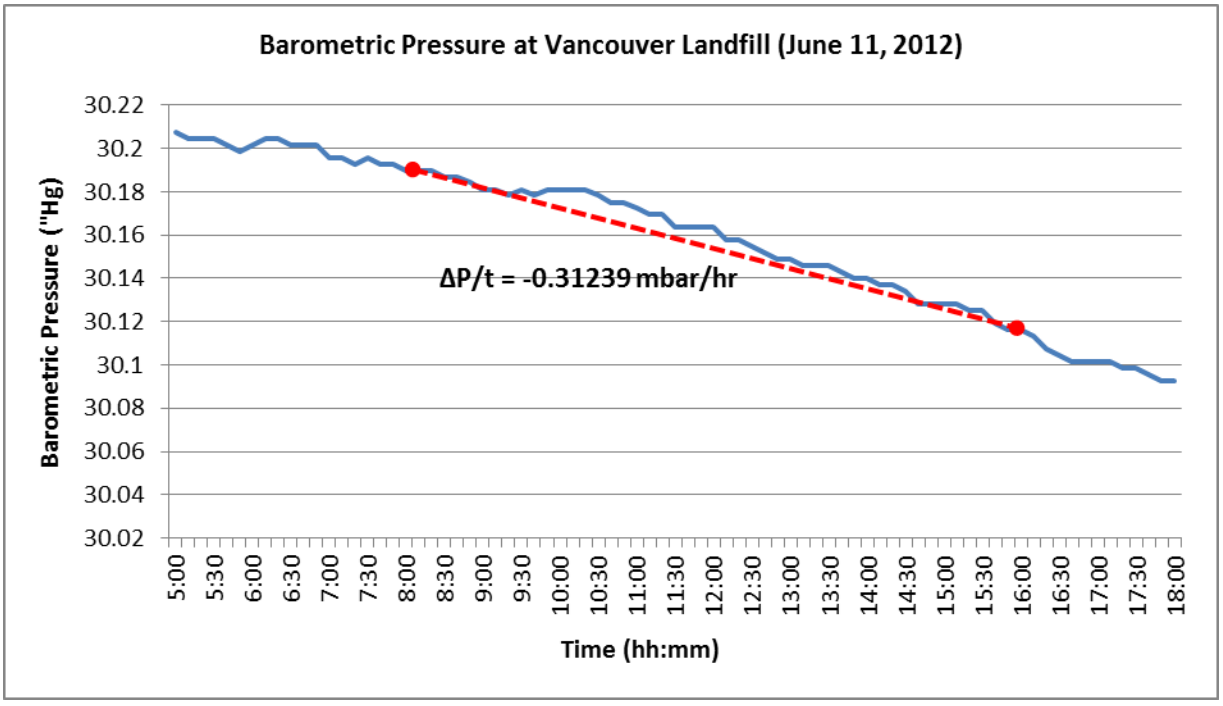

Barometric Pressure at Vancouver Landfill (December 6, 2011)
Barometric Pressure ("Hg)
30.5
30.49
30.48
30.47
30.46
30.45
30.44
30.43
30.42
30.41
30.4
ΔP/t = -0.1665 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

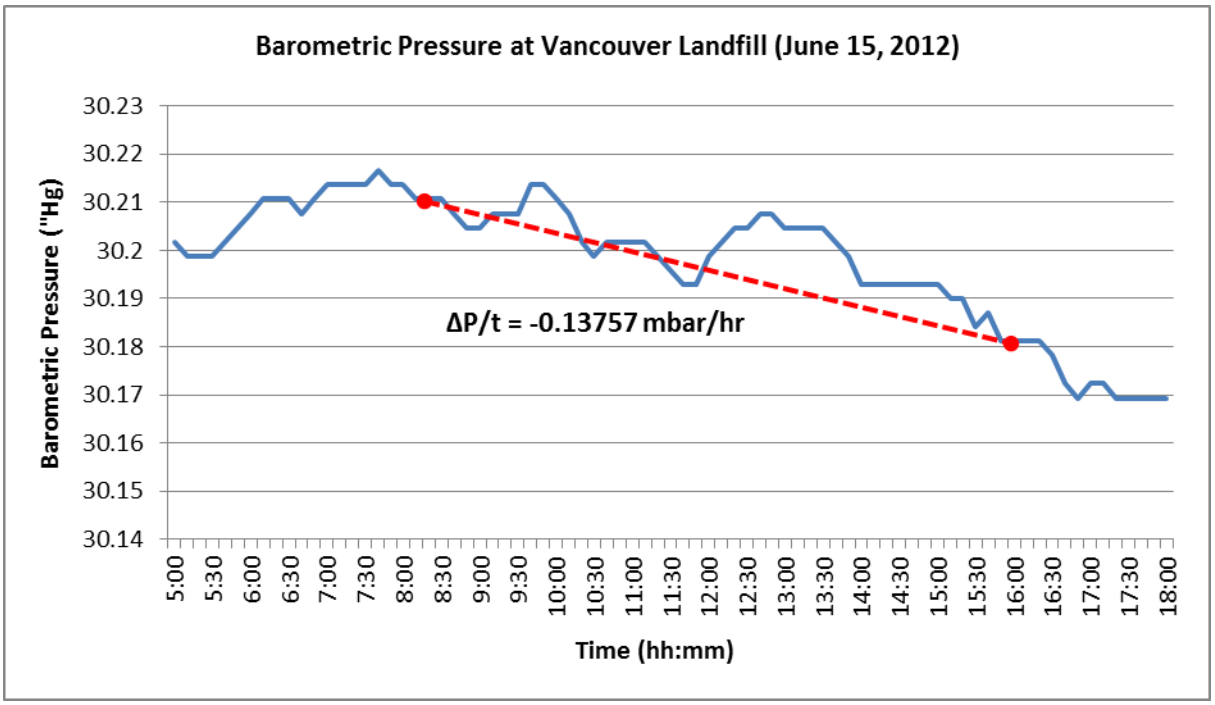

Barometric Pressure at Vancouver Landfill (December 7, 2011)
Barometric Pressure ("Hg)
30.51
30.5
30.49
30.48
30.47
30.46
30.45
30.44
30.43
ΔP/t = -0.30003 mbar/hr
ΔP/t = -0.1665 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

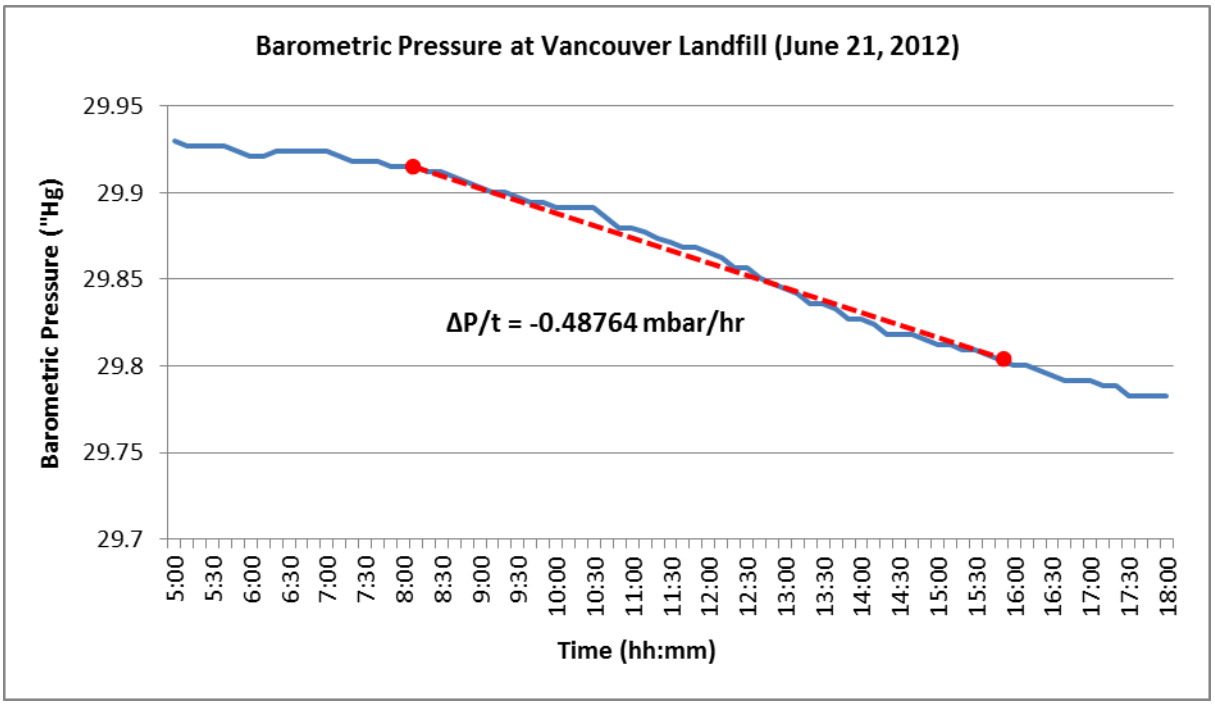

Barometric Pressure at Vancouver Landfill (December 8, 2011)
Barometric Pressure ("Hg)
30.52
30.5
30.48
30.46
30.44
30.42
30.4
30.38
ΔP/t = -0.30738 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

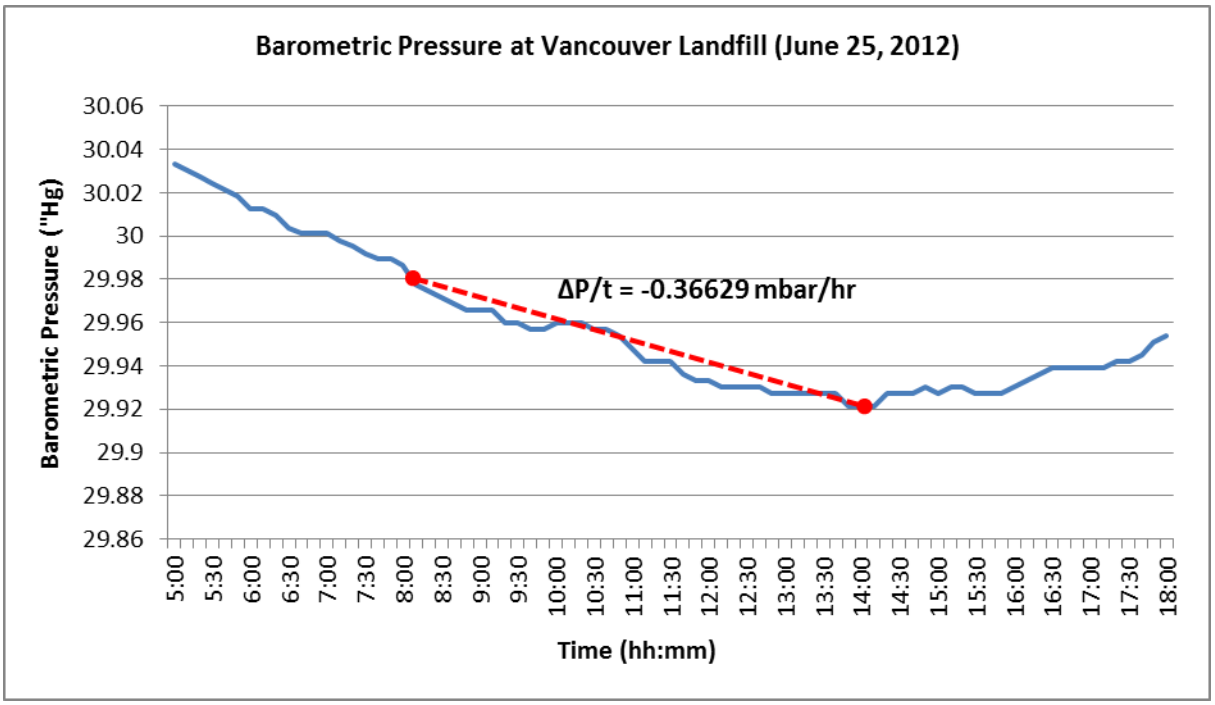

Barometric Pressure at Vancouver Landfill (December 9, 2011)
Barometric Pressure ("Hg)
30.4
30.35
30.3
30.25
30.2
30.15
30.1
ΔP/t = -0.59981 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

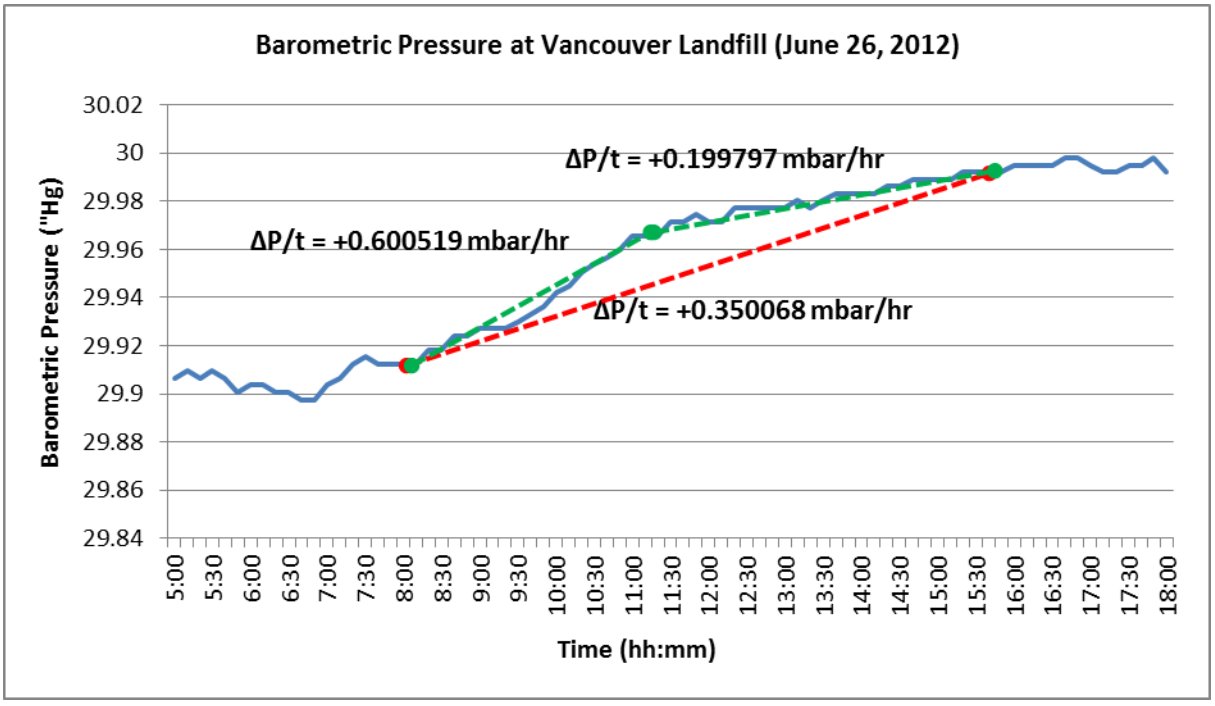

Barometric Pressure at Vancouver Landfill (December 12, 2011)
Barometric Pressure ("Hg)
30.35
30.3
30.25
30.2
30.15
30.1
ΔP/t = -0.50706 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

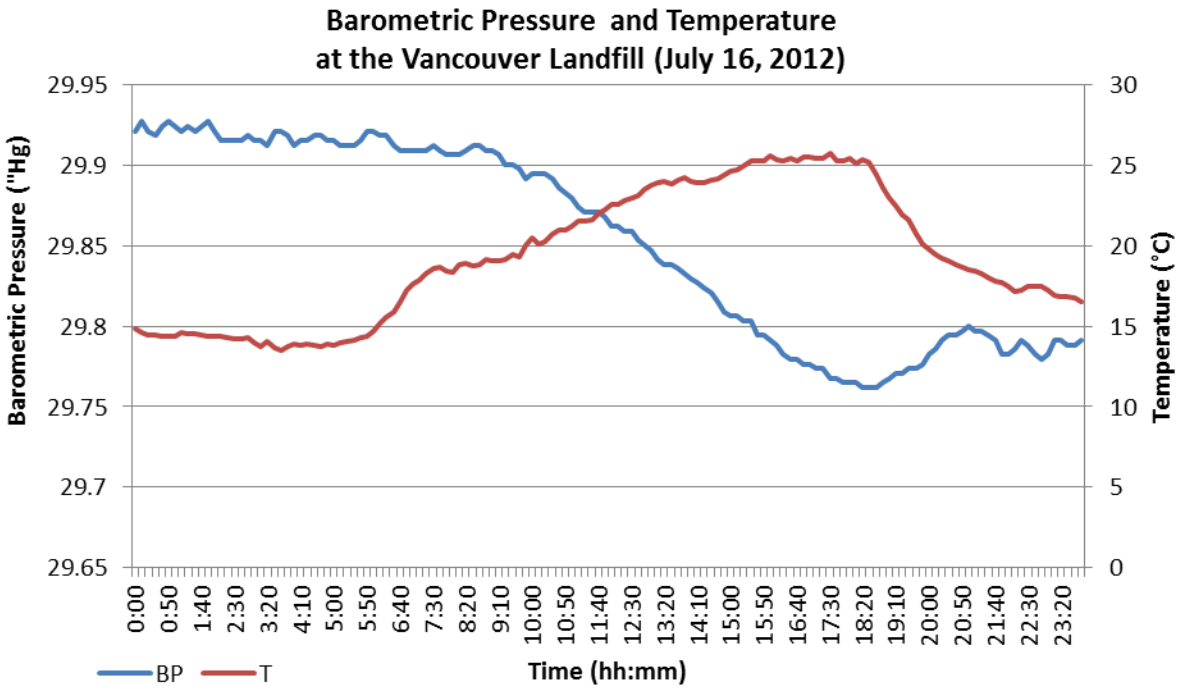

Barometric Pressure at Vancouver Landfill (June 11, 2012)
Barometric Pressure ("Hg)
30.22
30.2
30.18
30.16
30.14
30.12
30.1
30.08
30.06
30.04
30.02
ΔP/t = -0.31239 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

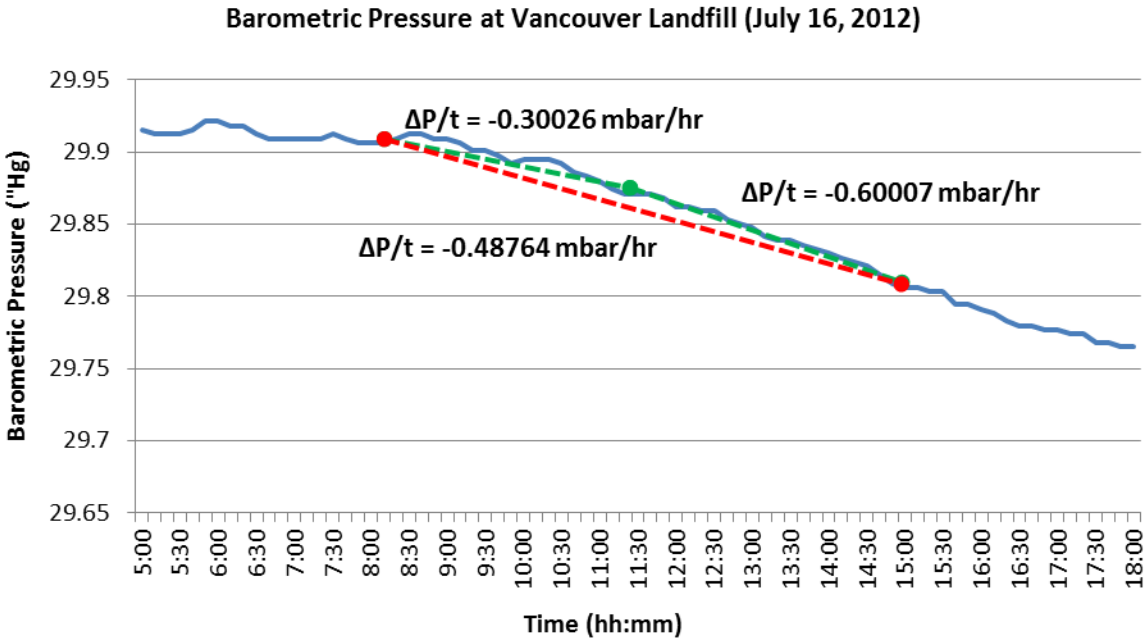

Barometric Pressure at Vancouver Landfill (June 15, 2012)
Barometric Pressure ("Hg)
30.23
30.22
30.21
30.2
30.19
30.18
30.17
30.16
30.15
30.14
ΔP/t = -0.13757 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

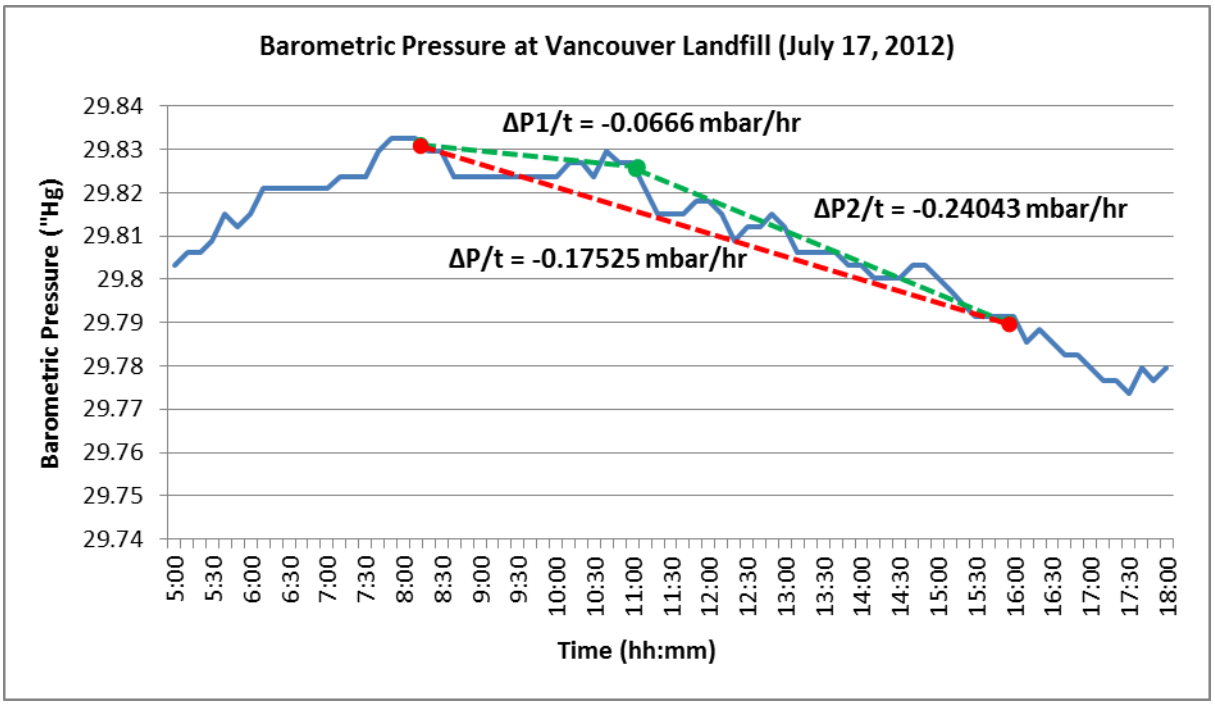

Barometric Pressure at Vancouver Landfill (June 21, 2012)
Barometric Pressure ("Hg)
29.95
29.9
29.85
29.8
29.75
29.7
ΔP/t = -0.48764 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

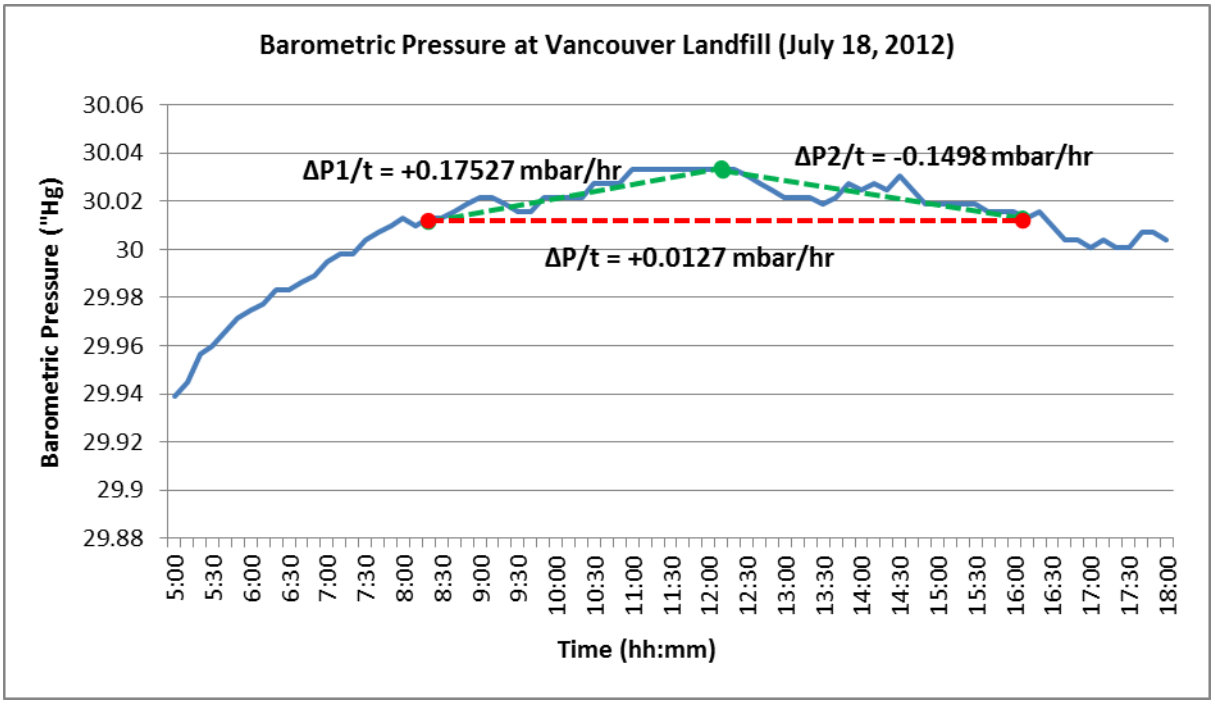

Barometric Pressure at Vancouver Landfill (June 25, 2012)
Barometric Pressure ("Hg)
30.06
30.04
30.02
30
29.98
29.96
29.94
29.92
29.9
29.88
29.86
ΔP/t = -0.36629 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

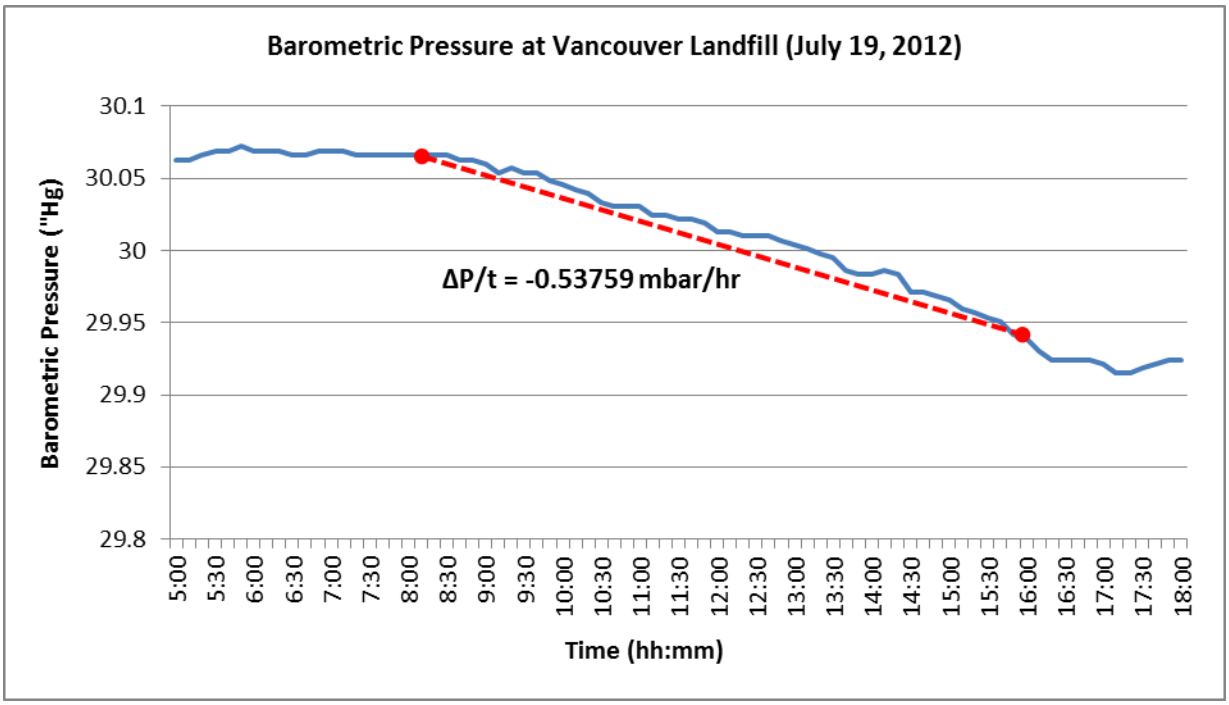

Barometric Pressure at Vancouver Landfill (June 26, 2012)
Barometric Pressure ("Hg)
30.02
30
29.98
29.96
29.94
29.92
29.9
29.88
29.86
29.84
ΔP/t = +0.199797 mbar/hr
ΔP/t = +0.600519 mbar/hr
ΔP/t = +0.350068 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)


Barometric Pressure and Temperature
at the Vancouver Landfill (July 16, 2012)
Barometric Pressure ("Hg)
Temperature (°C)
29.95
29.9
29.85
29.8
29.75
29.7
29.65
30
25
20
15
10
5
0
0:00
0:50
1:40
2:30
3:20
4:10
5:00
5:50
6:40
7:30
8:20
9:10
10:00
10:50
11:40
12:30
13:20
14:10
15:00
15:50
16:40
17:30
18:20
19:10
20:00
20:50
21:40
22:30
23:20
BP
T
Time (hh:mm)


Barometric Pressure at Vancouver Landfill (July 16, 2012)
Barometric Pressure ("Hg)
29.95
29.9
29.85
29.8
29.75
29.7
29.65
ΔP/t = -0.30026 mbar/hr
ΔP/t = -0.60007 mbar/hr
ΔP/t = -0.48764 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)


Barometric Pressure at Vancouver Landfill (July 17, 2012)
ΔP1/t = -0.0666 mbar/hr
ΔP2/t = -0.24043 mbar/hr
ΔP/t = -0.17525 mbar/hr
Barometric Pressure ("Hg)
29.84
29.83
29.82
29.81
29.8
29.79
29.78
29.77
29.76
29.75
29.74
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)


Barometric Pressure at Vancouver Landfill (July 18, 2012)
ΔP1/t = +0.17527 mbar/hr
ΔP2/t = -0.1498 mbar/hr
ΔP/t = +0.0127 mbar/hr
Barometric Pressure ("Hg)
30.06
30.04
30.02
30
29.98
29.96
29.94
29.92
29.9
29.88
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)


Barometric Pressure at Vancouver Landfill (July 19, 2012)
Barometric Pressure ("Hg)
30.1
30.05
30
29.95
29.9
29.85
29.8
ΔP/t = -0.53759 mbar/hr
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
Time (hh:mm)

D.4 Estimated Methane and Landfill Gas Emission Rate at the Vancouver Landfill Within the Study Boundary

	Grid No.	Date	$R_{\Delta P}$ mbar/hr	SEM ppm [CH_4]	SEM_a	MER_a gr/m^2/d	Area m^2	CH_4 Kg/d	CH_4 m3/hr	LFG scfm	CH_4 T/Y
Area 2W	92	07-Dec-11	-0.30003	8.7	5.5	3.15	7,300	22.96	1.41	1.66	12.7
	93	07-Dec-11	-0.30003	10.0	6.3	3.40	10,000	34.00	2.09	2.46	18.8
	94	07-Dec-11	-0.30003	10.7	6.7	3.54	10,000	35.43	2.18	2.56	19.6
	95	07-Dec-11	-0.30003	10.6	6.7	3.52	5,050	17.76	1.09	1.29	9.8
	96	07-Dec-11	-0.30003	11.3	7.1	3.66	5,880	21.51	1.32	1.56	11.9
	97	07-Dec-11	-0.30003	4.0	2.5	2.20	10,000	21.97	1.35	1.59	12.1
	98	08-Dec-11	-0.30738	3.2	2.0	2.03	10,000	20.33	1.25	1.47	11.2
	99	08-Dec-11	-0.30738	-0.5	1.0	1.71	7,300	12.46	0.77	0.90	6.9
	100	08-Dec-11	-0.30738	1.1	0.7	1.60	6,630	10.61	0.65	0.77	5.9
	101	12-Dec-11	-0.50706	14.6	7.3	3.72	10,000	37.21	2.29	2.69	20.6
	102	12-Dec-11	-0.50706	27.9	14.0	5.85	10,000	58.54	3.60	4.24	32.4
	103	12-Dec-11	-0.50706	51.6	25.8	9.64	8,110	78.21	4.81	5.66	43.3
	104	12-Dec-11	-0.50706	43.9	21.9	8.41	7,130	59.96	3.69	4.34	33.2
	105	08-Dec-11	-0.30738	3.8	2.4	2.15	12,090	26.00	1.60	1.88	14.4
	106	08-Dec-11	-0.30738	3.8	2.3	2.14	10,000	21.35	1.31	1.55	11.8
	107	08-Dec-11	-0.30738	5.3	3.3	2.44	10,000	24.45	1.50	1.77	13.5
	108	08-Dec-11	-0.30738	6.3	3.9	2.64	10,000	26.42	1.62	1.91	14.6
	109	12-Dec-11	-0.50706	30.5	15.3	6.28	5,950	37.34	2.30	2.70	20.7
	110	12-Dec-11	-0.50706	9.6	4.8	2.92	5,950	17.39	1.07	1.26	9.6
	111	12-Dec-11	-0.50706	13.0	6.5	3.47	10,000	34.70	2.13	2.51	19.2
	112	12-Dec-11	-0.50706	15.6	7.8	3.88	10,000	38.76	2.38	2.81	21.4
	113	08-Dec-11	-0.30738	6.3	3.9	2.65	10,000	26.48	1.63	1.92	14.6
	114	08-Dec-11	-0.30738	6.2	3.9	2.62	10,000	26.24	1.61	1.90	14.5
	115	08-Dec-11	-0.30738	6.2	3.8	2.62	6,150	16.11	0.99	1.17	8.9
	116	08-Dec-11	-0.30738	5.4	3.4	2.47	6,260	15.44	0.95	1.12	8.5
	117	12-Dec-11	-0.50706	6.1	3.1	2.37	10,000	23.70	1.46	1.72	13.1
	118	12-Dec-11	-0.50706	2.7	1.4	1.82	10,000	18.21	1.12	1.32	10.1
	119	12-Dec-11	-0.50706	4.8	2.4	2.16	10,000	21.59	1.33	1.56	11.9
	120	12-Dec-11	-0.50706	8.5	4.2	2.74	10,000	27.43	1.69	1.99	15.2
	121	12-Dec-11	-0.50706	1.7	0.8	1.65	5,900	9.76	0.60	0.71	5.4
	Total Methane Emission from Area 2W						**259,700**	**842**	**52**	**61**	**466**
Area 2E	122	08-Dec-11	-0.30738	6.701	4	2.72	4,250	11.57	0.71	0.84	6.4
	123	08-Dec-11	-0.30738	7.254	5	2.83	7,150	20.25	1.25	1.47	11.2
	124	08-Dec-11	-0.30738	6.346	4	2.65	7,150	18.96	1.17	1.37	10.5
	125	08-Dec-11	-0.30738	6.149	4	2.61	7,150	18.68	1.15	1.35	10.3
	126	08-Dec-11	-0.30738	7.455	5	2.87	7,150	20.54	1.26	1.49	11.4
	127	08-Dec-11	-0.30738	7.424	5	2.87	7,150	20.49	1.26	1.48	11.3
	128	08-Dec-11	-0.30738	6.862	4	2.75	7,150	19.69	1.21	1.43	10.9

	Grid No.	Date	$R_{\Delta P}$ mbar/hr	SEM ppm [CH_4]	SEM_a	MER_a gr/m^2/d	Area m^2	CH_4 Kg/d	CH_4 m3/hr	LFG scfm	CH_4 T/Y
	129	08-Dec-11	-0.30738	2.755	2	1.94	3,300	6.39	0.39	0.46	3.5
	130	08-Dec-11	-0.30738	4.927	3	2.37	4,850	11.49	0.71	0.83	6.4
	131	08-Dec-11	-0.30738	5.678	4	2.52	10,000	25.18	1.55	1.82	13.9
	132	08-Dec-11	-0.30738	6.117	4	2.61	10,000	26.06	1.60	1.89	14.4
	133	08-Dec-11	-0.30738	4.838	3	2.35	10,000	23.51	1.45	1.70	13.0
	134	08-Dec-11	-0.30738	3.387	2	2.06	10,000	20.62	1.27	1.49	11.4
	135	08-Dec-11	-0.30738	5.739	4	2.53	10,000	25.31	1.56	1.83	14.0
	136	12-Dec-11	-0.50706	0.079	0	1.40	10,000	13.99	0.86	1.01	7.7
	137	12-Dec-11	-0.50706	12.984	6	3.46	4,900	16.98	1.04	1.23	9.4
	138	12-Dec-11	-0.50706	16.432	8	4.02	4,700	18.88	1.16	1.37	10.4
	139	12-Dec-11	-0.50706	7.193	4	2.54	10,000	25.38	1.56	1.84	14.0
	140	12-Dec-11	-0.50706	4.152	2	2.05	10,000	20.51	1.26	1.48	11.3
	141	12-Dec-11	-0.50706	6.842	3	2.48	10,000	24.82	1.53	1.80	13.7
	142	12-Dec-11	-0.50706	4.250	2	2.07	10,000	20.67	1.27	1.50	11.4
	143	12-Dec-11	-0.50706	4.047	2	2.03	10,000	20.34	1.25	1.47	11.3
	144	12-Dec-11	-0.50706	3.450	2	1.94	10,000	19.39	1.19	1.40	10.7
	145	12-Dec-11	-0.50706	1.557	1	1.64	4,110	6.72	0.41	0.49	3.7
	Total Methane Emission from Area 2E						**189,010**	**456**	**28**	**33**	**252**
Area 3	146	12-Dec-11	-0.50706	32.241	16	6.55	5,050	33.06	2.03	2.39	18.3
	147	12-Dec-11	-0.50706	79.238	40	14.07	10,000	140.68	8.65	10.18	77.8
	148	12-Dec-11	-0.50706	22.306	11	4.96	10,000	49.57	3.05	3.59	27.4
	149	12-Dec-11	-0.50706	30.675	15	6.30	10,000	62.96	3.87	4.56	34.8
	150	12-Dec-11	-0.50706	22.178	11	4.94	10,000	49.36	3.04	3.57	27.3
	151	12-Dec-11	-0.50706	11.806	6	3.28	10,000	32.76	2.01	2.37	18.1
	152	12-Dec-11	-0.50706	9.372	5	2.89	10,000	28.87	1.78	2.09	16.0
	153	12-Dec-11	-0.50706	11.103	6	3.16	5,300	16.77	1.03	1.21	9.3
	154	12-Dec-11	-0.50706	6.710	3	2.46	5,400	13.29	0.82	0.96	7.3
	155	12-Dec-11	-0.50706	22.791	11	5.03	10,000	50.34	3.10	3.64	27.8
	156	12-Dec-11	-0.50706	8.121	4	2.69	10,000	26.86	1.65	1.94	14.9
	157	12-Dec-11	-0.50706	11.187	6	3.18	10,000	31.77	1.95	2.30	17.6
	158	12-Dec-11	-0.50706	21.176	11	4.78	10,000	47.76	2.94	3.46	26.4
	159	12-Dec-11	-0.50706	20.687	10	4.70	10,000	46.98	2.89	3.40	26.0
	160	12-Dec-11	-0.50706	4.985	2	2.18	10,000	21.85	1.34	1.58	12.1
	161	09-Dec-11	-0.59981	6.469	3	2.34	4,800	11.21	0.69	0.81	6.2
	Total Methane Emission from Area 3						**140,550**	**664**	**41**	**48**	**367**
Phase 1W	162	09-Dec-11	-0.59981	64.866	30	10.90	4,700	51.22	3.15	3.71	28.3
	163*	09-Dec-11	-0.59981	565.034	259	84.24	10,000	842.36	51.81	60.98	17.6
	164	09-Dec-11	-0.59981	14.728	7	3.55	10,000	35.46	2.18	2.57	19.6
	165	09-Dec-11	-0.59981	8.227	4	2.59	10,000	25.93	1.59	1.88	14.3
	166	09-Dec-11	-0.59981	7.833	4	2.54	10,000	25.35	1.56	1.84	14.0
	167	09-Dec-11	-0.59981	8.771	4	2.67	10,000	26.73	1.64	1.93	14.8
	168	09-Dec-11	-0.59981	9.750	4	2.82	10,000	28.16	1.73	2.04	15.6

	Grid No.	Date	$R_{\Delta P}$	SEM	SEM_a	MER_a	Area	CH_4	CH_4	LFG	CH_4
			mbar/hr	ppm [CH_4]		$gr/m^2/d$	m^2	Kg/d	m3/hr	scfm	T/Y
	169	09-Dec-11	-0.59981	23.989	11	4.90	5,580	27.37	1.68	1.98	15.1
	170	09-Dec-11	-0.59981	21.332	10	4.51	5,580	25.19	1.55	1.82	13.9
	171	09-Dec-11	-0.59981	14.468	7	3.51	10,000	35.08	2.16	2.54	19.4
	172	09-Dec-11	-0.59981	23.512	11	4.83	10,000	48.34	2.97	3.50	26.7
	173	09-Dec-11	-0.59981	19.946	9	4.31	10,000	43.11	2.65	3.12	23.8
	174	09-Dec-11	-0.59981	17.942	8	4.02	10,000	40.18	2.47	2.91	22.2
	175	09-Dec-11	-0.59981	20.597	9	4.41	10,000	44.07	2.71	3.19	24.4
	176	09-Dec-11	-0.59981	3.438	2	1.89	10,000	18.91	1.16	1.37	10.5
	177	09-Dec-11	-0.59981	14.730	7	3.55	5,050	17.91	1.10	1.30	9.9
	Total Methane Emission from Phase 1W						**140,910**	**1,335**	**82**	**97**	**290**
Phase 1E	178	09-Dec-11	-0.59981	9.532	4	2.78	5,000	13.92	0.86	1.01	7.7
	179	09-Dec-11	-0.59981	9.792	4	2.82	10,000	28.22	1.74	2.04	15.6
	180	09-Dec-11	-0.59981	1.557	1	1.62	10,000	16.15	0.99	1.17	8.9
	181	09-Dec-11	-0.59981	1.599	1	1.62	10,000	16.21	1.00	1.17	9.0
	182	09-Dec-11	-0.59981	1.597	1	1.62	10,000	16.21	1.00	1.17	9.0
	183	09-Dec-11	-0.59981	1.621	1	1.62	10,000	16.24	1.00	1.18	9.0
	184	09-Dec-11	-0.59981	1.534	1	1.61	10,000	16.12	0.99	1.17	8.9
	185	09-Dec-11	-0.59981	6.335	3	2.32	4,300	9.96	0.61	0.72	5.5
	186	09-Dec-11	-0.59981	2.155	1	1.70	4,300	7.32	0.45	0.53	4.0
	187	09-Dec-11	-0.59981	3.368	2	1.88	4,300	8.09	0.50	0.59	4.5
	188	09-Dec-11	-0.59981	3.107	1	1.84	4,300	7.92	0.49	0.57	4.4
	189	09-Dec-11	-0.59981	4.520	2	2.05	4,300	8.81	0.54	0.64	4.9
	190	09-Dec-11	-0.59981	3.578	2	1.91	4,300	8.22	0.51	0.60	4.5
	191	09-Dec-11	-0.59981	2.650	1	1.78	4,300	7.63	0.47	0.55	4.2
	192	09-Dec-11	-0.59981	1.528	1	1.61	4,251	6.85	0.42	0.50	3.8
	193	09-Dec-11	-0.59981	0.614	0	1.48	2,000	2.95	0.18	0.21	1.6
	Total Methane Emission from Phase 1E						**101,351**	**191**	**12**	**14**	**106**
	Total Methane Emission from Phase 1						242,261	1,526	94	110	396

* unreliable SMC data due to open LFG well at the time of sampling, therefore flux chamber results were used for this grid

Adjusted SEM (SEM_a) = SEM x (1+ **1.9731** x $|R_{\Delta P}|)^(R_{\Delta P}/|R_{\Delta P}|)$

Adjusted MER (MER_a) = SEMa x **0.3202** + **1.3867**

Methane Density = **0.6775** kg m^{-3}

E. Correction Factor (CF_E) = **1.515** =1/66%

Appendix E Stable Isotope Tests Raw Data and Full Results

E.1 Flux Chamber Initial and Final Gas Samples

Vial	Area /Phase	Grid#	Label (FC#)	Date	INI/FIN	[CH_4] (% Volume)	Average $\delta^{13}C$ (ppt)	Std Dev
1	Western 40	11	402	19-Jul-12	INI	0.2	**-40.54**	**0.221**
2					FIN	0.8	**-36.27**	**0.017**
3			406	19-Jul-12	INI	0.2	**-50.19**	**0.049**
4					FIN	1	**-46.64**	**0.010**
5	Area 2W	102	200	18-Jul-12	INI	0.9	**-52.98**	**0.085**
6					FIN	3.4	**-52.16**	**0.325**
7			205	18-Jul-12	INI	0.7	**-54.17**	**0.112**
8					FIN	11.7	**-52.69**	**0.016**
9		103	214	18-Jul-12	INI	0.8	**-51.07**	**0.311**
10					FIN	2.2	**-48.09**	**0.124**
11		104	309	19-Jul-12	INI	0.3	**-47.48**	**0.017**
12	Area 2E	135	114	17-Jul-12	INI	0.3	**-52.31**	**0.157**
13					FIN	0.9	**-48.33**	**0.023**
14		139	91B	17-Jul-12	INI	0.3	**-52.28**	**0.311**
15					FIN	2.5	**-50.68**	**0.040**
16	Area 3	146	71	16-Jul-12	INI	0.6	**-54.99**	**0.151**
17					FIN	4.9	**-51.31**	**0.074**
18		147	78	16-Jul-12	INI	0.4	**-54.03**	**0.169**
19					FIN	3.3	**-52.56**	**0.064**
20		151	311	19-Jul-12	INI	1.1	**-54.47**	**0.386**
21					FIN	8.3	**-50.45**	**0.291**
22			62	21-Jun-12	FIN	2.6	**-48.59**	**0.100**
23		158 (Anoxic taken)	44	26-Jun-12	INI	0.4	**-53.25**	**0.242**
24					FIN	2.5	**-53.10**	**0.019**
25			47	17-Jul-12	INI	0.4	**-53.38**	**0.108**
26					FIN	1	**-47.77**	**0.078**
27			48	17-Jul-12	INI	0.7	**-53.96**	**0.113**
28					FIN	7.9	**-47.51**	**0.040**
29			108	17-Jul-12	INI	0.2	**-43.47**	**0.011**
30					FIN	0.3	**-41.49**	**0.070**
31	Phase 1	162	91A	16-Jul-12	INI	0.2	**-49.37**	**0.238**
32					FIN	4.7	**-50.62**	**0.027**
33		163 (Anoxic taken)	35	15-Jun-12	INI	6	**-59.30**	**0.047**
34					FIN	28.6	**-56.22**	**0.109**
35					FIN(D)	32	**-56.38**	**0.051**
36			38	15-Jun-12	FIN	5.6	**-54.47**	**0.002**
37			300	18-Jul-12	INI	1.4	**-57.37**	**0.291**
38					FIN	7.6	**-56.07**	**0.105**

E.2 Soil Gas Samples Raw Data, GC-FID, and GCC-IRMS Results

Vial #	Label	Date	[CH_4] (% Volume)	Average $\delta^{13}C$ (ppt)	Std Dev
1	SG1/t0	20-Jul-12	4.9%	**-39.10**	**0.262**
2	SG1/t1	20-Jul-12	5.2%	**-39.52**	**0.095**
3	SG1/t2	20-Jul-12	4.0%	**-39.30**	**0.182**
4	SG1/t3	20-Jul-12	6.0%	**-38.82**	**0.112**
5	SG1/t4	20-Jul-12	5.8%	**-39.12**	**0.371**
6	SG2/t0	20-Jul-12	5.8%	**-39.03**	**0.099**
7	SG2/t1	20-Jul-12	4.3%	**-38.83**	**0.042**
8	SG2/t2	20-Jul-12	3.5%	**-37.77**	**0.017**
9	SG2/t3	20-Jul-12	5.6%	**-36.63**	**0.048**
10	SG2/t4	20-Jul-12	5.4%	**-36.06**	**0.091**
11	SG3/t0	20-Jul-12	4.9%	**-38.31**	**0.364**
12	SG3/t1	20-Jul-12	3.7%	**-35.47**	**0.072**
13	SG3/t2	20-Jul-12	1.7%	**-18.77**	**0.600**
14	SG3/t3	20-Jul-12	0.3%	**12.55**	**0.644**
15	SG3/t4	20-Jul-12	BDL		
16	SG4/t0	20-Jul-12	5.2%	**-39.48**	**0.003**
17	SG4/t1	20-Jul-12	5.1%	**-38.54**	**0.535**
18	SG4/t2	20-Jul-12	4.1%	**-39.08**	**0.022**
19	SG4/t3	20-Jul-12	5.6%	**-39.12**	**0.312**
20	SG4/t4	20-Jul-12	5.6%	**-39.11**	**0.216**
21	B1/t0	15-Aug-12	3.9%	**-32.71**	**0.007**
22	B1/t5	16-Aug-12	3.8%	**-32.85**	**0.096**
23	B1/t7	16-Aug-12	3.9%	**-32.41**	**0.204**
24	1a/t0	15-Aug-12	4.0%	**-33.48**	**0.439**
24	duplicate		4.0%	**-33.94**	**0.028**
25	1a/t2	15-Aug-12	2.8%	**-24.48**	**0.236**
26	1a/t3	15-Aug-12	2.6%	**-21.63**	**0.248**
27	1a/t4	15-Aug-12	2.1%	**-16.59**	**0.130**
28	1a/t5	16-Aug-12	<0.2%	**BDL**	
29	1b/t0	15-Aug-12	4.1%	**-34.31**	**0.305**
30	1b/t2	15-Aug-12	3.3%	**-31.12**	**0.309**
31	1b/t4	15-Aug-12	3.2%	**-29.36**	**0.058**
32	1b/t5	16-Aug-12	2.2%	**-20.99**	**0.195**
33	1b/t7	16-Aug-12	1.5%	**-13.53**	**0.071**

Vial #	Label	Date	[CH_4] (% Volume)	Average $\delta^{13}C$ (ppt)	Std Dev
34	2a/t0	15-Aug-12	4.4%	**-35.12**	**0.149**
35	2a/t4	15-Aug-12	3.3%	**-27.16**	**0.064**
36	2a/t5	16-Aug-12	1.1%	**0.35**	**0.269**
37	2a/t6	16-Aug-12	0.4%	**BDL**	
38	3a/t0	15-Aug-12	4.3%	**-35.58**	**0.035**
39	3a/t2	15-Aug-12	3.5%	**-31.56**	**0.121**
40	3a/t4	15-Aug-12	3.4%	**-29.92**	**0.004**
41	3a/t5	16-Aug-12	2.7%	**-23.13**	**0.044**
42	3a/t7	16-Aug-12	2.2%	**-16.93**	**0.203**
43	3b/t0	15-Aug-12	4.5%	**-36.02**	**0.129**
44	3b/t1	15-Aug-12	3.3%	**-28.08**	**0.260**
45	3b/t2	15-Aug-12	1.9%	**-17.34**	**0.025**
46	3b/t3	15-Aug-12	1.6%	**-9.05**	**0.151**
47	3b/t4	15-Aug-12	0.5%	**12.05**	**0.465**
48	B2/t0	15-Aug-12	4.0%	**-36.30**	**0.128**
49	B2/t5	16-Aug-12	3.9%	**-36.41**	**0.284**
50	B2/t7	16-Aug-12	4.0%	**-36.53**	**0.148**
51	4a/t0	15-Aug-12	4.2%	**-36.45**	**0.034**
52	4a/t4	15-Aug-12	4.1%	**-35.73**	**0.016**
53	4a/t5	16-Aug-12	4.0%	**-35.44**	**0.082**
54	4a/t7	16-Aug-12	3.9%	**-35.10**	**0.048**
55	4b/t0	15-Aug-12	4.5%	**-36.57**	**0.013**
56	4a/t2	15-Aug-12	3.8%	**-34.67**	**0.239**
57	4b/t4	15-Aug-12	2.8%	**-33.42**	**0.059**
58	4b/t5	16-Aug-12	2.0%	**-29.13**	**0.016**
59	4b/t7	16-Aug-12	1.4%	**-25.70**	**0.029**
60	5a/t0	15-Aug-12	4.4%	**-36.13**	**0.138**
61	5a/t1	15-Aug-12	1.7%	**-26.15**	**0.059**
62	5a/t2	15-Aug-12	1.2%	**-10.38**	**0.199**
63	5a/t3	15-Aug-12	0.6%	**4.17**	**0.228**
64	5a/t4	15-Aug-12	<0.2%	**BDL**	
65	5a/t5	16-Aug-12	ND	**BDL**	
66	5b/t0	15-Aug-12	4.7%	**-36.26**	**0.071**
67	5b/t1	15-Aug-12	3.0%	**-28.27**	**0.030**
68	5b/t2	15-Aug-12	1.5%	**-14.87**	**0.006**
69	5b/t3	15-Aug-12	0.8%	**-3.43**	**0.218**
70	5b/t4	15-Aug-12	<0.2%	**BDL**	
71	6a/t0	15-Aug-12	4.7%	**-36.07**	**0.036**

Vial #	Label	Date	[CH_4] (% Volume)	Average $\delta^{13}C$ (ppt)	Std Dev
72	6a/t4	15-Aug-12	4.4%	**-36.24**	**0.086**
73	6a/t5	16-Aug-12	4.6%	**-36.33**	**0.023**
74	6a/t7	16-Aug-12	4.3%	**-36.66**	**0.035**
75	6b/t0	15-Aug-12	4.4%	**-36.73**	**0.107**
76	6b/t4	15-Aug-12	4.3%	**-35.95**	**0.090**
77	6b/t5	16-Aug-12	4.1%	**-33.74**	**0.025**
78	6b/t7	16-Aug-12	3.8%	**-32.20**	**0.187**

Soil Incubation Test, FID Responses and CH_4 Percentage Calculations

Date/Time	to = 0 (August 15, 2012)							t_0 (August 15, 2012)				t_1				t_2				t_3				t_4				t_5 (Aug 16, 2012)				t_6				t_7 (Final FID Run)				Notes
15-Aug-12	FID Response						CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	FID Response			CH_4	
16-Aug-12	Area	Time	Δt (mins)	Avg	SD	CV	(%)	Area	Time	Δt	(%)	Area	Time	Δt	(%)	Area	Time	Δt	(%)	Area	Time	Δt	(%)	Area	Time	Δt	(%)	Area	Time	Δt	(%)	Area	Time	Δt (H:M:S)	(%)	Area	Time	Δt (H:M:S)	(%)	
#B1	22449.5	10:12	0:00:00	22351.9	316.8	1.4%	**3.9%**	22351.9	10:12	0:00	**3.9%**	22218.9	13:37	3:25	**3.8%**	21330.3	16:15	6:03	**3.7%**	22154.4	17:50	7:38	**3.8%**	22125.2	20:02	9:50	**3.8%**	22064.2	9:12	23:00	**3.8%**	21861.1	13:14	27:02:00	**3.8%**	22343.6	17:16	31:04:00	**3.9%**	Blank at 25 °C
	22608.5	10:15	0:00:00																																				
	21997.8	10:17	0:00:00																																				
#1a	23052.5	10:19	0:00:00	23387.8	306.6	1.3%	**4.0%**	23387.8	10:19	0:00	**4.0%**	20214.0	13:39	3:20	**3.5%**	16099.7	16:18	5:59	**2.8%**	14963.1	17:52	7:33	**2.6%**	12043.3	20:04	9:45	**2.1%**	604.8	9:14	22:55	<0.2%	--	--	--	NS	--	--	--	NS	Phase 1 at 25°C with 7.7% Moisture w/w
	23653.8	10:22	0:00:00																																				
	23457.2	10:24	0:00:00																																				
#1b	23694.1	10:26	0:00:00	23510.2	212.3	0.9%	**4.1%**	23510.2	10:26	0:00	**4.1%**	21736.1	13:41	3:15	**3.7%**	18887.1	16:22	5:56	**3.3%**	19514.8	17:54	7:28	**3.4%**	18458.1	20:06	9:40	**3.2%**	12912.4	9:16	22:50	**2.2%**	10580.1	13:17	26:51:00	**1.8%**	8650.5	17:19	30:53:00	**1.5%**	Phase 1 at 25°C with 10.7% Moisture w/w
	23277.8	10:28	0:00:00																																				
	23558.6	10:30	0:00:00																																				
#2a	25363.2	10:33	0:00:00	25729.4	331.2	1.3%	**4.4%**	25729.4	10:33	0:00	**4.4%**	22977.1	13:43	3:10	**4.0%**	20966.6	16:24	5:51	**3.6%**	20274.7	17:57	7:24	**3.5%**	19094.3	20:08	9:35	**3.3%**	6604.5	9:18	22:59	**1.1%**	2733.4	13:19	27:00:00	**0.4%**	440.9	17:21	31:02:00	<0.2%	Grid 158 at 25°C with 9.7% Moisture w/w
	25816.9	10:35	0:00:00																																				
	26008.0	10:38	0:00:00																																				
#3a	25127.9	10:40	0:00:00	25138.6	38.9	0.2%	**4.3%**	25138.6	10:40	0:00	**4.3%**	22468.7	13:46	3:06	**3.9%**	20125.4	16:26	5:46	**3.5%**	20906.4	17:59	7:19	**3.6%**	19823.7	20:11	9:31	**3.4%**	15935.2	9:20	22:54	**2.7%**	13945.6	13:22	26:56:00	**2.4%**	12708.7	17:23	30:57:00	**2.2%**	Grid 151 at 25°C with 7.1% Moisture w/w
	25181.7	10:42	0:00:00																																				
	25106.1	10:44	0:00:00																																				
#3b	26138.2	10:46	0:00:00	25879.9	283.9	1.1%	**4.5%**	25879.9	10:46	0:00	**4.5%**	19111.7	13:48	3:02	**3.3%**	11119.2	16:29	5:43	**1.9%**	9235.7	18:01	7:15	**1.6%**	3460.2	20:13	9:27	**0.5%**	-	9:23	23:04	**ND**	--	--	--	NS	--	--	--	NS	Grid 151 at 25°C with 11.8% Moisture w/w
	25925.6	10:49	0:00:00																																				
	25576.0	10:51	0:00:00																																				
#B2	21823.5	10:53	0:00:00	22894.6	938.8	4.1%	**4.0%**	22894.6	10:53	0:00	**4.0%**	22022.4	13:51	2:58	**3.8%**	20906.6	16:33	5:40	**3.6%**	22834.4	18:03	7:10	**3.9%**	23089.6	20:15	9:22	**4.0%**	22829.4	9:26	23:00	**3.9%**	23474.7	13:24	26:58:00	**4.1%**	23012.2	17:26	31:00:00	**4.0%**	Blank at 5°C
	23575.1	10:55	0:00:00																																				
	23285.1	10:58	0:00:00																																				
#4a	24738.9	11:00	0:00:00	24134.7	585.0	2.4%	**4.2%**	24134.7	11:00	0:00	**4.2%**	23392.9	13:54	2:54	**4.0%**	22189.6	16:36	5:36	**3.8%**	23556.9	18:05	7:05	**4.1%**	23626.4	20:18	9:18	**4.1%**	23027.6	9:28	23:09	**4.0%**	22419.2	13:26	27:07:00	**3.9%**	22326.1	17:29	31:10:00	**3.9%**	Grid 151 at 5°C with 7.1% Moisture w/w
	23571.0	11:02	0:00:00																																				
	24094.3	11:05	0:00:00																																				
#4b	26587.4	11:07	0:00:00	25823.6	781.0	3.0%	**4.5%**	25823.6	11:07	0:00	**4.5%**	21296.5	13:56	2:49	**3.7%**	19088.3	16:38	5:31	**3.3%**	17680.3	18:07	7:00	**3.0%**	16430.1	20:20	9:13	**2.8%**	11682.7	9:31	23:05	**2.0%**	9976.1	13:28	27:02:00	**1.7%**	8379.5	17:31	31:05:00	**1.4%**	Grid 151 at 5°C with 11.8% Moisture w/w
	25857.0	11:10	0:00:00																																				
	25026.4	11:12	0:00:00																																				
#5a	25351.2	11:14	0:00:00	25326.9	21.4	0.1%	**4.4%**	25326.9	11:14	0:00	**4.4%**	10121.5	13:59	2:45	**1.7%**	7398.7	16:41	5:27	**1.2%**	4164.1	18:10	6:56	**0.6%**	347.9	20:23	9:09	<0.2%	--	9:33	23:14	**ND**	--	--	--	NS	--	--	--	NS	Grid 102 with emission at 25° and 12.4% Moisture
	25311.1	11:16	0:00:00																																				
	25318.4	11:19	0:00:00																																				
#5b	27577.9	11:21	0:00:00	27151.2	407.7	1.5%	**4.7%**	27151.2	11:21	0:00	**4.7%**	17469.4	14:01	2:40	**3.0%**	9021.5	16:43	5:22	**1.5%**	5387.9	18:12	6:51	**0.8%**	975.5	20:25	9:04	<0.2%	--	9:39	23:13	**ND**	--	--	--	NS	--	--	--	NS	Grid 102 with emission at 25° and 16.0% Moisture
	27110.2	11:23	0:00:00																																				
	26765.6	11:25	0:00:00																																				
#6a	26916.4	11:28	0:00:00	26906.2	26.1	0.1%	**4.7%**	26906.2	11:28	0:00	**4.7%**	24861.2	14:03	2:35	**4.3%**	23434.1	16:46	5:18	**4.0%**	26117.6	18:14	6:46	**4.5%**	25411.5	20:27	8:59	**4.4%**	26409.0	9:46	23:27	**4.6%**	26744.4	13:31	27:12:00	**4.6%**	24753.8	17:33	31:14:00	**4.3%**	Grid 102 without emission at 25° and 4.2% Moisture
	26876.5	11:30	0:00:00																																				
	26925.6	11:32	0:00:00																																				
#6b	26156.8	11:34	0:00:00	25562.2	749.6	2.9%	**4.4%**	25562.2	11:34	0:00	**4.4%**	21848.2	14:05	2:31	**3.8%**	24237.8	16:48	5:14	**4.2%**	24532.5	18:17	6:43	**4.2%**	24830.8	20:29	8:55	**4.3%**	23817.9	9:48	23:22	**4.1%**	23090.2	13:33	27:07:00	**4.0%**	21904.3	17:36	31:10:00	**3.8%**	Grid 102 without emission at 25° and 14.0% Moisture
	24720.1	11:39	0:00:00																																				

Initial Sample Taken

Soil Gas Sample Taken

Final Sample Taken

NS: Not Sampled

ND: Not Detected

Appendix F Landfill Gas Collection System Wellfield Readings

F.1 Collected LFG Flow Rates at Manifolds, Adjusted to 50% Methane Content

#	Date	Collected LFG Flow Rate (scfm)				
		Area 2W	Area 2E	Area 3	Phase 1	Work Site
1	22-Mar-11	161		129	1,208	
2	31-Mar-11	163	143	247	1,343	1,895
3	11-Apr-11	151	87	296	1,348	1,883
4	20-Apr-11	176	164	301	1,369	2,009
5	29-Apr-11	189	100	313	1,215	1,817
6	11-May-11	174	154	234	1,199	1,761
7	16-May-11	126	166	282	1,282	1,857
8	24-May-11	246	208	275	1,274	2,003
9	2-Jun-11	246	208	132	1,383	1,969
10	10-Jun-11	170	205	246	1,087	1,710
11	14-Jun-11		136		1,198	
12	22-Jun-11	138	152	283	1,208	1,781
13	30-Jun-11	196	214	173	1,153	1,736
14	21-Jul-11	139		190	1,230	
15	28-Jul-11			190	1,331	
16	5-Aug-11	108	117	107	1,432	1,764
17	2-Sep-11	157	133	77	1,424	1,791
18	8-Sep-11				1,459	
19	16-Sep-11				1,459	
20	19-Sep-11	199			1,262	
21	20-Oct-11		96		1,277	
22	3-Nov-11	142	130	96	1,401	1,769
23	10-Nov-11				1,203	
24	24-Nov-11	165			1,261	
25	25-Nov-11				1,245	
26	12-Dec-11			116	1,104	
27	15-Dec-11		105		1,308	
28	16-Dec-11					
29	19-Dec-11			112		
30	21-Dec-11		97			
31	3-Jan-12	95	99	109	1,155	1,458
32	4-Jan-12					
33	9-Jan-12	43	142	91	1,205	1,481
34	11-Jan-12			110		

#	Date	Collected LFG Flow Rate (scfm)				
		Area 2W	Area 2E	Area 3	Phase 1	Work Site
35	23-Jan-12		154	240	1,248	
36	2-Feb-12				1,071	
37	3-Feb-12	145	160	219	1,121	1,645
38	9-Feb-12				1,259	
39	10-Feb-12	122	134	171	1,329	1,756
40	13-Feb-12	140	147	239	1,275	1,801
41	14-Feb-12	246				
42	15-Feb-12	166				
43	28-Feb-12			255		
44	29-Feb-12	167	43	281	1,339	1,830
45	7-Mar-12		147	199	1,261	
46	14-Mar-12	105			1,504	
47	21-Mar-12	213	117	266	1,376	1,972
48	5-Apr-12	168				
49	11-Apr-12	203				
50	31-May-12			275		
51	4-Jun-12	147		257	1,464	
52	7-Jun-12				1,351	
53	11-Jun-12				1,153	
54	14-Jun-12	158				
55	19-Jun-12	137	155	229	1,179	1,700
56	25-Jun-12	161	145	99	1,052	1,457
57	26-Jun-12	112				
58	27-Jun-12		103			
59	28-Jun-12			189		
60	3-Jul-12	84	183	204	1,214	1,685
61	5-Jul-12	132	118	137		
62	11-Jul-12				1,119	
63	12-Jul-12	149	149	106	1,232	1,636
64	23-Jul-12	131	187	99	1,251	1,668
65	10-Aug-12	208	171	152	1,094	1,625
	Average	**157**	**142**	**193**	**1,264**	**1,758**
	St. Dev	43	38	73	112	151
	CV%	27%	27%	38%	9%	9%
	Total # of readings	40	35	40	39	27