

# Heat Transfer Model for an Engineered Landfill in Sainte-Sophie, Quebec, Canada

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## **Abstract**

A conceptual and numerical heat transfer model was developed for a landfill gas to energy (LFGTE) facility in Ste. Sophie, Quebec. The operating LFGTE facility was instrumented with sensors to measure parameters affecting waste stabilization.

Temperature data from the field was used to calibrate a heat transfer model to better understand the thermal processes and parameters. Waste was observed to stay frozen for up to 1.5 years when placed in thick layers during the winter. Detection of oxygen within the top 1 m of waste was directly correlated with temperature rises, indicating a heat source, likely aerobic biodegradation. In simulating the placement of five waste lifts over a five year period, aerobic digestion in the top 1 m generated 56% of the total heat generated. A brief sensitivity analysis was completed and the model was used to show the effect of waste sequencing on the vertical temperature profile over time.

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# Table of Contents

1 Introduction.....	1
1.1 Project Significance.....	1
1.2 Description of Problem .....	2
1.3 Sainte Sophie Landfill Gas to Energy (LFGTE) Facility.....	3
1.4 Overview of Thesis .....	4
2 Literature Review.....	6
2.1 Landfill Design.....	6
2.1.1 Historical Disposal Practices .....	6
2.1.2 Cover design.....	7
2.1.3 Landfill barrier.....	8
2.1.4 Landfill Gas Collection System.....	8
2.1.5 Leachate Collection System .....	9
2.2 Waste Stabilization.....	10
2.2.1 Phase I: Hydrolysis.....	13
2.2.2 Phase II: Acid Fermentation .....	13
2.2.3 Phase III: Acetogenesis .....	14
2.2.4 Phase IV: Methanogenesis.....	14
2.3 Factors Affecting Waste Stabilization.....	15
2.3.1 Moisture.....	15

2.3.2 pH .....	16
2.3.3 Oxygen.....	16
2.3.4 Nutrient Content .....	16
2.3.5 Density.....	17
2.3.6 Temperature.....	18
2.4 Thermal Properties of Waste.....	19
2.4.1 Specific Heat.....	20
2.4.2 Thermal Conductivity.....	21
2.5 Landfill Gas to Energy (LFGTE) Facilities .....	22
2.5.1 Bioreactor Landfill Research.....	22
2.5.2 Liquid Addition .....	24
2.5.3 Air Addition.....	25
2.5.4 Landfills in Cold Climates.....	26
2.6 Heat Transfer Processes within Landfill .....	27
2.6.1 Radiation.....	28
2.6.2 Convection.....	29
2.6.3 Conduction.....	30
2.6.4 Latent Heat of Fusion .....	30
2.6.5 Heat Generation.....	31
2.7 Landfill Modelling Efforts .....	34

2.7.1 Chemical and Biological Models .....	34
2.7.2 Heat Transfer Models .....	35
3 Instrumentation of Ste. Sophie LFGTE facility.....	41
4 Field Data and Model Results.....	45
4.1 Conceptual and Numerical Heat Transfer Model of a Landfill in a Northern Climate .....	45
4.1.1 Abstract.....	45
4.1.2 Introduction .....	46
4.1.2.1 Ste. Sophie LFGTE Instrumentation.....	48
4.1.3 Temperature Field Data .....	51
4.1.4 Model Formulation .....	54
4.1.5 Model Results and Discussion.....	57
4.1.5.1 Heat Budget.....	67
4.1.6 Conclusion and Future Work.....	70
5 Model Application .....	72
5.1 Sensitivity Analysis.....	72
5.1.1 Specific Heat Capacity .....	72
5.1.2 Thermal Conductivity.....	74
5.2 Effect of waste placement sequencing on the temperature profile in a LFGTE facility.....	75

5.2.1 Model Structure .....	77
5.2.2 Model Results of Scenario Case.....	78
6 Conclusions and Future Work .....	83
7 Bibliography .....	86
Appendix A- Field Data.....	92

## List of Figures

Figure 1 Aerial view of Ste. Sophie LFGTE facility; zone four outlined.....	4
Figure 2 Anaerobic biodegradation processes (modified from Ahring et al., 2003) .....	12
Figure 3 Zone 4 Ste. Sophie landfill footprint (modified from Genivar, 2008) .....	41
Figure 4 Placement of 12 instrument bundles in two vertical profiles in the Ste. Sophie LFGTE facility.....	42
Figure 5 Bundle installation at the Ste. Sophie LFGTE facility during waste placement; approximate depths of each waste lift are shown to the right and the time of waste placement are shown to the left. ....	50
Figure 6 Ambient temperature and average sensor temperatures at bundle locations from November 2010 to October 2014; includes waste placement lifts and bundle installation times.....	52
Figure 7 Heat transfer processes within a waste column.....	56
Figure 8 Model domain for five simulation periods (from January 2010 to August 2014) with initial temperatures and specific thermal properties for each waste profile .....	59
Figure 9 Comparison of field and simulated temperatures of all 5 waste lifts in the Ste. Sophie LFGTE facility from January 2010 to August 2014.....	61
Figure 10 Simulated temperature profiles at the end of a) Dec 12, 2010, b) Jan 27, 2011, c) Aug 22, 2011, d) Mar 14, 2012, e) January 9, 2013, and f) May 23, 2014; points represent the field data for bundles 1, 3, 5, 7, 9 and 11 .....	65
Figure 11 Measured and simulated temperatures from bundles 3, 5, 7, 9 and 11 with $C_p = 1200 \text{ J/kgK}$ .....	73

Figure 12 Measured and simulated temperatures from bundles 3, 5, 7, 9 and 11 with $k=0.3 \text{ W/mK}$ .....	74
Figure 13 Second waste lift (3.5 m) placed in the summer rather than the winter .....	77
Figure 14 Temperature profile within waste lifts in Ste. Sophie at if second waste lift is placed in the summer at the end of a) Jun 16, 2010 , b) Jan 27, 2011, c) August 22, 2011, d) March 14, 2012, and e) January 9, 2013, f) May 23, 2014 .....	80
Figure 15 Effect of waste placement pattern on total number of days where biodegradation may occur.....	81
Figure 16 Comparing the effect of lift sequencing patterns on the number of degree days reached in Ste. Sophie LFGTE facility .....	82
Figure A1 Oxygen consumption in bundles 11 and 12 upon installation in final waste lift (May 24, 2012).....	92
Figure A2 Oxygen concentration in bundles 1 to 12 from November 2009 to October 2014 and bundle installation times .....	93
Figure A3 Total settlement for bundles 1 to 12 from November 2010 to September 2014 and time of placement of five waste lifts in Ste. Sophie LFGTE facility.....	94
Figure A4 Total earth pressure for bundles 1 to 12 from November 2010 to September 2014 and time of bundle installations in Ste. Sophie LFGTE facility .....	96
Figure A5 Piezometric pressure for bundles 1-4 November 2010 to September 2014 ....	97

## List of Tables

Table 1 Waste disposal per capita and diversion rate in Canada, Quebec, and Ontario (modified from Statistics Canada, 2011) .....	1
Table 2 Range of key constituents in landfill leachate (modified from Kjeldsen et al., 2002) .....	10
Table 3 Benefits and problems of leachate recirculation.....	24
Table 4 Heat generation rates from aerobic and anaerobic biodegradation (modified from Yesiller et al., 2005).....	33
Table 5 Summary of thermal parameters for waste found in the literature .....	47
Table 6 Time period and height of waste during each simulation period.....	59
Table 7 Thermal parameters used in the final calibrated model .....	63
Table 8 Processes which impact the heat budget during the 5 simulation periods.....	68
Table 9 Simulation time periods for base case and scenario simulation for the five waste lifts in Ste. Sophie .....	78
Table A10 Surveyed locations of bundles and elevations during installation and total settlement as of September 2014 .....	95

## Nomenclature

MSW	Municipal solid waste	
LFGTE	Landfill gas to energy facility	
LCS	Leachate collection system	
LFG	Landfill gas	
$\alpha$	Thermal diffusivity	
$\varepsilon$	Emissivity	
$w$	Mass fraction of water content in soil	
$w_u$	Ratio of unfrozen water to total water within the soil	
$\sigma$	Stefan Boltzmann constant for blackbody radiation	W/m <sup>2</sup> K <sup>4</sup>
$A$	Surface area	m <sup>2</sup>
$t$	Time	s
$k$	Thermal conductivity	W/mK
$h$	Convection coefficient	W/m <sup>2</sup> K
$v$	Wind speed	m/s
$\rho$	Bulk waste density	kg/m <sup>3</sup>
$c$	Volumetric heat capacity	J/m <sup>3</sup> K
$C_p$	Specific heat	J/kgK
$C_s$	Specific heat for frozen waste	J/kgK
$C_l$	Specific heat for non-frozen waste	J/kgK
$T_{sky}$	Sky temperature	K
$T_{amb}$	Ambient temperature	K
$T$	Waste temperature	K

$L_s$	Volumetric latent heat of fusion for soil	$\text{kJ/m}^3$
$L_w$	Latent heat of fusion for water	$\text{kJ/m}^3$
$\gamma_d$	Dry density	$\text{kg/m}^3$
$Q_o$	Net shortwave solar radiation	$\text{W/m}^2$
$Q_c$	Convective heat	W
$Q_l$	Long wave radiation	W
$Q$	Heat generation rate	$\text{W/m}^3$
$Q_i$	Heat generation rate scaling factor	$\text{W/m}^3$
$Q_{i, \text{aerobic}}$	Heat generation rate scaling factor within aerobic zone	$\text{W/m}^3$
$Q_{i, \text{anaerobic}}$	Heat generation rate scaling factor within anaerobic zone	$\text{W/m}^3$
$A_t$	Peak heat generation rate	$\text{W/m}^3$
$B_t$	Shape factor	Day
$C_t$	Shape factor	Day
$D$	Decay rate factor	Day

# 1 Introduction

Waste management is becoming increasingly more important as the limited resources of the world are being exhausted. The improvement and sophistication of waste management technologies is an important and growing research field. Generation of municipal solid waste (MSW) is an increasing problem due to population growth and increase in waste generation (McBean et al., 1995). Although there are several positive initiatives in diversion strategies, it needs to be acknowledged that some organics will still remain in the MSW residual stream. Landfill disposal is the most common waste management practice in the world.

## 1.1 Project Significance

In 2008, on average, a Canadian produced 776.5 kg of waste; although the diversion rate in Canada is 24.7%. As seen in Table 1, final disposal of waste is still an important consideration in Canada (Statistics Canada, 2011).

**Table 1 Waste disposal per capita and diversion rate in Canada, Quebec, and Ontario (modified from Statistics Canada, 2011)**

	Waste disposed per capita (kg/cap)			Diversion rate (%)		
	2004	2006	2008	2004	2006	2008
Canada	789.8	795.9	776.5	22	23	24.7
Quebec	856.4	827.8	794.5	24.8	27.8	28.6
Ontario	791.7	766.7	744.8	19.8	19.8	22.6

Obtaining new licenses to expand or build new landfills is difficult, so current landfill operators need to utilize landfill volumes as efficiently as possible. Enhancing the waste degradation process within the landfill will improve the use of the approved landfill

airspace, will increase methane (CH<sub>4</sub>) generation rates, will reduce the contamination lifespan of the landfill and will improve post-closure maintenance and re-development. One technique used to improve waste degradation is the control of temperature within the landfill (Warith, 2003). Research shows that waste placed frozen in the winter months can stay frozen for years (Bonany et al., 2013a).

## **1.2 Description of Problem**

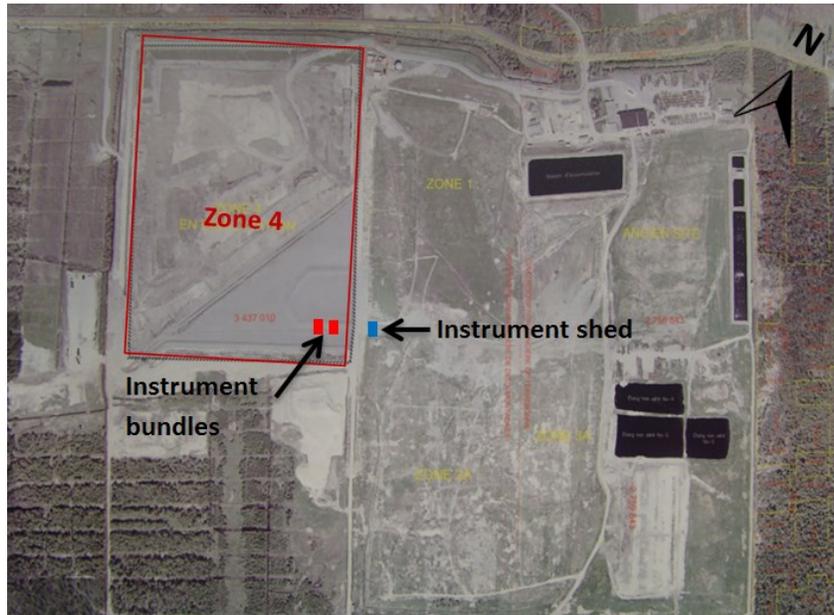
A project was initiated in 2009 to investigate the waste stabilization processes occurring in a landfill located in a northern climate. The landfill, located in Ste. Sophie Quebec, was instrumented with 12 instrument bundles as the waste was placed in the landfill cell. The overall goal of the project is to better understand the parameters that impact waste stabilization with a goal to optimize the landfill operations to enhance waste stabilization. Vingerhoeds (2011) and Bonany (2012) have documented the bundle instrumentation and research pertaining to this project up to 2012. This thesis contains the installation of the final instrumentation bundles, the most recently updated dataset, and a refined heat transfer model. By building a computer model to simulate what is occurring in the field, the thermal properties of the waste and heat transfer processes can be better understood. The model created by Bonany (2012) simulated the temperatures within the first three waste lifts (which were placed in a frozen state). The model however was not capable of accurately representing the trends observed when the waste was placed at warmer temperatures. Therefore, the focus of the research presented herein was to improve our understanding of the heat generation and transfer processes and thermal parameters to improve the model and its ability to simulate the data collected in the field. The model was then used to investigate the impact of different waste placement strategies on the

waste temperature, which will in turn impact the stabilization of the waste. This will help landfill operators better manage their landfills, enhance waste stabilization and landfill gas production, increase settlement, and create more air space to add more waste per unit area of the landfill.

### **1.3 Sainte Sophie Landfill Gas to Energy (LFGTE) Facility**

The Ste. Sophie LFGTE facility is located in the village of Ste. Sophie, 50 km from Montreal, in Quebec, Canada. The facility is about 17 km from a weather station in Mirabel, Quebec. The average maximum daily temperature is 15.9°C and average minimum daily temperature is 4.4°C in Mirabel, Quebec (Government of Canada, 2014). The facility is owned and operated by Waste Management of Canada and can accept up to 1,000,000 tonnes of waste per year. At the beginning of this research, the site had four zones which contributed to methane generation and collection. The methane collected was then converted into a source of energy. The Ste. Sophie LFGTE facility produces 70 million cubic metres of landfill gas per year. A gas pipeline transports landfill gas from the facility to Cascade Inc., a pulp and paper mill. The energy supplied fulfills all the heat requirements at the facility. The site now has a new zone, zone 5, which is actively being filled with waste.

In the southeast corner of zone 4 (as shown in Figure 1), twelve instrument bundles were placed within two vertical waste profiles. There was no leachate recycle within this zone and it was operated anaerobically.



**Figure 1 Aerial view of Ste. Sophie LFGTE facility; zone four outlined**

In the area of the instrument bundles, waste was placed as five waste lifts between January 2010 and March 2012. The first three waste lifts were placed frozen during the winter months. Measured temperature data showed that the waste can stay frozen for more than a year. Waste Management was notified of this finding and modified its operation to place the subsequent two lifts during the spring and summer months. The final cover above the waste profiles containing the instrument bundles was placed in June of 2014. Almost five years of data have been collected at the site and are the focus of this thesis.

## **1.4 Overview of Thesis**

This thesis is composed of eight sections. The first section is the introduction containing the project description and significance. Following the introduction is an exhaustive

literature review of existing research. The third section of this thesis is a description and explanation of the Ste. Sophie field instrumentation. Section 4 is presented as a journal article containing an analysis of the field data, formulation of the conceptual and numerical model, and model results. A brief sensitivity analysis and simulated scenario are presented in section five. The conclusion section contains a summary of the findings. A bibliography is found in section seven and the final section presents additional project details in the appendices.

## **2 Literature Review**

### **2.1 Landfill Design**

A sanitary landfill is a designed facility that is engineered for the disposal of municipal solid waste in a way that minimizes public health and adverse environmental impacts. Landfills act as the final disposal stage of residual MSW after recycling and other waste management strategies. Currently landfills perform better than in the past because of continuous improvement in their design and monitoring. Some concerns may arise from landfills such as potential leakage of leachate, odour, vermin, dust, transportation of the waste, and leakage of landfill gas. Landfill gas is a combination of different gases generated by waste degradation. One of the main components of landfill gas is methane, which is a valuable resource when captured (Townsend et al., 2008); however, it also is a significant greenhouse gas with a global warming potential of at least 25 times that of carbon dioxide.

To minimize the public health and environmental impacts that may arise from leachate and landfill gas, complex design procedures are implemented. There are four major engineered components in landfills: leachate collection system (LCS), liner, landfill gas collection system, and final cover.

#### **2.1.1 Historical Disposal Practices**

Municipal solid waste (MSW) is commonly known as trash or garbage, which originates from residential, commercial, and institutional locations (United States Environmental Protection Agency, 2014). In the United States, landfilling is the most common disposal

practice (The Hinkley Center For Solid and Hazardous Waste Management, 2008). Up to the 1900s, solid waste was disposed directly onto land. During the 1950s, proper planning and engineering processes were used to maximize operation of disposal facilities (McBean et al., 1995). Open pit dumping was common practice and sometimes combustion of the waste occurred. Major problems arose with these disposal methods such as odour, noise, seagulls, smoke and other adverse environmental impacts. In traditional landfills, also known as dry tomb landfills, soil or cover material was added on top of the buried waste as a daily cover to reduce the amount of moisture entering the landfill (Lee & Jones-Lee, 1996). Moisture generated within the dry tomb landfill was then collected and treated. In dry tomb landfills, it can take 30-50 years for the waste to stabilize (Townsend et al., 2008). Dry tomb sanitary landfills lower leachate production but produce CH<sub>4</sub>, which is slowly released into the atmosphere (Hunte et al., 2011). Modern day landfills have engineered components to minimize negative effects on the environment and optimize the degradation of the waste. Modern landfill technology provides the optimal environment for microorganisms to decompose the waste and waste stabilization can be reached within 5-10 years (Townsend et al., 2008). In summary, the function of the modern MSW landfill is to maximize storage of the waste per unit area, isolate the waste from the environment, and possibly convert the waste to an energy resource.

### **2.1.2 Cover design**

The cover controls the amount of water that can percolate into the waste and ultimately the amount of leachate generated (Kjeldsen et al., 2002). It also regulates the concentration of gases within the landfill. The final cover usually contains a soil that has

a low hydraulic conductivity such as compacted clay or glacial till. The cover may also contain topsoil and a vegetative cover. The daily cover is usually composed of certain materials such as wood chips, compost, soils, sands or a removable geosynthetic material that is applied on top of the waste at the end of the working day to reduce odours and vermin (Ministry of Environment, 2010).

### **2.1.3 Landfill barrier**

To protect the subsurface water and soils, a liner system is an important design component for control of contaminant transport. In the United States, regulations state that the amount of liquid on top of the liner cannot exceed 30 cm (Zhao et al., 2008). Advection and diffusion are the main mechanisms for contaminant transport through the liner. During advection, suspended solids or dissolved material moves with water or leachate and can be transported through pores of a liner based on the hydraulic head. Diffusion may be a significant transport process in low permeability liner systems.

### **2.1.4 Landfill Gas Collection System**

Landfill gas (LFG) is produced as a by-product of the decomposition of the waste in the landfill. The main two components of LFG include: methane and carbon dioxide. Nitrogen, oxygen, hydrogen and water vapor are detected in LFG. Trace amounts of volatile organics and other gases are also found. In a stabilized landfill the gas composition is as follows: CH<sub>4</sub> (40-70%), CO<sub>2</sub> (30-60%), H<sub>2</sub> (0-5%), N<sub>2</sub> (0-3%), O<sub>2</sub> (0-3%), and HS (0-2%) (El-Fadel et al., 1996a). The main concern with landfill gas is that methane acts as a greenhouse gas if it is released into the environment and not captured. Another concern with methane gas is buildup of the gas in landfills with low permeability

covers that can cause explosions or cause the LFG to travel laterally in the subsurface. The amount of LFG generated depends on: waste composition, moisture content, temperature, waste age, pH, and particle size of the waste.

The largest amount of CH<sub>4</sub> is generated right after closure of the waste cell (Pacey et al., 1999). A landfill gas collection system attempts to minimize the release of LFG into the atmosphere. As of 2010, 1.5 million cubic metre landfills are now required to install a LFG collection system in Ontario, Canada (Ministry of Environment, 2010). Once the gas is pumped out of the landfill it can be used for energy production or flared.

### **2.1.5 Leachate Collection System**

The leachate collection system (LCS) is designed to control leachate, which may flow from the bottom of the landfill (Rowe, 1990). Leachate in MSW is contaminated liquid that contains dissolved and suspended materials generated from the expulsion of liquid, due to compaction and percolation through the waste. The composition of leachate varies in each landfill depending on waste composition, amount of water available and landfill age (Kjeldsen et al., 2002). Table 2 shows the wide range of some of the characteristics in landfill leachate. Rainwater percolates through the landfill cover into the waste playing an important role in leachate generation.

**Table 2 Range of key constituents in landfill leachate (modified from Kjeldsen et al., 2002)**

<b>Parameter</b>	<b>Range (mg/L)</b>
pH	4.5-9
Total Solids	2,000-60,000
Total Organic Carbon (TOC)	30-29,000
Biological Oxygen Demand (BOD <sub>5</sub> )	20-57,000

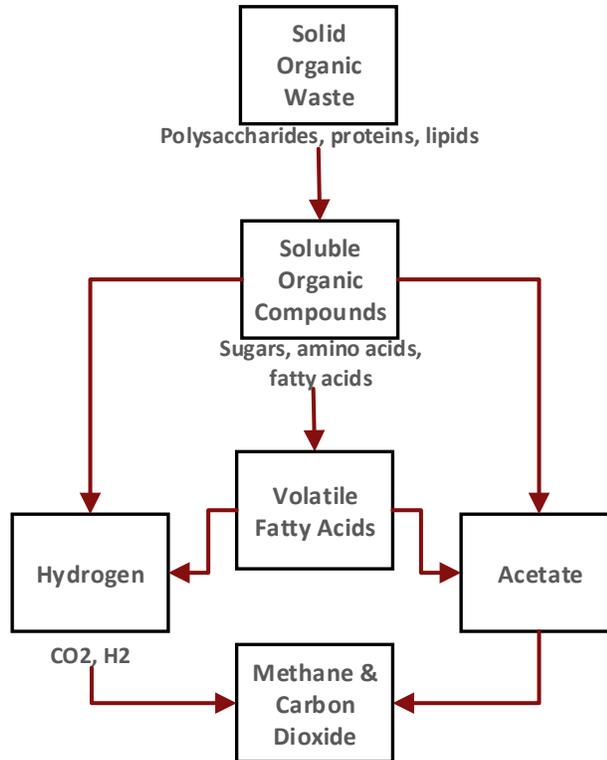
The LCS consists of three main components: filters (geotextiles/sand), coarse stone (drain), and the perforated pipe system. One of the main challenges with LCS design is finding a solution to clogging (Warith, 2002). The function of the LCS is to lower the leachate mound (minimize leachate seeps), reduce leachate head on the liner system (reduce the hydraulic gradient and Darcy velocity out of the landfill), and allow for the removal of contaminants (reduce the amount of contaminants available for transport through the barrier system) (Rowe, 1990). Contingency measures are designed in case contaminants unpredictably reach the aquifer.

## **2.2 Waste Stabilization**

Waste placed in the landfill is converted into leachate, gas, transformed mass or remains unchanged. MSW can biodegrade naturally, breaking down the organic matter into smaller compounds (Gholamifard et al., 2008). The biodegradation, or decay, of the MSW occurs with a large collection of microorganisms that can digest the waste (McBean et al., 1995; Stams et al., 2003). Waste biodegradation can occur during the presence of oxygen (aerobic biodegradation) and in the absence of oxygen (anaerobic biodegradation). A landfill may be operated in three main operation modes: 1) aerobic, 2) anaerobic, and 3) hybrid. A hybrid landfill is designed to operate in both aerobic and

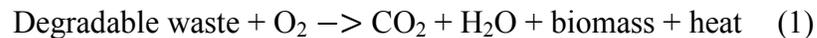
anaerobic modes (Karthikeyan & Joseph, 2007). The waste biodegradation occurs through phases. If aerobic conditions prevail, aerobic biodegradation occurs. If the diffusion of oxygen to the waste becomes limited, anaerobic biodegradation commences.

Anaerobic digestion is the biological process where carbon is transformed by oxidation and reduction reactions into  $\text{CO}_2$  and  $\text{CH}_4$ , as seen in Figure 2 (Angelidaki et al., 2003). Many different groups of bacteria and archaea are involved in anaerobic digestion and rely on each other in complex ways (Bareither et al., 2013; Donoso-Bravo et al., 2011). Optimization of anaerobic digestion is increasingly important for the feasibility of landfill gas to energy technology. The most important value in anaerobic digestion is the formation of biogas or landfill gas (Ahring, 2003). This energy rich gas can be used to produce electricity and heat (Angelidaki et al., 2003). Four main phases occur during anaerobic biodegradation: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Haarstrick et al., 2001).



**Figure 2 Anaerobic biodegradation processes (modified from Ahring et al., 2003)**

Aerobic decomposition occurs when the waste is initially placed in the landfill. During this phase, the organic content within the waste is degraded by aerobic bacteria. In aerobic conditions, oxygen is the electron acceptor and the degradable waste is mineralized into water and carbon dioxide as seen in Equation 1 (Stams et al., 2003).



Since this biological reaction is exothermic, temperature of the waste can reach 10 – 20°C higher than the initial waste placement temperature (Warith, 2003). During this phase, the aerobic degradation of the organic fraction in the MSW usually occurs for a limited time. This is because the organic waste has a high oxygen demand and a limited amount of oxygen diffuses into the landfill. The upper layer of the landfill is the only

layer that may experience aerobic degradation for extended periods of time. In the upper layer of the waste lift, oxygen can be trapped in the fresh waste that is placed and can be found in rainfall. Kjeldsen et al. (2002) states that the aerobic phase in a landfill would only take a few days because once the waste is covered no more oxygen will be able to diffuse into the waste mass. Once the oxygen content becomes depleted, anaerobic decomposition begins. Anaerobic decomposition was observed to occur within weeks or months since waste placement (Hanson et al., 2005).

### **2.2.1 Phase I: Hydrolysis**

The degradation of the organic waste into monomeric compounds is referred to as hydrolysis. Hydrolysis is the most important step in the biodegradation of the waste as it may be the rate-limiting step (Bareither et al., 2013; El-Fadel et al., 1996a; Gholamifard et al., 2008; Haarstrick et al., 2001; Nopharatana et al., 2007). Complex polymers in the waste such as polysaccharides, proteins and lipids are broken down into simpler organic compounds such as simple sugars, amino acids and long chain fatty acids (Ahring, 2003).

### **2.2.2 Phase II: Acid Fermentation**

During acid fermentation, organic acids and alcohols break down with the help of anaerobic bacteria causing a decrease in pH. The increased acidity helps breakdown more complex organic compounds producing  $H_2$  and  $CO_2$  (Ahring, 2003). These smaller molecules produced by hydrolysis are further broken down through the acidogenesis reaction. Microorganisms convert the molecules into lower molecular mass compounds such as acetic acid ( $CH_3COOH$ ). The main gas created in this phase is  $CO_2$ , some  $H_2$  is also produced lowering the pH to 5 or lower (Warith, 2003). El-Fadel (1999) suggests

that the formation of carboxylic acids generates the most heat compared to other phases of anaerobic degradation.

### **2.2.3 Phase III: Acetogenesis**

Acetogenic bacteria consume organic acids and raise the pH allowing the methanogenic bacteria to grow. A small fraction of acetate and hydrogen are produced during the acid fermentation phase; 51% is produced from the hydrolysis of complex organic material and 19% is produced from the acidogenesis products (Ahring, 2003). During acetogenesis, the volatile fatty acids are converted to acetate and hydrogen, which are used in the methanogenesis phase.

### **2.2.4 Phase IV: Methanogenesis**

The methanogenic bacteria consume the acetate and CO<sub>2</sub> to produce CH<sub>4</sub>. Methane is the main gas produced during this phase while CO<sub>2</sub> levels decrease. This is a slow process, taking from months to decades (Cossu et al., 1992). Methane formation from acetate is the most common pathway for CH<sub>4</sub> generation (producing 70% of CH<sub>4</sub> generated) (El-Fadel et al., 1996a). As seen in Equations 2 and 3, there are two main paths for methanogenesis present in a MSW landfill: acetotrophic and hydrogenotrophic decomposition (Bareither et al., 2013).



Hydrogenotrophic bacteria consume H<sub>2</sub>, CO<sub>2</sub> or formate, while acetotrophic bacteria consume acetate to form methane. Upon the biodegradation of the organic portion of the

MSW and the production of landfill gas the waste is stabilized and the rate of landfill gas generation is reduced.

## **2.3 Factors Affecting Waste Stabilization**

To enhance the waste stabilization process within the landfill, waste properties can be measured and analyzed. The composition of the waste is important in determining the properties of the waste. Instrumentation ensures maximum utilization of the landfill by making it possible to record different parameters that affect the anaerobic biodegradation process (Ahring, 2003). Some of the physical properties monitored within a landfill include: moisture content, nutrient content, pH, oxygen, density and temperature (El-Fadel et al., 1996a; Pacey et al., 1999).

### **2.3.1 Moisture**

The moisture content of the waste is one of the most important parameters for waste stabilization (El-Fadel et al., 1996a; Gawande et al., 2003; Pommier et al., 2007; Warith, 2002). During the hydrolysis step in anaerobic biodegradation, water is consumed to decompose polymers into monomers (Pommier et al., 2007). Field capacity is a measure of the ability of soil or waste to hold water against gravity, ranging from 5-20% by volume, and depends on the distribution of particle size (Warith, 2003). Zhao et al. (2008) state the initial moisture content of MSW is about 25% (wet basis) based on facility operators. Due to the heterogeneity of waste placed in a landfill, water will flow in preferred pathways (Gawande et al., 2003). Gas production can increase between 25 to 50% with moisture movement as compared to minimal moisture movement (Warith, 2003) The optimum moisture content was reported in literature to be 60% or higher

(Karthikeyan & Joseph, 2007; Rees, 1980). It was observed that an increase in moisture content in three different landfills showed an increase in gas production (Rees, 1980).

### **2.3.2 pH**

The optimum pH ranges from 6.7-7.5 in anaerobic conditions (Pacey et al., 1999; Townsend et al., 2008). Within this range, the methanogens can grow and yield maximum amount of CH<sub>4</sub> production.

### **2.3.3 Oxygen**

Oxygen content plays an important role in the aerobic biodegradation phase of the organic fraction of the waste. The oxygen content is also important for LFG quality; methanogenic bacteria are very sensitive to the presence of oxygen. The presence of oxygen is toxic to the anaerobic microorganisms.

### **2.3.4 Nutrient Content**

The microorganisms that are required for the biodegradation processes in the landfill require nutrients to grow and flourish. These nutrients include: nitrogen, phosphorous, sodium, potassium, calcium, and magnesium (Warith, 2003). Leachate recirculation enhances the re-distribution of nutrients within the waste and dilutes compounds that may be toxic to anaerobic bacteria. The presence of toxins or harmful chemicals may also cause a delay in the stabilization of the waste, as the microorganisms may not grow in this environment. Nutrient addition is not common or necessary to improve the biodegradation of the organic fraction within the waste (Townsend et al., 2008).

### **2.3.5 Density**

The density at the Ste. Sophie LFGTE facility was determined to be 930 kg/ m<sup>3</sup> (Bonany et al., 2013a). Density changes with biodegradation and compaction. The settlement of the waste with time affects the storage capacity and plays an important role in the design of the cover, barrier, and collection pipes (Townsend et al., 2008). The main difficulty with determining the amount of settlement that occurs in the landfill is due to the heterogeneity of the waste. The height of the landfill affects the overburden pressure; the greater the overburden pressure, the greater the settlement. The waste compaction and placement also affects the settlement of the waste. A few main mechanisms cause the MSW to settle in a landfill. Initial settlement occurs in a landfill due to instantaneous settlement because of mechanical compression. The second mechanism that influences the settlement is mechanical consolidation that is due to the movement of water or air out of the waste. The voids in the waste contain water and/or air and as a confining pressure is applied, the water or air can move out allowing the waste to compress and settle. If the waste is placed with an initial high density then the void ratio is low which will result in a low settlement. The movement of finer particles into larger voids also occurs allowing the waste to settle. The third mechanism influencing settlement in a landfill is biodegradation induced settlement. The composition of the waste also affects the amount of settlement that will occur; the higher the organic content, the greater the settlement, as more waste will be stabilized.

### 2.3.6 Temperature

In anaerobic digesters, temperature is stated as one of the most important parameters affecting the growth of the microorganisms required for anaerobic digestion (Angelidaki et al., 2003; Bareither et al., 2013). During anaerobic digestion, Ward (1983) states that methane generation doubles with a 10°C increase in temperature. The optimum temperature is 30-40°C for mesophilic bacteria and 50-70°C for thermophilic bacteria to thrive (Ahring et al., 2003; Mata-Alvares & Marinez-Viturtia, 1986; Rees, 1980; Townsend et al., 2008). However, Angelidaki et al. (2003) states that methanogenesis is possible in colder temperatures (<25°C) with the aid of psychrophilic bacteria. However, lower temperatures in anaerobic digester laboratory experiments show retardation of the establishment of microbial communities and a longer lag time for methanogenesis to occur (Bareither et al., 2013).

The temperature within the landfill is found to depend on various factors: 1) water content, 2) waste constituents, 3) waste filling rate, 4) waste thickness, 5) regional climate (Rowe & Islam, 2009; Rowe et al., 2010). Temperature is also important for the design of landfill components as it is a key parameter affecting their properties and behaviors (Neusinger et al., 2005; Rowe & Islam, 2009; Rowe et al., 2010). In Europe and Japan temperatures of 60°C are reported at the liner of the landfill while values ranging from 10-30°C are measured in North America (Hanson et al., 2005). Hanson et al. (2005) suggest that the highest temperatures are generally found in the middle of a waste column in a landfill, with decreasing temperatures towards the top and bottom of the landfill. Koerner & Koerner (2006) monitored temperatures in geomembranes within

two cells (one dry and one wet cell) in a MSW landfill in Pennsylvania, U.S.A for 10.5 years. The geomembranes in the final cover in both cells followed ambient temperatures. The geomembrane in the liner showed an average temperature of 20°C for 5.5 years and suddenly increased to 30°C and continues to slowly rise. In the wet cell, the initial temperature was 25°C and gradually increased to 41-46°C within the first 3.7 years (Koerner & Koerner, 2006).

## 2.4 Thermal Properties of Waste

The two main thermal parameters in the analysis of the unsteady state thermal behavior of MSW are the heat capacity and thermal conductivity of the waste. The thermal diffusivity,  $\alpha$ , relates the thermal conductivity to the heat capacity of a material:

$$\alpha = \frac{k}{c} \quad (4)$$

where  $\alpha$  is the thermal diffusivity

$k$  is the thermal conductivity

$c$  is the volumetric heat capacity

A high thermal diffusivity means the material can change temperatures rapidly while a low value means that more time is required to observe a change in temperature. Faitli et al. (2014) measured thermal conductivity and specific heat of MSW and concluded that landfills are capable of storing a large amount of heat. The study suggests that better understanding of the thermal properties of waste can improve the utilization of heat stored in landfills. A numerical model was developed by Onnen (2014) to study the effect of installing heat extraction systems in landfills. The study results show that managing

the heat within the landfill can provide enhanced landfill gas generation and improve landfill operations (Onnen, 2014).

#### **2.4.1 Specific Heat**

The heat capacity is the heat energy required to raise the temperature of a material by one degree. The specific heat value of waste was approximated in early research as the specific heat value for sawdust (Rees, 1980). As research progressed in this area, more studies were conducted on the thermal properties of waste in landfills. Houi et al. (1997) and Zanetti et al. (1997) assumed waste had a specific heat value of 2200 J/kgK and 2170 J/kgK respectively. In a heat transfer model developed by Yoshida et al. (1997), a specific heat value of 3300 J/kgK was calculated using the theoretical specific heat of individual components which compose MSW. Lefebvre et al. (2000) measured specific heat from extracted waste samples which varied from 1900 J/kgK to 3000 J/kgK throughout a 10 m deep waste cell. A specific heat capacity as low as 719 J/kgK was used to model the heat transfer within a landfill in Anchorage, Alaska (Hanson et al., 2006). The specific heat within a landfill depends on the different materials in the waste and can be approximated based on the individual components found in the MSW (Hanson et al., 2008). Faitli et al. (2014) recently developed laboratory testing on MSW from a landfill in Hungary and measured the specific heat to range from 900 J/kgK to 2100 J/kgK. In the literature, the specific heat value ranged from 719 J/kgK to 2360 J/kgK (Hanson et al., 2006; Yoshida et al., 1997).

### 2.4.2 Thermal Conductivity

Thermal conductivity is the rate at which heat energy flows through a unit area of matter because of a temperature gradient. In early experiments, thermal conductivity is assumed to be the same as sawdust, which is approximately 0.08 W/mK at 25°C (Rees, 1980). Lefebvre et al. (2000) used an average thermal conductivity of 0.1 W/mK in their model development. A value of 1 W/mK was used by Neusinger et al. (2005) to model the thermal conductivity of MSW. The thermal conductivity used to model the heat transfer in a landfill in Alaska was 0.23 W/mK (Hanson et al., 2006). A mathematical model developed by Gholamifard et al. (2008) for the anaerobic methanogenic phase assumed an initial thermal conductivity of 0.4 W/mK. Site data was later obtained from landfills in France providing better estimates of the thermal conductivity of the waste (0.6-0.8 W/mK) (Gholamifard et al., 2008). Thermal conductivity measured in a landfill in Hungary ranged from 0.24-1.15 W/mK (Faitli et al., 2014).

Hanson et al. (2000) conducted lab and field thermal conductivity probe experiments to determine thermal properties of MSW. The needle probe method resulted in variable measurements of thermal conductivity of MSW ranging from 0.01 to 0.7 W/mK (Hanson et al., 2000). Results from Hanson et al. (2000) suggest that the variability in the thermal conductivity measurements of the MSW is due to the heterogeneity of MSW composition. The thermal conductivity was very low and comparable to the values for air probably due to the air occupying the voids in the MSW.

## **2.5 Landfill Gas to Energy (LFGTE) Facilities**

Several technologies exist to convert waste into energy. Within a landfill context, landfill gas to energy (LFGTE) is a viable option to convert waste into a resource. Several research studies have been conducted to improve the treatment of waste to improve air space recovery, landfill gas recovery and energy generation from waste. A bioreactor landfill aims to control leachate recirculation and gas collection to improve waste stabilization. Although the Ste. Sophie LFGTE facility does not recirculate leachate, it aims to enhance waste stabilization and actively monitors and collects LFG. Research in the literature about LFGTE facilities in cold climates is limited, but a summary is included at the end of this section.

### **2.5.1 Bioreactor Landfill Research**

A bioreactor landfill is a designed landfill that is monitored and controlled to optimize the processes occurring in the landfill. This is accomplished by providing improved environmental conditions for the microorganisms to stabilize the waste. The main method utilized in bioreactor landfill design is liquid addition primarily by leachate recirculation (Gawande et al., 2003). As opposed to the “dry tomb” design that minimizes water entering the landfill, leachate is recirculated to provide a more favorable condition for the microbiological processes to occur within a landfill (Gawande et al., 2003). Another method that may be used in bioreactor landfill design is aeration, providing air to improve the biodegradation processes within the waste.

Davies & Colbran (2010) studied a pilot scale biocell landfill in Calgary, Canada. The concept of a sustainable landfill biocell begins similar to any landfill treatment where the cell is prepared and engineered to minimize impact on the groundwater and surrounding soil. The cell is then filled with waste and managed as an anaerobic landfill for five years; leachate is recirculated and LFG is collected. The cell is then operated as an aerobic landfill and finally it is mined and resources are recovered. In an ideal situation, the final products recovered from the biocell include methane gas from the anaerobic phase; compost material and recyclables during the aerobic and mining phases. The waste was shown to stabilize within 2 years with 55% CH<sub>4</sub> produced after 2 years of the placement of the first waste lift (Hunte et al., 2011).

The bioreactor landfill accelerates the stabilization of waste (5-10 years) compared to a conventional landfill, which can take up to 50 years (Pacey et al., 1999; Townsend et al., 2008). A bioreactor landfill can provide a 15-30% gain in landfill airspace (Townsend et al., 2008). The recovered airspace is important and more profitable during waste addition before closure. Some potential problems with bioreactor landfills include: 1) leachate seeps, 2) landfill slope stability, 3) temperature control, 4) fire and explosions and 5) gas and odour control (Townsend et al., 2008). Bioreactor landfill tests with leachate recirculation exist in: United States of America, Canada, United Kingdom, Australia, Netherlands, Japan, Sweden, Denmark, New Zealand and Germany (Karthikeyan & Joseph, 2007; Reinhart, 1996).

### 2.5.2 Liquid Addition

The most common liquid added to the landfill is leachate. Table 3 summarizes the benefits and potential problems associated with leachate recirculation. Laboratory studies by Tittlebaum (1982) show that landfills operating anaerobically stabilize faster with leachate recirculation. There are various methods of liquid addition to the landfill such as: waste pre-wetting, spray irrigation, drip irrigation, truck application, infiltration ponds, surface trenches, horizontal subsurface devices, vertical injection wells, or a combination of these methods (Reinhart 1996; Swati & Joseph, 2005; Townsend et al., 2008).

**Table 3 Benefits and problems of leachate recirculation**

<b>Benefits of leachate recirculation</b>	
Decrease cost for leachate treatment	(Davies & Colbran, 2010; Hunte et al., 2011)
Improved waste settlement	(Warith 2002; Townsend et al., 2008)
Enhanced biodegradation of MSW	(Gawande et al., 2003; Mata-Alvarez & Martinez-Viturtia 1986; Pacey et al., 1999; Swati & Joseph, 2005)
Improves distribution of nutrients, enzymes, methanogens	(Reinhart 1996; Gholamifard et al., 2008)
May dilute inhibitory compounds and act as pH buffer	(Reinhart 1996)
<b>Problems with leachate recirculation</b>	
Leachate seeps and ponding at landfill surface	(Reinhart, 1996; Townsend et al., 2008)
Problems with solid hard pan at surface during leachate spraying in northern climates	(Reinhart, 1996)

Leachate recirculation in the Trail Road landfill in Ontario, Canada used infiltration lagoons for 8 years, which improved settlement and 25% of the landfill airspace was recovered (Warith, 2002). In a bioreactor landfill in Florida, it was noted in Townsend et al. (2008) that the waste was not compacted to high levels to allow for leachate

recirculation and that the lost airspace would be compensated by the accelerated waste stabilization.

### **2.5.3 Air Addition**

Aeration can be used to mitigate the long stabilization time required for waste in landfills. The two main parameters to consider when determining vertical pipe setup for aeration are the oxygen consumption rate and air diffusion (Kallel et al., 2003). Air addition can be done by creating a vacuum and drawing air into the landfill. Aeration in landfills is similar to the aeration process occurring in compost plants. It is important to balance the amount of air and water in the system to provide optimum conditions for the microorganisms to exist and grow. If too much water is present, it may prevent the air from reaching the waste. For the oxygen to be used by the aerobic microorganisms, it must be transferred from the gas phase to the liquid phase. The volumetric rate of air added to a landfill is based on the composition of the waste, the operational objectives and aerobic waste biodegradation processes. Hudgins & Harper (1999) studied two landfill cells operating aerobically. Air injected into an aerobically operated landfill via vertical air injection wells increased the biodegradation rate by more than 50% and there was a 4.5% increase in settlement (Hudgins & Harper, 1999). The New River Regional Landfill (NRRL) in Florida was operated as a full scale bioreactor landfill, where air was added to the waste. At the NRRL it was noted that the greatest settlement occurred near the air injection wells and that temperature increased as air was added. In Japan a commonly used landfill design is the semi-aerobic landfill that supplies oxygen through leachate collection pipes, accelerating waste degradation and improving leachate quality and settlement (Kallel et al., 2003).

#### **2.5.4 Landfills in Cold Climates**

At low temperatures, environmental conditions for anaerobic biodegradation are not ideal, prolonging the startup of a bioreactor landfill (Zhao et al., 2008). The Northern Oaks Recycling and Disposal Facility in Michigan, USA was instrumented with temperature sensors and it was found that waste lifts placed in largely frozen conditions remained frozen for over 6 months (Zhao et al., 2008). It was observed that methane generation occurred after 3 months in waste lifts placed during the summer but after 8 months in waste lifts placed during the winter. Because of the low thermal conductivity of waste and specific heat capacity of the MSW, the temperature conditions during waste placement may persist for long periods of time. Zhao et al. (2008) suggest an effective way to potentially increase the temperature of the MSW is by using heat generated from the aerobic phase. In Anchorage Alaska, temperature sensors were placed within the waste and analyzed by Hanson et al. (2006). A 7 m thick waste lift was placed frozen between two layers placed in the summer and spring and some of the waste remained frozen for 2 years (Hanson et al., 2006). In the Calgary bioreactor landfill, Hunte et al. (2011) encountered a major problem with freezing of condensate in pipe lines which decreased gas collection and the vacuum was increased to compensate. However, this allowed O<sub>2</sub> to increase up to 4.4% and CH<sub>4</sub> to decrease from about 50% to 40%. Ambient temperatures were observed to have a limited effect on temperature of the waste and waste was indicated to be a good insulator. At the Ste. Sophie LFGTE facility, Bonany et al. (2013a, 2013b) states that waste placed in a frozen state remained frozen for 1.5 years and the latent heat of fusion was shown to have a large impact on the heat budget of a landfill operated in a cold climate.

## 2.6 Heat Transfer Processes within Landfill

Three main heat transfer mechanisms occur in a landfill system: 1) conduction, 2) radiation, and 3) convection. At the top of the landfill, heat may be transferred by: air via convection, long wave radiation, and incoming solar radiation. The energy from the sun is high in energy and is emitted as short wave radiation (ultraviolet radiation). This incident short wave radiation hits the surface of the landfill to increase the temperature at the surface, which increases the heat transfer into the waste. The waste emits long wave radiation (in the form of infrared radiation). Convection also occurs at the top of the landfill surface; air movement above the landfill can transfer heat to or from the landfill surface.

The net heat transferred at the surface of the landfill is transmitted into the landfill waste mainly through conduction. Leachate and landfill gas may also transfer heat through convection within the void spaces in the MSW. This may occur due to LFG extraction, atmospheric pressure changes, and substantial production of gases during anaerobic decomposition of easily hydrolysable organic content within MSW (Neusinger et al., 2005). In cold climates, the frozen liquid portion of the MSW also plays an important role in the heat budget of a landfill, as additional energy is required for phase change (Bonany et al., 2013a). Within the placed waste, heat may be generated through aerobic and anaerobic biodegradation, which occur naturally as the organic fraction of waste is biodegraded. Heat generated within the waste can be transferred by conduction through the different waste constituents, by convection via leachate or landfill gas movement, or stored in the waste. At the base of the landfill, heat can be transferred to/from the waste

depending on the temperature gradient between the waste and subsurface material. These heat transfer processes are described in more depth in this section.

### 2.6.1 Radiation

Radiation occurs across air by the propagation of heat energy as electromagnetic waves (Farouki, 1981). Primary radiation fluxes on the ground surface include short and long wave radiation. Short wave radiation is the radiation that is from the sun and ranges from 0.3-3  $\mu\text{m}$ : this is the total solar radiation (Duffie & Beckman, 2006). Long-wave radiation has wavelengths greater than 3  $\mu\text{m}$  and originates from the radiation emitted by the atmosphere (Duffie & Beckman, 2006).

The sky can be considered a blackbody to consider the long wave radiation between the ground surface and the sky. The long wave radiation can be explained with the following equation:

$$Q_l = \varepsilon A \sigma (T_{sky}^4 - T^4) \quad (5)$$

where  $Q_l$  [W] is the long wave radiation,  $\varepsilon$  is the emissivity,  $A$  [ $\text{m}^2$ ] is the surface area,  $T_{sky}$  [K] is the ambient temperature,  $T$  [K] is the temperature of the waste at the landfill surface,  $\sigma$  [ $\text{W}/\text{m}^2\text{K}^4$ ] is the Stefan Boltzmann constant for blackbody radiation.

Empirical derivations relating the ambient temperatures to the sky temperatures for clear skies were developed in Swinbank (1963). For the radiative heat transfer at the surface of the Ste. Sophie landfill the sky temperature was assumed to be the ambient temperature. This is a reasonable assumption since the ambient temperature does not play a large role

on the heat transfer processes, and to eliminate error associated with empirical equations used to calculate the sky temperature. In most thermodynamic applications, the sky temperature is approximated by the ambient temperature.

### 2.6.2 Convection

Heat loss from the ground surface due to wind can be considered by the thermal processes of convection. This heat transfer mode can occur at the ground surface due to the flow of air (wind) above the surface. The mechanism for heat transfer through convection can be modelled with the following equation:

$$Q_c = hA(T_{amb} - T) \quad (6)$$

where  $Q_c$  [W] is the convective heat,  $h$  [W/m<sup>2</sup>K] is the convection coefficient, and  $T_{amb}$  [K] is the ambient temperature.

The convection coefficient can be determined through empirical equations dependent on the wind velocity above the ground surface. McAdams (1954) developed an empirical equation to determine the heat transfer coefficient based on the velocity of wind:

$$h = 5.7 + 3.8v \quad (7)$$

where  $v$  [m/s] is wind speed and  $h$  [W/m<sup>2</sup>K] is the convection coefficient. However, this convection coefficient included the effect of radiation. Watmuff et al. (1977) developed another empirical relationship between ambient velocity and the heat transfer coefficient:

$$h = 2.8 + 3.0v \quad (8)$$

where  $v$  [m/s] is wind speed and  $h$  [W/m<sup>2</sup>K] is the convection coefficient.

### 2.6.3 Conduction

Conduction is the principle heat transfer mechanism within a soil (Neusinger et al., 2005). The thermal conductivity and specific heat capacity are important parameters required to determine the amount of conduction that occurs, and these parameters are strongly dependent on moisture content (Faitli et al., 2014; Neusinger et al., 2005). Increasing the moisture content can be translated as an increase in thermal conductivity because water improves the transfer of heat. The effect of moisture content can influence the thermal balance in the landfill by changing the thermal conductivity.

### 2.6.4 Latent Heat of Fusion

Limited research has been completed on the study of latent heat for frozen waste in the literature. Hanson et al. (2006) used values of 1.7 and 32.1 kJ/kg as the latent heat of soil and waste respectively in order to model temperature profiles of a landfill in Anchorage, Alaska. Bonany et al. (2012) determined a range of values for the latent heat of fusion based on the following equation developed by Andersland & Anderson (1978) to approximate the latent heat of fusion in soils:

$$L_s = L_w w \gamma_d (1 - w_u) \quad (9)$$

where  $L_s$  [kJ/m<sup>3</sup>] is the volumetric latent heat of fusion for soil,  $w$  is the mass fraction of water content in soil,  $\gamma_d$  [kg/m<sup>3</sup>] is the dry density and  $w_u$  is the ratio of unfrozen water to total water within the soil. Bonany et al. (2012) calculated that the latent heat of fusion of waste would range from 10 to 20% of the latent heat of fusion of water. A latent heat of fusion of 38 kJ/kg (11% of the latent heat of fusion of water) was determined for the waste, based on the calibrated model developed by Bonany et al. (2013b).

### **2.6.5 Heat Generation**

The biodegradation of the organic fraction in MSW can occur by aerobic or anaerobic biodegradation as previously mentioned. The biodegradation processes occurring within the landfill generate heat from the biochemical reactions that occur. The anaerobic biodegradation produces a small amount of heat (Ward, 1983). In a study about the impact of temperature on the landfill liner, the two main contributors to heat generation are biodegradation of MSW and heat produced through hydration of ash (Rowe & Islam, 2009). If a landfill is managed aerobically or is exposed to air, aerobic biodegradation occurs, generating a large amount of heat (Rees, 1980).

El-Fadel (1999) mentions temperatures at the top of the landfill can be 16.6°C higher than ambient temperatures due to aerobic biodegradation of the organic fraction. According to theoretical amounts, 1 kg of glucose generates 1520 kCal and 9 kCal when decomposed aerobically and anaerobically respectively (El-Fadel, 1999). This shows that heat generated via aerobic biodegradation is about 169 times more than the amount generated anaerobically. Lefebvre et al. (2000) stated that aerobic decomposition produces 460 kJ/mole O<sub>2</sub>. Nelson et al. (2003) created a mathematical model to study the heat generation in compost piles. Cellulosic material was allowed to undergo exothermic reactions in the presence of microorganisms in order to model and evaluate how the cellulosic material responds to changes in temperature. The heat generation processes occurring in compost piles are similar to those occurring in industrial processes that have large volumes of organic materials such as MSW landfills. The heat generation rate was

modelled using the Arrhenius relationship with temperature (Nelson et al., 2003). Yoshida & Rowe (2003) developed an aerobic heat generation rate of  $4.67 \text{ W/m}^3$ .

In a heat transfer model developed by Neusinger et al. (2005), a heat source of  $1 \text{ W/m}^3$  was applied over the landfill volume. The heat source was multiplied by a scaling factor to show the impact of heat generation on temperature. A comprehensive literature review of heat generation potential of MSW was published in 2005, as seen in Table 4 (Yesiller et al., 2005).

**Table 4 Heat generation rates from aerobic and anaerobic biodegradation (modified from Yesiller et al., 2005)**

Authors	Heat Generation	Analysis Approach	Decomposition Conditions
Pirt (1978)	6,360 kJ/kg glucose, 1,147 kJ/mol-O <sub>2</sub>	Aerobic digestion of glucose	Aerobic
Pirt (1978)	0.377 kJ/kg glucose, 68 J/mol- CH <sub>4</sub>	Complete conversion of organic fraction to CO <sub>2</sub> and CH <sub>4</sub>	Anaerobic
El-Fadel <i>et al.</i> (1996c)	1023 kJ/mol- organic material converted	Enthalpy of reactants of the stoichiometric biochemical reaction	Anaerobic
El-Fadel <i>et al.</i> (1996c)	255 kJ/mol- CH <sub>4</sub>	Enthalpy of reaction of the stoichiometric biochemical reaction	Anaerobic
El-Fadel <i>et al.</i> (1996c)	109 kJ/mol- CH <sub>4</sub>	Stepwise biochemical reactions	Anaerobic
Lefebvre <i>et al.</i> (2000)	10 MJ/m <sup>3</sup>	Heat accumulation in the waste	Aerobic
Yoshida <i>et al.</i> (1997)	460 kJ/mol-O <sub>2</sub>	Enthalpy of the stoichiometric equation of biological reaction	Aerobic
Yoshida <i>et al.</i> (1997)	45 kJ/mol-CH <sub>4</sub>	Enthalpy of the stoichiometric equation of biological reaction	Anaerobic
Yoshida and Rowe (2003)	4.67 J/m <sup>3</sup> -s	Biological decomposition (equivalent glucose)	Aerobic
Yoshida and Rowe (2003)	0.218 J/m <sup>3</sup> -s	Biological decomposition (equivalent glucose)	Anaerobic
Hanson <i>et al.</i> (2008)	2.5–11.3 J/m <sup>3</sup> -s	step-function for waste decomposition	Aerobic
Hanson <i>et al.</i> (2008)	0.08-0.38 J/m <sup>3</sup> -s		Anaerobic
Bonany <i>et al.</i> (2013b)	16.5 J/m <sup>3</sup> -s	Numerical modelling to simulate the heat flux and heat generation	Aerobic
Bonany <i>et al.</i> (2013b)	0.30 J/m <sup>3</sup> -s		Anaerobic

A mathematical model developed by Gholamifard et al. (2008) estimated the heat generation rate during anaerobic digestion based on the hydrolysis reaction and the amount of methane produced. In the model, heat generation rates of 170 kJ/mol and 80 kJ/mol were used for heat generated during hydrolysis and methanogenesis respectively (Gholamifard et al., 2008). Hanson et al. (2008) modeled the heat generation within a

landfill; no heat was generated at temperatures below 0°C and above 80°C. Heat generation was highest for fresh waste and lower for older wastes. The heat generation rate was used to calibrate the model to simulate the temperatures recorded at field sites. Based on gas analysis, MSW was assumed to biodegrade aerobically in the first 4 months and anaerobically afterwards (Hanson et al., 2008). The anaerobic and aerobic heat generation rates varied from 0.08-0.38 W/m<sup>3</sup> and 2.5-11.3 W/m<sup>3</sup> respectively (Hanson et al., 2008). Bonany et al. (2013b) summarizes the heat generation rates from the literature for anaerobic and aerobic biodegradation ranges from 0.218 -34.79 W/m<sup>3</sup>.

## **2.7 Landfill Modelling Efforts**

Different types of models have been created to represent different processes that occur within a landfill. It is important for a model to understand the system, express the hypothesis and predict how the system will react in the future (Donoso-Bravo et al., 2011). Various mathematical models have been established to analyze the biological and chemical reactions that occur within a landfill. Chemical models have been established to analyze the kinetics of anaerobic biodegradation. The different phases of anaerobic digestion have been well represented by mathematical models. Heat and mass transfer models have been created to improve biogas generation.

### **2.7.1 Chemical and Biological Models**

Many models have been created to simulate the chemical and biological processes occurring during aerobic and anaerobic biodegradation. A couple of the models presented in the literature that relate to waste are presented in this section. The gas generation and microbial growth model developed by El-Fadel et al. (1996d) predicts methane

generation rates for anaerobic biodegradation. The model developed by El-Fadel et al. (1996c) represents the biochemical and physical processes within a landfill. Each layer in the landfill was treated as a batch reactor and a mass balance was coupled with first order Monod kinetics. The waste within the landfill was assumed to be horizontally homogeneous. The model was used to simulate measured gas generation values from the Mountain View Controlled Landfill Project, California and model results were in good agreement with collected data. Haarstrick et al. (2001) created a mathematical model of the organic fraction of MSW in landfills and landfill gas and heat generation during anaerobic biodegradation; initial mass of organic material was 30 kg per m<sup>3</sup> of MSW (Haarstrick et al., 2001). It is important to note that even though modelling has been conducted at several sites and the parameters were adjusted to fit the observed data, not all previous models are adequate for extrapolation or use on other sites (Rodriguez et al., 2009).

### **2.7.2 Heat Transfer Models**

El-Fadel et al. (1996b, 1996d) produced a numerical model for the generation and transport of gas and heat in MSW landfills based on test cells in the Mountain View Controlled Landfill Project, California. The model included biokinetic equations for microbes in the landfill and modelled the transport of the gas and heat within the different layers of a MSW landfill. The model considered the waste as a porous material and was used to simulate field data. El-Fadel et al. (1996b, 1996d) produced a numerical model for the generation and transport of gas and heat in MSW and were the first research group to model the heat and mass transfer in space and time within a landfill. It was suggested that heat generation was directly related to gas generation. The majority of the heat from

anaerobic biodegradation was determined to occur during acidogenesis; hence, heat generation was proportional to acetic acid (acetic acid was assumed to be a good indicator of carboxylic acids) formation rate. The model included the effect of temperature on previous models, which aimed to describe anaerobic digestion within the landfill. The overall average landfill heat capacity, density and thermal conductivity were calculated based on the weighted average of these properties within all three phases (solid, liquid and gas). Limitations to this research included that these measured data are from test cells not a full scale operating landfill, only the anaerobic digestion process is considered in the model, and uncertainty in biological parameters. The model did not consider changes in ambient air temperatures, waste temperatures and heat transfer processes at the surface (El-Fadel et al., 1996b, 1996d).

A numerical method was established by Rowe et al. (2010) with an aim to reduce the temperature of liners in the Tokyo Port landfill. Cooling pipes were installed in order to lower the temperature near the liner. Liner temperatures in this landfill were expected to range from 30-40°C and reached up to 60°C (Rowe et al., 2010). A 2-D (0.25m quadrilateral elements) and 3-D model were created to model the thermal behavior with the surface temperature kept at a constant 15°C, which is the average temperature in the region. When modelling the aerobic phase during waste placement, the top 1 m was assumed to undergo aerobic biodegradation. However, the heat generation terms were determined by fitting based on measured data from the landfill. The heat generation rates used in the model for MSW at the surface, MSW above leachate level, and MSW below leachate level were: 4.67 W/m<sup>3</sup>, 0.436 W/m<sup>3</sup>, and 0.763 W/m<sup>3</sup> (Rowe et al., 2010).

Previous research mainly focused on heat generation from anaerobic biodegradation and limited research exists about the impact of heat generated from the aerobic phase within a MSW landfill. Lefebvre et al. (2000) instrumented a MSW landfill in South of France with sensors to measure temperature and gas composition. During the first 20 days, the average temperature increased by 20°C. The thermal conductivity and diffusivity were measured with a thermal probe. This research stated that the predominant method for increasing the temperature was by oxygen diffusion and aerobic reactions. The temperature of the MSW changed with time and it was observed to increase upon placement during the first few weeks and then decreased to a steady value. Laboratory experiments were conducted where oxygen was fed to the waste and the rate of oxygen consumption was found to range between  $10 \times 10^{-5}$  to  $10 \times 10^{-3}$  mol O<sub>2</sub>/m<sup>3</sup>s. It was observed from field data that measured temperatures usually peaked at 10-15°C higher than waste placement temperatures. In this landfill the waste density varied between 600 to 950 kg/m<sup>3</sup> and waste was placed weekly in 0.2-0.6m thick layers. The upper layer of the waste had concentrated sensors (17 probes) placed in the top 0.3-4m of the waste cell. The fresh waste was exposed to the atmosphere for 2 months (oxygen was continuously detected) and although the ambient temperature fell below 15°C, the measured temperatures within the waste reached 35-50°C after 20 days. Once the waste was covered, aerobic activity stopped, and the main source of heat generation occurred from within the anaerobic zone. However, this research did not consider the effects of radiation, rainfall, evaporation and convection by vertical movement of LFG upwards (Lefebvre et al., 2000).

Heat generation and gas production in a MSW landfill were studied by Hanson et al. (2005). Gas and temperature measurements were taken at 140 different locations in the liner and cover of a 21 m high landfill in Michigan, USA. New waste placed in the landfill cell showed a temperature increase of 1-15°C/year while the liner temperature showed an increase of 2-4°C/year. The initial temperature increase within the waste was observed to be higher for waste placed during warm seasons than waste placed at cooler temperatures. It was also observed that the age of the waste may have influenced the observed temperature changes. Hanson et al. (2005) observed a cell receiving fresh waste to increase by 10°C/year while another cell receiving old waste to increase by 2.5°C/year. Anaerobic decomposition was detected weeks to months after the waste is placed. At shallow depths and near the edges of the landfill, the temperature within the waste changed due to fluctuations in seasonal temperatures while dampening at 8 m depth of MSW. Older waste was observed to remain at 50-60°C. Hanson et al. (2006) used finite element analysis to study the effect of waste placement practices on heat generation and the biodegradation of waste in a MSW landfill in Alaska. Temporal and spatial thermal analysis was conducted. A sinusoidal function for ambient temperature was used to define the thermal boundary condition at the top of the waste profile. The bottom boundary condition was a prescribed temperature value based on a constant temperature found 75 m below the bottom of the landfill. The heat generation was modelled as a step function where in the first 120 days a value of 2.5 W/m<sup>3</sup> was used and 0.08 W/m<sup>3</sup> afterwards (Hanson et al., 2006). The heat generation rates were adjusted to simulate the measured field temperatures. In 2008, Hanson et al. analyzed and modelled temperatures

of landfills in Michigan, New Mexico, Alaska and British Columbia. Initially, the heat generation was modelled using a step function that assumed an aerobic heat generation rate varying from 2.5-11.3 W/m<sup>3</sup> for the first 4 months (based on measured gas concentration data) and then an anaerobic heat generation rate of 0.08-0.38 W/m<sup>3</sup> henceforth. The heat generation model was then improved and a model similar to that used for gas generation rates (e.g. USEPA's LFG generation model) was used; a sharp rise to a maximum generation rate followed by a slow decline:

$$Q = A_t \left( \frac{t}{B_t + t} \right) \left( \frac{C_t}{C_t + t} \right) e^{-\sqrt{t/D}} \quad (10)$$

where  $Q$  is the heat generation rate (W/m<sup>3</sup>),  $t$  is the time (day),  $A_t$  is the peak heat generation rate factor (W/m<sup>3</sup>),  $B_t$ ,  $C_t$  is the shape factors (day), and  $D$  is the decay rate factor (day). This exponential growth and decay heat generation was used to determine the peak heat generation rate by empirically calibrating it to the temperatures recorded at the aforementioned landfill sites. The peak heat generation rate was used to improve the heat generation model by scaling the heat generation to show the dependence between temperature and heat generation rate. A dual ramped scaling function was developed where the peak heat generation rate was assigned during optimal temperatures (30-60°C) for biodegradation and linearly increases and decreases from (0-30°C) and (60-90°C) respectively.

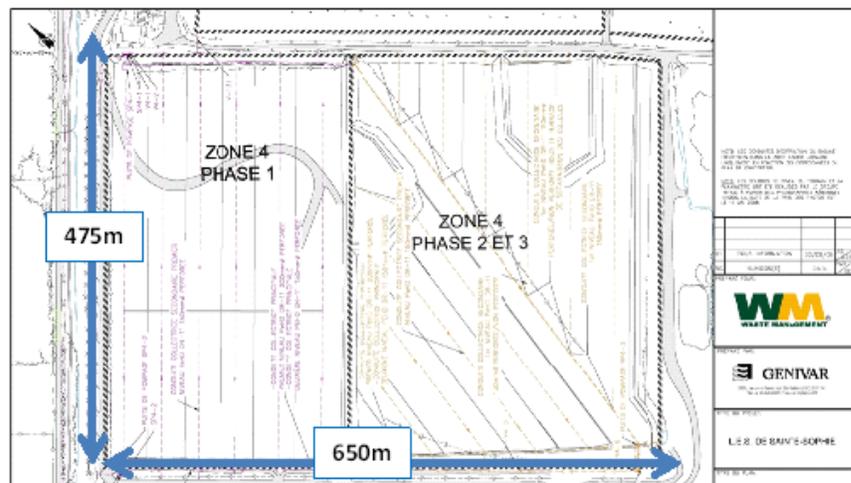
The heat transfer model was used to analyze the temperatures within the different components of the landfill: liner, waste, cover. The 1-D analysis was completed using the finite element analysis program ABAQUS 6.5 with an element size of 0.1 m - 0.6 m and

a 1 day time step (Hanson et al., 2008). Hanson et al. (2013) formulated a heat generation rate, which was expressed independently of time in the form of the Weibull distribution. The heat generated was related to energy expended instead of time. This was accomplished by integrating the heat generation over time for a given landfill site. The energy expended is the integration of heat generation vs. time at a certain time plotted against the heat generation rate at a point of interest. This relationship was scaled based on temperature with higher heat generation peaks during optimal biodegradation temperatures. Although this model eliminates the influence of the age of the waste on heat generation rates, it is still specific to each site and varies from one landfill site to another. The model did not simulate gas transport, and the heat generation model was determined based on fitting the temperature data of the study.

Bonany et al. (2013a) modelled the heat transfer within the first three waste lifts placed in the Ste. Sophie LFGTE facility; more details of this simulation are found in section 4. The model presented in this thesis contains detailed lift by lift temperature and oxygen data that are incorporated in the formulation of the model. The surface processes at the top of the landfill are accounted for in the conceptual and numerical model, unlike previous modelling efforts. A volumetric heat generation rate that is dependent on temperature is used to quantify the total heat generation. Most importantly, what characterizes the research presented in this thesis is the consideration of the potential heat generation zone at the surface (which is dependent on oxygen diffusion) and studying the impact of aerobic heat generation on the temperatures of a landfill in a cold climate.

### 3 Instrumentation of Ste. Sophie LFGTE facility

As mentioned earlier, to better understand the biodegradation process that occurs in an anaerobically operated landfill, instrumentation of zone 4 (see Figure 3) at the Ste. Sophie facility was completed. An instrument bundle refers to a combination of instrument sensors that are mounted on a 60 cm x 60 cm plate. There are 12 bundles in total which were designed and installed in the landfill to measure temperature and oxygen. All the bundles include an oxygen sensor, moisture and electrical conductivity sensor, a total earth pressure cell and a liquid settlement system. Bundles 1-4 include a vibrating wire piezometer to measure mounding of leachate. Wires from each instrument sensor go to a central connection box and are combined into a single cable which connected the instrument bundle to a CR1000 FlexDAQ data logger in an instrument shed located outside the landfill footprint.

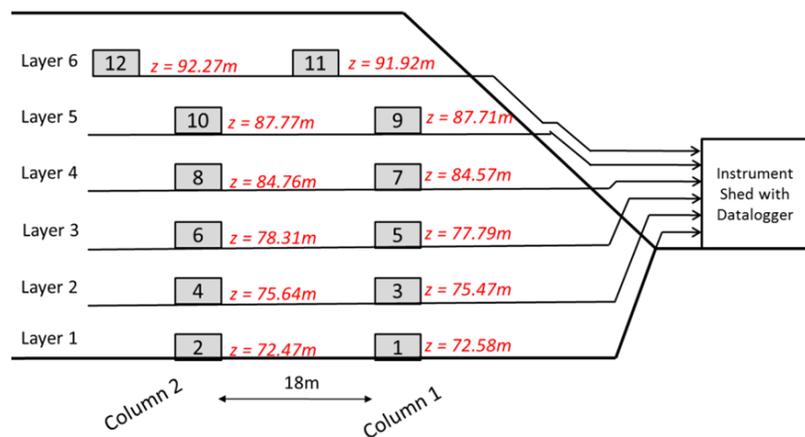


**Figure 3 Zone 4 Ste. Sophie landfill footprint (modified from Genivar, 2008)**

Initially, one instrument bundle was designed and tested by Vingerhoeds (2011) to be able to withstand the harsh environment in the landfill; the design was used to order a

total of 12 instrument bundles. The instrumentation bundles were manufactured by RST Instruments. The 12 bundles were installed in the landfill between January 2009 and May 2012.

The bundles were placed progressively in the waste and were covered with 30-40 cm of sand at different elevations in the landfill as seen in Figure 4.



**Figure 4 Placement of 12 instrument bundles in two vertical profiles in the Ste. Sophie LFGTE facility**

The total earth pressure cell measures the overburden pressure due to the waste placed on top of the instrument bundle. The oxygen sensor measures the amount of oxygen present (% by volume) and the sensor is vertically placed into the sand. The moisture sensor measures the moisture content in the sand surrounding the instrument bundle and could be used to infer the increase or decrease in moisture content of the surrounding waste. The amount each bundle settles over time is measured by the settlement gage which is a pressure transducer. It measures pressure at the bundle and is hydraulically connected to another pressure transducer which is located in the instrument shed. The difference in

pressure between the 2 pressure transducers as the bundle settles is used to calculate settlement. The vibrating wire piezometer measures any positive head of leachate that may mound at the bottom of the landfill and is only installed in the bottom four bundles.

From the instrument bundles, there is also a filter and two hollow tubes wrapped together with a plastic which connect from the bundle to the instrument shed. This allows for the possibility to draw liquid, or landfill gas out. These hollow tubes can also be used to pump air into the waste. The total earth pressure cell, oxygen sensor, moisture and electrical conductivity sensor and settlement system all measure temperature because the temperature is required in correction calculations. Oxygen sensors have a small heater which is used to prevent condensation on the sensor so the temperature readings have been observed to be about 0.5°C higher than the other sensors.

Electricity to the instrument shed was provided by Waste Management at the Ste. Sophie site, used to power the data acquisition system and sensors as needed. In the instrument shed, a modem is connected to the data acquisition system to access the data remotely. A battery back-up is also found in the instrument shed for emergency power outages on site.

The focus of this thesis is on the temperature data and modelling of a heat budget for the waste. However as part of the project the following tasks were completed: (1) field installation of bundles 11 and 12, (2) continuous downloading and processing of measured instrument bundle results, and (3) continued maintenance/troubleshooting of all instrument bundles in the field. A full data set (November 2009 to October 2014) of

temperature, oxygen, settlement, total earth pressure, moisture, and total head data are available, however only oxygen and temperature data are discussed in detail in this thesis. Complete settlement, total earth pressure, piezometric pressure and oxygen plots are found in Appendix A. A discussion of temperature and oxygen data is provided in the following section.

## **4 Field Data and Model Results**

This section is presented as a journal paper which shows the model formulation and results of all five waste lifts. The paper discusses the effect of the different thermal processes on the heat budget of an operating anaerobic landfill in a northern climate.

Title: Conceptual and Numerical Heat Transfer Model of a Landfill in a Northern Climate

Authors: Dina Megalla, Paul J. Van Geel

Submitted to: Waste Management

Data collection and modeling was completed by Dina Megalla. The text was written by Dina Megalla and edited by Paul Van Geel.

### **4.1 Conceptual and Numerical Heat Transfer Model of a Landfill in a Northern Climate**

#### **4.1.1 Abstract**

A landfill gas to energy (LFGTE) facility in Ste. Sophie, Quebec was instrumented with sensors which measure temperature, oxygen, moisture content, settlement, total earth pressure, electrical conductivity and mounding of leachate. These parameters were monitored during the operating phase of the landfill in order to better understand the biodegradation and waste stabilization processes occurring within a LFGTE facility. Conceptual and numerical models were created to describe the heat transfer processes which occur in a 24 m waste profile placed in five lifts over a two-year period. A finite

element model was created to simulate the temperatures within the waste and a heat budget was completed for the different waste lifts placed. The calibrated model was able to simulate the temperatures measured to date within the instrumented waste profile at the site. The model was used to evaluate a heat budget for the waste profile. The model simulations and heat budget provide a better understanding of the heat transfer processes occurring within the landfill and the relative impact of the various heat source/sink and storage terms. Aerobic biodegradation appears to play an important role in the overall heat budget at this site generating 56% of the total heat generated within the waste profile.

#### **4.1.2 Introduction**

Landfills still remain a principal method of final disposal around the world. In Canada, 25 million tonnes of waste were sent to a landfill for final disposal in 2010 (Statistics Canada, 2010). Modern landfills are engineered and managed to enhance waste stabilization. Accelerating the biodegradation of waste in a LFGTE facility is important to increase waste settlement, regain airspace, and increase methane generation. The anaerobic biodegradation process depends on a variety of environmental factors such as moisture content, nutrient content, pH, oxygen concentration, density, and temperature (Pacey et al., 1999).

Instrumentation of landfills is a method of monitoring and potentially controlling some of the parameters that influence the biodegradation of the waste. In northern climates it was observed that temperature plays an important role in the rate of biodegradation of waste. Waste placed frozen was observed to remain frozen for 6 months to 2 years upon

placement (Bonany et al., 2013a; Hanson et al., 2006; Zhao et al., 2008). This poses a problem because mesophilic and thermophilic bacteria required during the anaerobic biodegradation of waste function optimally between 30-40°C and 50-60°C respectively (Rowe & Islam, 2009). Research groups have measured temperature changes within landfills with time (Lefebvre et al., 2000; Lanini et al., 2001; Yoshida & Rowe, 2003; Hanson et al., 2005; Zhao et al., 2008; Hunte et al., 2011). Spatial and temporal variations of temperature were recorded and in some cases modelled. The two main thermal parameters needed to simulate heat transfer in waste include the thermal conductivity and specific heat capacity. Estimates of these parameters in the literature are summarized in Table 5. Most of the values found in the literature are not directly measured but are estimated from calibrated models.

**Table 5 Summary of thermal parameters for waste found in the literature**

<b>Reference</b>	<b>Thermal Conductivity (W/mK)</b>	<b>Specific Heat (J/kgK)</b>
Houi et al. (1997)	0.10	1,900 to 3,000
Yoshida et al. (1997)	0.53	3,300
Zanetti et al. (1997)	0.0445	2,200
Lefebvre et al. (2000)	0.10	1,900 to 3,000
Hanson et al. (2006)	0.30	719
Hanson et al. (2008)	0.6 to 1.5	1,200 to 2,200
Rowe et al. (2010)	0.35 to 0.96	1,940 to 2,360
Bonany et al. (2013b)	0.67	1400
Faitli et al. (2014)	0.24 to 1.15	900 to 2100

In a northern climate it was observed that waste placed during the winter months can remain frozen for years. This is important for the anaerobic biodegradation process since temperatures are below the optimal range, limiting waste stabilization and the amount of methane-rich landfill gas produced during this time period. In order to optimize

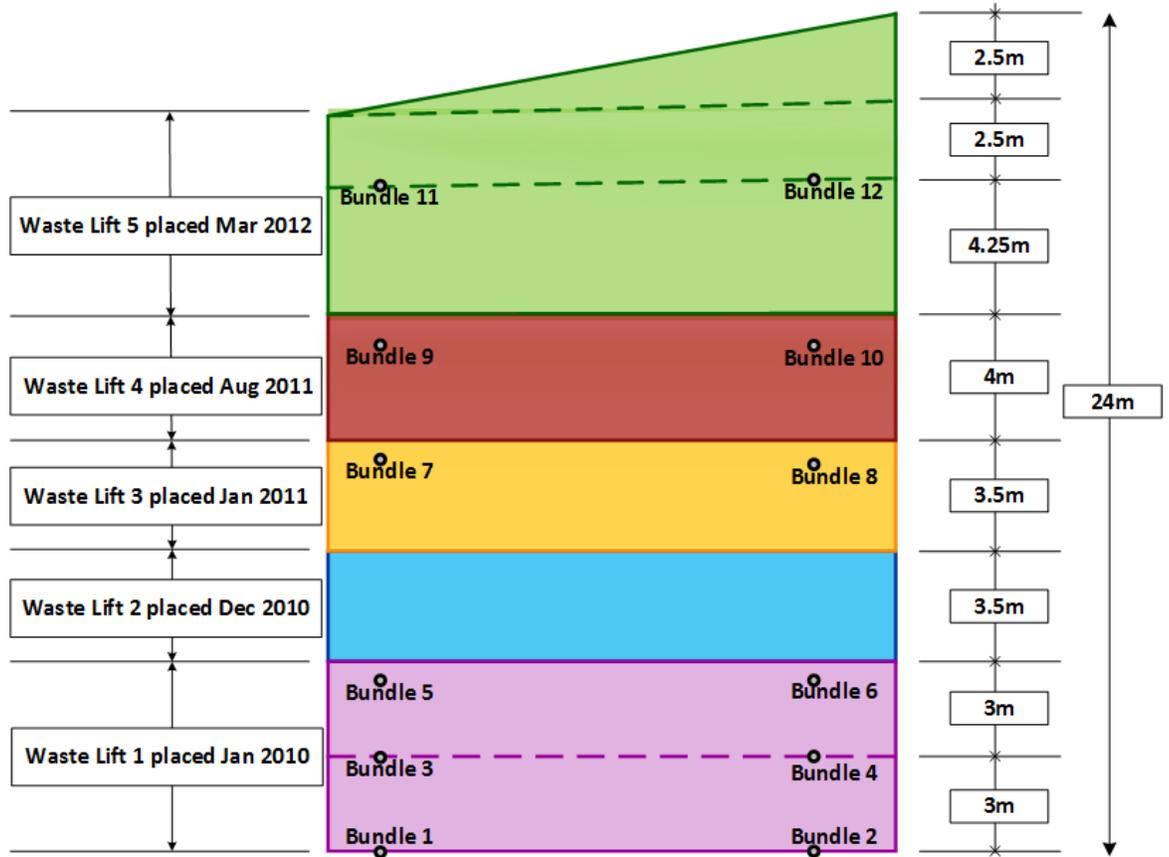
operations at a landfill in a northern climate to enhance waste stabilization, a LFGTE facility in Ste. Sophie Quebec was instrumented with sensors to measure some of the environmental parameters. This site is capable of accepting up to one million tonnes of garbage per year and is operated anaerobically with no leachate recycle. Landfill gas is collected on site via horizontal and vertical collection wells and converted into energy; some of the landfill gas is transported to a nearby pulp and paper mill where the landfill gas is used as its primary heat source.

The goal of this paper was to simulate waste temperatures over time within five waste lifts as they were placed in a landfill operating in a northern climate to illustrate the impacts of temperature and aerobic and anaerobic biodegradation on an energy/heat budget for the waste. The model contains the heat transfer that occurs at the base of the landfill and at the waste surface which is exposed to the ambient surroundings. The heat sinks and sources such as the latent heat for phase change, sensible heat, anaerobic zone heat generation and heat generated from aerobic biodegradation, are incorporated in the model domain. Measured temperature data from the Ste. Sophie LFGTE facility are used to calibrate the model and the model is used to develop a heat budget for the waste column as sequential waste lifts are added. This model is used to better understand the thermal processes which occur in an operating anaerobic landfill located in a northern climate.

#### **4.1.2.1 Ste. Sophie LFGTE Instrumentation**

To monitor the Ste. Sophie LFGTE facility, a prototype instrument bundle was designed and tested in the lab prior to fabricating twelve bundles to be installed in the field

(Vingerhoeds, 2011). Each instrument bundle includes a: total earth pressure cell, oxygen sensor, moisture and electrical conductivity sensor, vibrating wire piezometer to record any leachate mounding, and a liquid settlement system. The moisture, settlement, oxygen, and total earth pressure sensors all contain a thermistor which measures temperature. Data are recorded every half hour using a data acquisition system. Installation of instrument bundles in the field began in November 2009 and data has been continuously collected since. Figure 5 shows the placement of 12 instrument bundles (6 bundles in each of the 2 vertical profiles) within the 24 m deep waste cell. The waste was progressively added as five waste lifts between January 2010 and March 2012; the final cover was placed in June 2014.



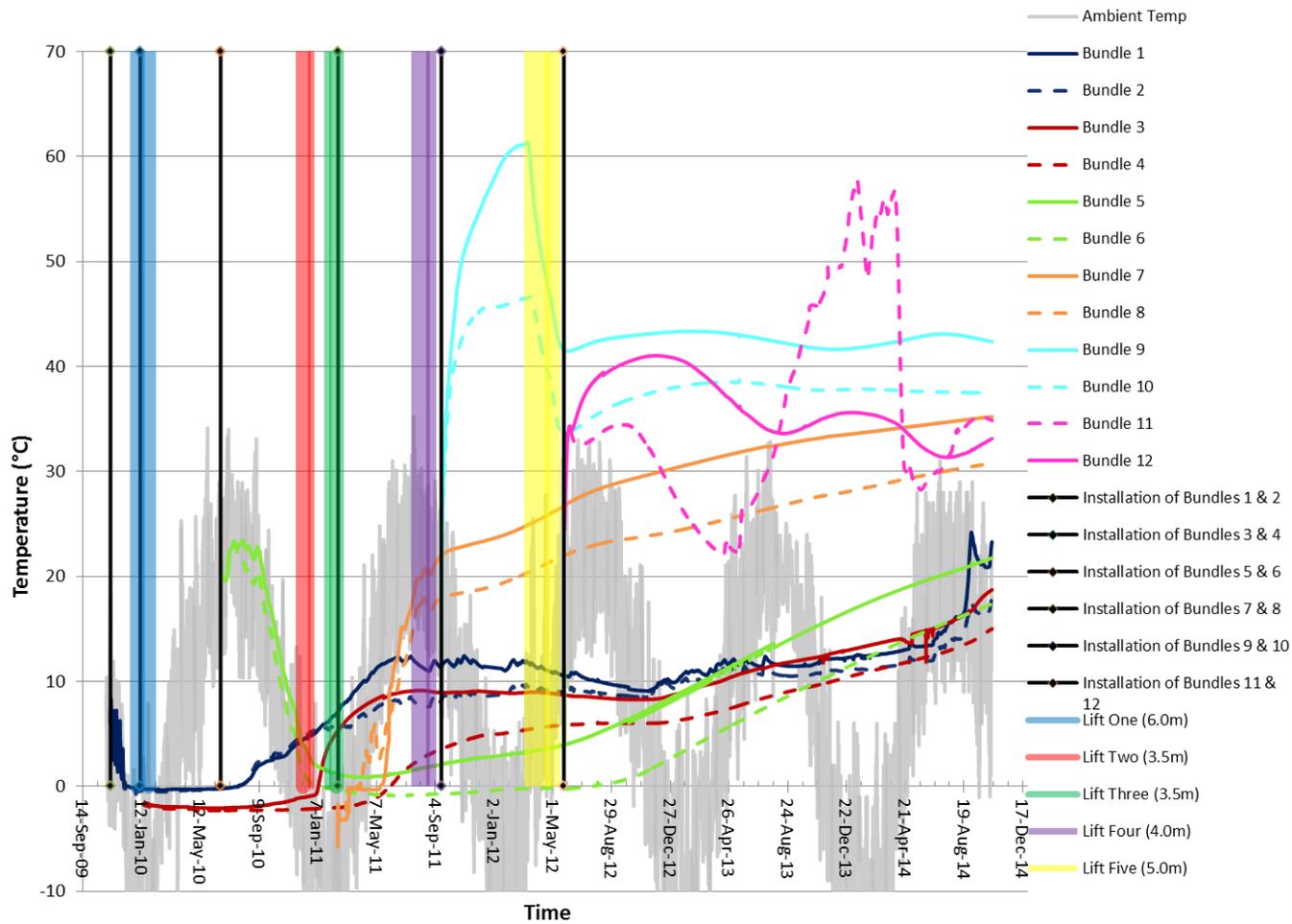
**Figure 5 Bundle installation at the Ste. Sophie LFGTE facility during waste placement; approximate depths of each waste lift are shown to the right and the time of waste placement are shown to the left.**

Bundles 1 and 2 were placed on top of the leachate collection system and the first waste lift (6 m deep) was placed in January 2010. Bundles 3 and 4 were placed in the middle of the first waste lift and immediately covered with waste. Bundles 5 and 6 were installed in June 2010 at a depth of approximately 0.75 m below the top of the first waste lift. The second waste lift was placed in December 2010 and the third waste lift in January 2011. Bundles 7 and 8 were installed at a depth of approximately 0.75 m below the top of the third waste lift in February 2011.

Due to the observed temperature data of the first three lifts and to avoid placing a fourth waste lift in the winter, the landfill operators agreed to alter their waste placement plans and placed the fourth waste lift in August 2011. Bundles 9 and 10 were subsequently placed approximately 1 m below the top of the fourth lift. The final two bundles, bundles 11 and 12, were installed in the fifth and final waste lift placed in March 2012.

#### **4.1.3 Temperature Field Data**

As noted earlier, at least four sensors recorded temperature at each bundle. The temperature of the oxygen sensor was, on average, approximately 0.5 degrees higher than the other sensors as the oxygen sensor has a small heater to avoid condensation on the sensor; as a result, this temperature was not used. The maximum difference between any two temperature measurements of the remaining sensors at a given bundle was less than 0.5 °C during the course of the study; reinforcing the credibility of the temperature data. The average temperature of the sensors at each bundle is plotted in Figure 6.



**Figure 6 Ambient temperature and average sensor temperatures at bundle locations from November 2010 to October 2014; includes waste placement lifts and bundle installation times**

Temperatures at the bottom two bundles (bundle 1 and bundle 2) followed ambient temperatures as they were only covered with a 0.3 m sand layer upon installation. The first waste lift was then placed in January 2010 over the bundles and they remained frozen for approximately 8 months until temperatures started to reach values above 0°C. The temperatures then increased to about 10°C, most likely due to a positive heat flux from the soil below the landfill, and then appear to plateau in June 2012. In August 2014, a rise sharp in temperature was observed at bundle 1 which could be attributed to oxygen diffusion from below; the landfill operators confirmed that the pumping rate in the gas collection pipe closest to the bundles was increased one week prior to the start of the temperature increase. They also noted that one month later the same collection pipe appeared stressed (i.e. elevated oxygen) and the pumping rates were reduced. Bundles 3 and 4 were placed in the middle of the first waste lift and immediately covered and remained frozen for over a year. At the top of the first waste lift, bundles 5 and 6 followed ambient temperatures because they were covered with only 0.75 m of waste and interim cover. Temperatures measured in bundle 6 indicated below zero temperatures for 1.5 years. Bundles 7 and 8 installed at the top of the third waste lift also initially followed ambient temperatures and then once covered by the fourth waste lift, slowly increased at a steady rate of about 5°C/year between September 2011 and October 2014. The fourth waste lift was placed in August 2012 and bundles 9 and 10 were installed in September 2012. In contrast to bundles located near the surface of the previous lifts, the temperatures at bundles 9 and 10 sharply increased indicating a heat source. This will be discussed in greater detail in the following paragraphs. The fifth waste lift was placed in March 2012 and bundles 11 and 12 were installed within this lift. It is believed the

temperature variations seen at bundle 11 are due to re-grading activities in this location and corresponding elevated oxygen levels were recorded at bundle 11.

The temperatures near the top of waste lifts 1, 3 and 5 appear to lag the ambient air temperatures and it is hypothesized that the interim cover soils for these lifts limited oxygen diffusion through the cover soil and hence limited heat generation due to aerobic activity. Zero oxygen was recorded at bundles 5 and 6 (lift 1), bundles 7 and 8 (lift 3) and bundle 12 (lift 5). The increased temperatures recorded at bundles 9 and 10 at the top of the fourth waste lift indicate a significant heat source; likely aerobic degradation. This was confirmed using observed oxygen data for bundles 9 and 10 which indicated oxygen levels up to 3 and 1.5% respectively, and were directly correlated with temperature increases at the respective bundles at the top of the fourth waste lift. Similarly, the increased temperatures measured at bundle 11 due to re-grading activities correspond to increased oxygen levels at bundle 11. The detection and measurement of oxygen was only measured in the top of the fourth waste lift, with the exception of bundle 11 as explained earlier, and could be due to the interim cover containing less fine particles allowing greater oxygen diffusion through this interim cover material in comparison to the interim cover materials used for lifts 1 and 3 or increased pumping of landfill gas within lift 4 drawing oxygen into the waste.

#### **4.1.4 Model Formulation**

Bonany et al. (2013a) developed conceptual and numerical models to simulate the heat transfer processes within a landfill. The model used in this paper was built on the foundations of that model with several modifications. Conduction was the main

mechanism for heat transfer within the waste in the landfill. The governing equation for the heat transfer within the domain is:

$$\nabla(k\nabla T) + Q = \rho C_p \frac{dT}{dt} \quad (11)$$

where  $k$  [W/mK] is the thermal conductivity,  $T$  [K] is the temperature,  $Q$  [W/m<sup>3</sup>] is the heat generated during biodegradation in the aerobic and anaerobic zone,  $\rho$  is the bulk waste density [kg/m<sup>3</sup>],  $C_p$  [J/kgK] is the specific heat, and  $t$  [s] is time. Within the domain, the processes that affect the temperatures include the latent heat of phase change, sensible heat (governed by specific heat) and heat generation during aerobic and anaerobic biodegradation. The formulation for the latent heat for phase change was taken from Bonany et al. (2013a).

$$C_p = \begin{cases} C_s & T < 271.4 K \\ \frac{L}{\Delta T} & 271.4 K < T < 272.4 K \\ C_l & 272.4 K < T \end{cases} \quad (12)$$

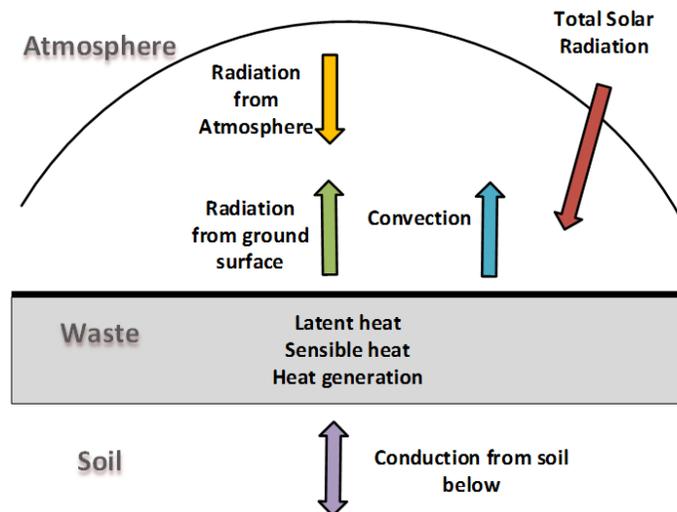
where  $C_s$  [J/kgK] is the specific heat for frozen waste and  $C_l$  [J/kgK] is the specific heat for non-frozen waste. This is the amount of energy required to increase the temperature of the waste mass by 1 °C.  $L$  [J/kg] is the latent heat which is the energy required to thaw frozen waste and is assumed to occur over 1°C.

The heat generation term  $Q$  [W/m<sup>3</sup>] was defined by a quadratic equation relating the temperature to the heat generation rate (Neusinger et. al, 2005):

$$Q = Q_i(-0.000413T^2 + 0.27143T - 43.677) \quad (13)$$

where  $Q_i$  is a scaling factor. Bonany et al. (2013a) used this equation with a scaling factor of 0.3 and  $16.5\text{W/m}^3$  to define the anaerobic and aerobic heat generation rates respectively and assumed that heat generation only occurred at waste temperatures higher than  $10^\circ\text{C}$ . In order to simulate the field data presented in this paper, modifications were made to the heat generation terms above and this is discussed in greater detail in section 4.1.5.

Conduction from the soil below is the main mechanism for heat transfer at the bottom boundary of the domain. The three main forms of heat transfer from/to the atmosphere that occur at the top of the landfill include: convection, radiation and conduction. As seen in Figure 7, once the waste is placed in the landfill cell, heat can be lost or gained at the surface via: (1) longwave radiation with the atmosphere, (2) convection with the surrounding air, and (3) shortwave radiation from the sun. This heat transferred at the surface is transferred into the landfill primarily through conduction.



**Figure 7 Heat transfer processes within a waste column**

The heat flux at the top of the landfill, used in the model developed in this paper is given by:

$$\nabla(k\nabla T) = \varepsilon Q_o + h(T_{amb} - T) + \varepsilon\sigma(T_{amb}^4 - T^4) \quad (14)$$

where  $h$  [ $\text{W}/\text{m}^2\text{K}$ ] is the convection coefficient,  $\varepsilon$  is the surface emissivity,  $Q_o$  [ $\text{W}/\text{m}^2$ ] is the net shortwave solar radiation,  $T_{amb}$  [K] is the ambient air temperature, and  $\sigma$  [ $\text{W}/\text{m}^2\text{K}^4$ ] is the Stefan- Boltzmann constant for blackbody radiation. Equation 14 was different than that used by Bonany et al. (2013a), as the short and long wave radiation terms in Equation 14 are separated and a different method was used to define the convection coefficient. The new convection coefficient term used in this model was related to the ambient wind velocity described by Watmuff (1977):

$$h = 2.8 + 3.0v \quad (15)$$

where  $v$  [m/s] is the wind velocity. The incident solar radiation, velocity and ambient temperatures used in the model were obtained from a weather station at Mirabel Airport approximately 17 km from the LFGTE facility.

#### **4.1.5 Model Results and Discussion**

Bonany et al. (2013a, 2013b) focused on developing a model to simulate the temperatures within the first three waste lifts which were all placed under freezing conditions in the winter months. The first three waste lifts were modelled and model results were in good agreement with measured temperatures. It was found that the latent heat of fusion played an important role on the heat budget for waste layers placed under frozen conditions during the winter months. The impact of biodegradation in the modelling presented by

Bonany et al. (2013a) was limited given the low waste temperatures in the first three waste lifts. In the improved model presented in this paper, the heat generation due to aerobic and anaerobic biodegradation has a greater impact as the waste temperatures were greater and was modified to be able to simulate the high measured temperatures recorded in the fourth waste lift.

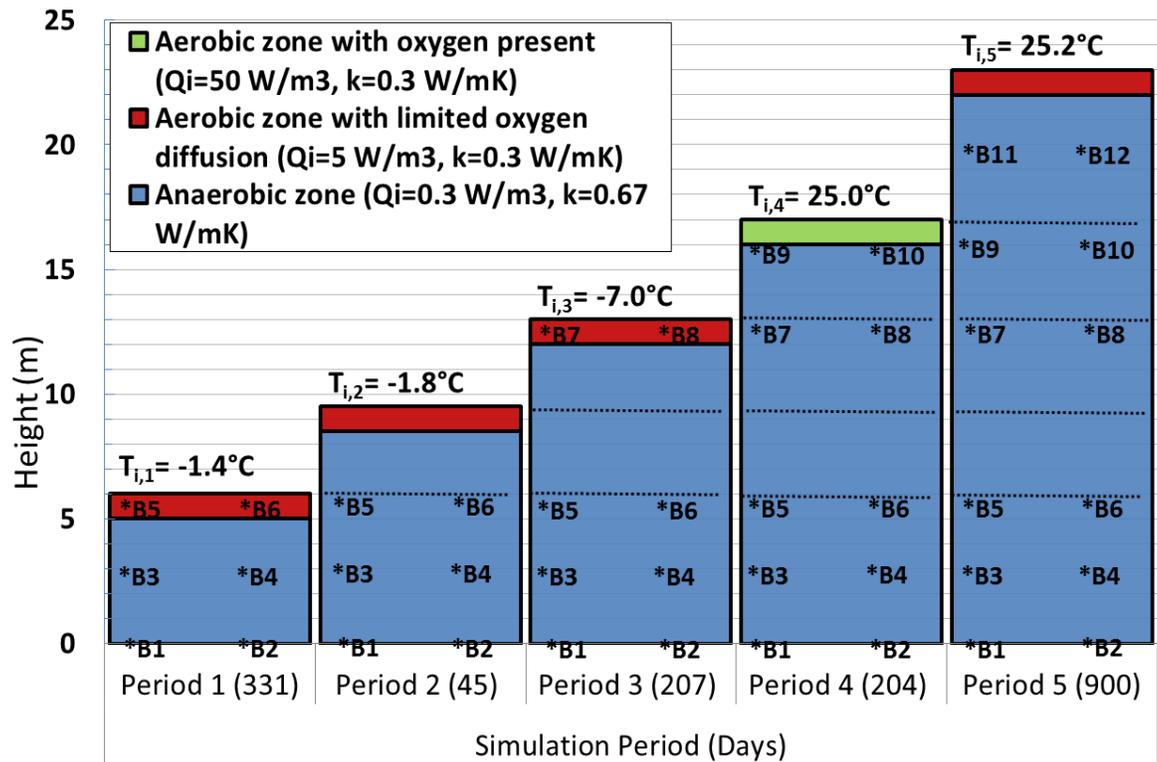
In order to simulate the temperatures at Ste. Sophie, a 1-D numerical model was created to represent the heat processes that occur in a LFGTE facility and solved using COMSOL Multiphysics, a commercial finite element model package. The bottom boundary of the model was defined as a prescribed temperature based on the measured temperature values of bundle 1, which was placed at the bottom of the waste cell. The side boundaries are defined as zero heat flux boundaries. Note that the data from bundles 3, 5, 7, 9 and 11 were simulated and discussed in this paper; similar results were obtained for the other vertical waste profile containing bundles 4, 6, 8, 10 and 12.

The five waste lifts at the Ste. Sophie facility were modelled as seen in Figure 8. The model was broken into five simulation periods to reflect the placement of each waste lift. The first period simulates the heat transfer within the first waste lift (from the placement of the first waste lift until the placement of the second waste lift) as summarized in Table 6.

**Table 6 Time period and height of waste during each simulation period**

Simulation Period	Date	Total height of waste (m)
1	Jan 16, 2010 - Dec 12, 2010	6
2	Dec 13, 2010 - Jan 27, 2011	9.5
3	Jan 28, 2011 - Aug 22, 2011	13
4	Aug 23, 2011 - Mar 14, 2012	17
5	Mar 14, 2012 - Aug 31, 2014	23

The following waste lifts are subsequently added to the model. A mesh with element sizes of 0.01 m was selected to discretize the 1-D domain after an extensive study to identify the optimal mesh size and convergence error. Time steps of 200 seconds were used to simulate the data for the first 4 simulation periods and time steps of 1200 seconds were used for the final simulation period.

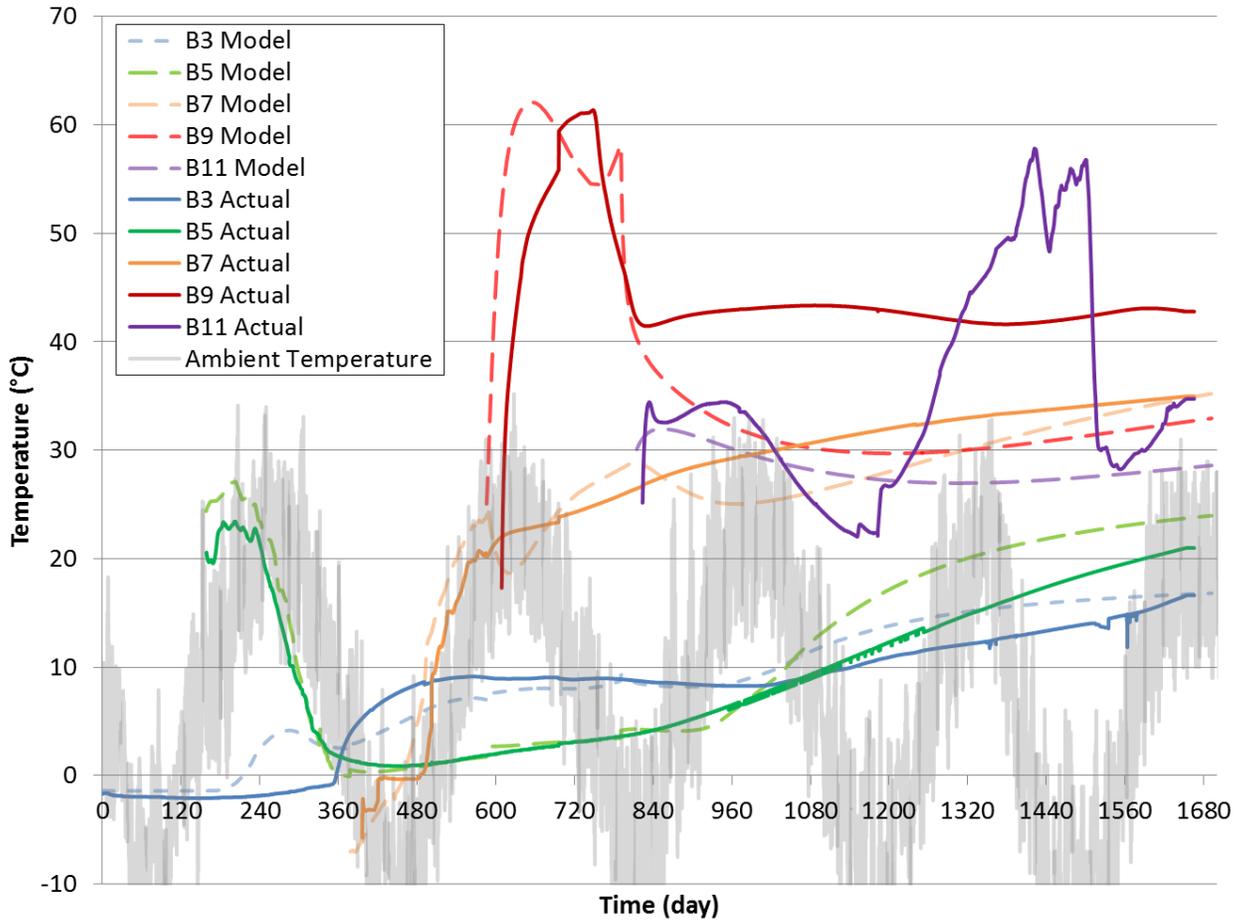


**Figure 8 Model domain for five simulation periods (from January 2010 to August 2014) with initial temperatures and specific thermal properties for each waste profile**

The increased temperatures recorded at bundles 9 and 10 at the top of the fourth waste lift indicate a significant heat source; likely aerobic degradation as mentioned earlier in section 4.1.3 (temperature field data). The oxygen concentrations at bundles 9 and 10 indicated that oxygen was able to diffuse into the top 1 metre of the fourth waste lift. In order to simulate the high temperatures observed at bundle 9, a larger aerobic heat generation scaling factor,  $Q_i$  as shown in Equation 13, was used. The elevated temperatures observed in bundle 9 were not observed in bundles 5 and 7 although they were also located within the top 1 m of the first and third waste lifts respectively as mentioned earlier. This indicates that more oxygen migrated down through the interim cover used for the fourth waste lift due to increased diffusion and/or advection due to gas collection in lift 4; hence a larger heat generation rate was applied at the top of the fourth waste lift. As noted earlier, this increased aerobic activity was supported by increased oxygen levels recorded at bundles 9 and 10. The temperature variations due to re-grading near bundle 11 were not simulated due to the uncertainty in the oxygen diffusion and heat generation rates with time in this area.

When the diffusion of oxygen becomes limited, the residual oxygen in the airspace can only increase the temperature of the waste by a maximum of 2-3°C based on the lowest specific heat value presented in Table 5. For the anaerobic zone (blue zones in Figure 8), the heat generated is about twenty times less than the amount of heat generated from aerobic biodegradation. In this model it was assumed that the maximum heat generated

from the anaerobic zone occurred at the onset of anaerobic biodegradation which occurred once the temperature was greater than 10°C.



**Figure 9 Comparison of field and simulated temperatures of all 5 waste lifts in the Ste. Sophie LFGTE facility from January 2010 to August 2014**

The simulated and actual measured data are compared in Figure 9; dashed lines represent the simulated temperatures from the model and the solid lines show the actual temperatures. The model results are generally in good agreement except for bundle 11 as expected and discussed earlier.

The aerobic heat generation rate used in the model was based on Equation 13 with different scaling factors as noted in Figure 8. The high temperatures observed at bundle 9 were only reached by applying a greater aerobic heat generation scaling factor of 50  $\text{W}/\text{m}^3$ , instead of 5  $\text{W}/\text{m}^3$  which was used for the other lifts, to accommodate the sharp temperature increase. A scaling factor of 50  $\text{W}/\text{m}^3$  corresponds to a maximum heat generation rate of 46.3  $\text{W}/\text{m}^3$  based on the heat generation equation used in the model developed by Neusinger et al. (2005). The heat generation model assumes that heat generation occurs only once a temperature of 10°C is reached. The maximum heat generation rate of 46.3  $\text{W}/\text{m}^3$  is comparable to values measured in aerobic composting piles (Zambra et al., 2011). For the other waste lifts (1, 2, 3 and 5), a heat generation scaling factor of 5  $\text{W}/\text{m}^3$  was used to model the top 1 m of waste which was assumed to be an aerobic zone with limited oxygen diffusion. This value for aerobic heat generation falls within the range of aerobic rates at landfills found in the literature.

The anaerobic heat generation rate was determined differently than the aerobic heat generation rate. It was assumed that the anaerobic zone heat generation rate was a constant value of 0.3  $\text{W}/\text{m}^3$  when the temperatures were above 10°C and was applied to the entire domain except for the top 1 m of the model domain which is exposed to the atmosphere and an oxygen source. Anaerobic heat generation rates for waste in the literature vary from 0.08-0.763  $\text{W}/\text{m}^3$  (Bonany et al. 2013a; Rees, 1980; Rowe et al., 2010; Yoshida and Rowe, 2003). The anaerobic zone heat generation rate used in this model is in the middle of the range found in the literature, however it is a simplified approach to modelling the anaerobic heat generation rate because it was assumed to be a

fixed rate. In reality the heat generation rate probably has a quadratic relationship with an optimal temperature corresponding to the optimal temperature for gas generation.

As the waste settles, it becomes more compact and dense which would increase the thermal conductivity. The thermal conductivity was set as 0.67 W/mK; however a lower value of 0.3 W/mK was used in the top 1 m of the model domain. Rowe et al. (2010) used a similar approach to model the thermal conductivity within the waste; waste exposed to air and waste above the leachate level was assigned a thermal conductivity of 0.35 W/mK and for waste below the leachate level a thermal conductivity of 0.96 W/mK was applied.

The solution of the model presented herein is not a unique solution; however it does provide a better understanding of the heat transfer processes within the waste placed in a LFGTE facility under varying climatic conditions. Changing the thermal parameters may allow for better agreement between the model and the actual data in one area of the waste column and be in less agreement in other areas. The final thermal parameters used in the model are summarized in Table 7.

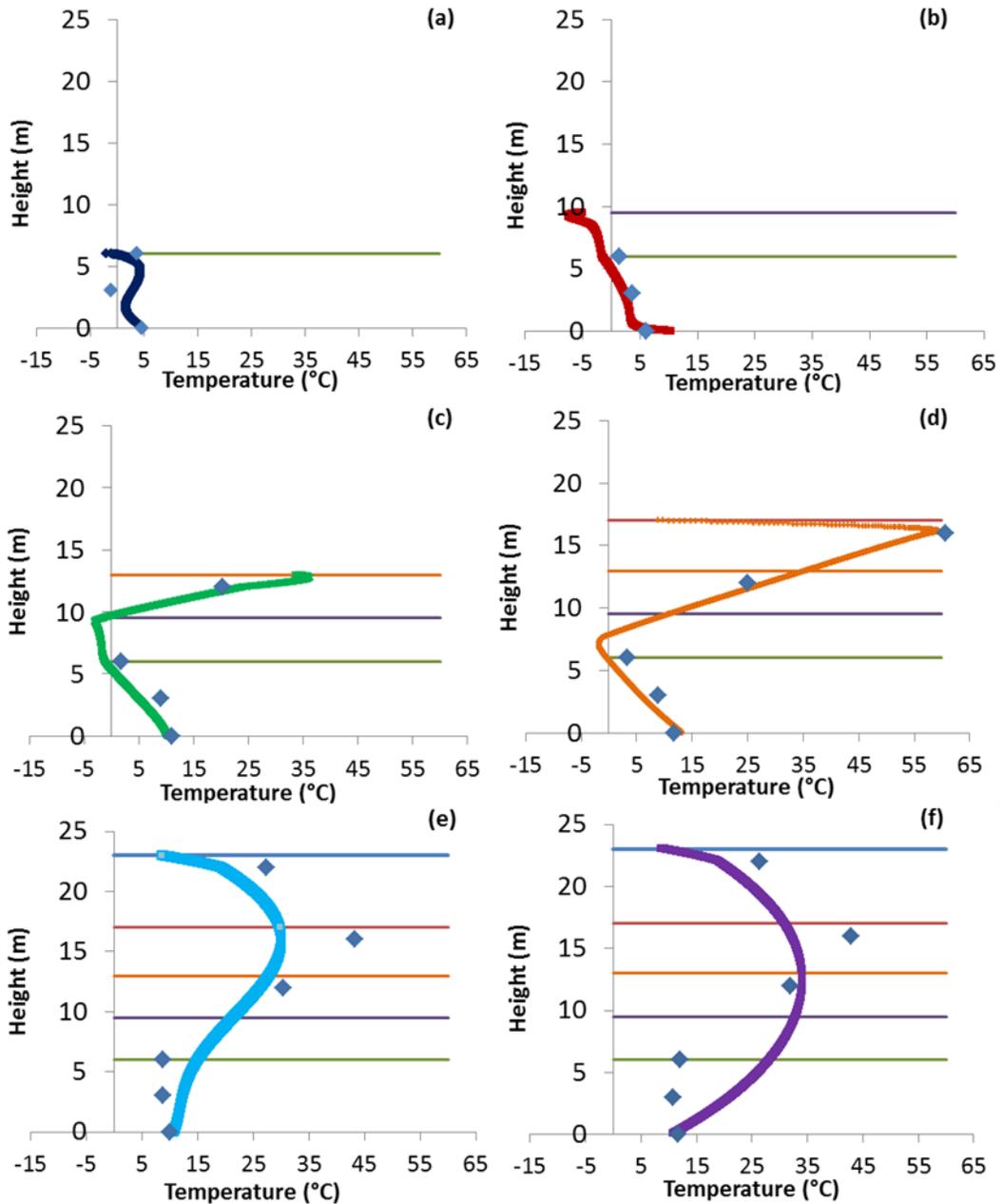
**Table 7 Thermal parameters used in the final calibrated model**

<b>k</b> <b>(W/mK)</b>	<b><math>C_p</math></b> <b>(J/kgK)</b>	<b><math>\rho</math></b> <b>(kg/m<sup>3</sup>)</b>	<b><math>Q_{i, aerobic}</math></b> <b>(W/m<sup>3</sup>)</b>	<b><math>Q_{i, anaerobic}</math></b> <b>(W/m<sup>3</sup>)</b>	<b><math>\epsilon</math></b>	<b>L</b> <b>(kJ/kg)</b>
0.3 <sup>a</sup> and 0.67	800	930	5 and 50 <sup>b</sup>	0.3	0.9	38,000

<sup>a</sup>Used in the top 1 m of all waste lifts, <sup>b</sup>Used in the top 1 m of the waste lift 4

Decreasing the specific heat capacity from 1400 J/kgK used in Bonany et al. (2013a, 2013b) to 800 J/kgK provided better agreement between the model and actual data for bundles 9 through 12 while still providing a reasonable fit to bundles 3-6. Lowering the

specific heat means less energy is required to increase the temperature of the waste mass. This allows for the temperatures to increase faster in response to an energy source (i.e. aerobic degradation or heat transfer at the surface) and in turn creates greater temperature gradients to allow for greater conduction of heat to waste layers above and below.



**Figure 10 Simulated temperature profiles at the end of a) Dec 12, 2010, b) Jan 27, 2011, c) Aug 22, 2011, d) Mar 14, 2012, e) January 9, 2013, and f) May 23, 2014; points represent the field data for bundles 1, 3, 5, 7, 9 and 11**

To better understand the simulated temperature distribution within the waste profile, the vertical temperature profiles in the waste were plotted with time in Figure 10. The first waste lift was placed at an initial temperature of  $-1.4^{\circ}\text{C}$ . The initial temperatures of each

waste lift reflect the approximate steady state temperature the bundles acclimated to after installation. At the end of the first simulation period, the temperature within the first 6 m lift varied between -2 and 5°C. After slightly less than a year since the placement of the first waste lift, the second waste lift was placed at -1.8°C during the winter months. At the end of the simulation period in January 27, 2011, the temperatures within the second lift remained below 0°C for the entire second simulation period varying from -7.5°C to -2°C and the first lift remained below 10°C. The third waste lift, similar to the previous two lifts, was placed in frozen conditions at an initial temperature of -7.0°C. At the end of the third simulation period in August 2011, the simulated temperatures within the first two lifts were still below 10°C preventing anaerobic biodegradation to occur. The main source of heat was from the soil below via conduction. The top of the third waste lift reached a temperature above 30°C which is due to the warm ambient temperatures at the end of this simulation period (August 2011) and due to the aerobic heat generation rate in this oxygen limited diffusion zone.

The fourth lift was placed in August 2011 and the initial temperature of the waste was 25°C. Even though temperatures at the top of the fourth waste lift reached higher than 60°C, the bottom 10 m of the waste profile remained below 10°C until the end of the fourth simulation period and a portion of the second waste lift still remained below 0°C. The fifth waste lift was placed in March 2012 at an initial temperature of 25.2°C. By the end of the fifth simulation period, maximum temperatures were found in the middle of the waste column and solution approaching the steady state temperature profile.

#### 4.1.5.1 Heat Budget

To illustrate the magnitude of the potential impact of aerobic and anaerobic degradation on waste temperature, Megalla et al. (2014) simulated a  $1 \text{ m}^3$  domain. For anaerobic conditions, the model domain was assumed to be insulated with no heat transfer out of the domain. A fixed heat generation rate of  $0.3 \text{ W/m}^3$  generated a temperature increase of approximately  $12^\circ\text{C}/\text{year}$  for a specific heat value of  $800 \text{ J/kgK}$ . The maximum aerobic heat generation rate that was used in the simulation presented earlier was based on Equation 13 and a scaling factor  $50 \text{ W/m}^3$ . If this was applied to  $1 \text{ m}^3$  of waste without allowing heat transfer, the temperatures after a year would be excessively high. However, if this was applied to the top 1m of waste at an initial waste temperature of  $10^\circ\text{C}$  and the top metre of waste was assumed to increase to  $60^\circ\text{C}$  after which it was assumed that half the heat generated would be lost to the atmosphere and half the heat generated would travel downward, this would cause an increase in temperature of  $30^\circ\text{C}$  to an equivalent depth of 8.6 m (Megalla et al., 2014).

**Table 8 Processes which impact the heat budget during the 5 simulation periods**

<b>Number of Days per Period</b>	<b>331</b>	<b>45</b>	<b>207</b>	<b>204</b>	<b>900</b>	<b>1687</b>
<b>Heat Term [MJ/m<sup>2</sup>]</b>	<b>Period 1</b>	<b>Period 2</b>	<b>Period 3</b>	<b>Period 4</b>	<b>Period 5</b>	<b>Cumulative</b>
<b>Convection</b>	-2441	-111	-1473	-1282	-6319	-11626
<b>Solar Radiation</b>	3739	154	2419	1250	8580	16142
<b>Long Wave Radiation</b>	-1323	-49	-823	-523	-2555	-5273
<b>Net Heat Flux</b>	-25	-6	123	-555	-294	-757
<b>Conduction from Soil Below</b>	49	6	30	24	-96	13
<b>Total Heat Generation</b>	44	0	42	700	570	1356
<b>Aerobic Heat Generation</b>	35	0	33.5	652	40	761
<b>Anaerobic Zone Heat Generation</b>	9	0	8.5	48	530	595
<b>Latent Heat</b>	49	8	116	76	45	294
<b>Sensible Heat</b>	20	-8	79	93	136	320

To understand the overall heat budget for the waste, the heat generated, lost and stored during each simulation period is presented in Table 8. The data presented for Period 1 refers to the heat generated, lost and stored during simulation period 1 for lift 1; the data presented for Period 2 refers to the heat generated, lost and stored during simulation period 2 for waste lifts 1 and 2; etc. The last column in Table 8 shows the cumulative value of heat from each process over the entire simulation period (1687 days; 4.62 years). The total convection, solar radiation and long wave radiation were calculated by integrating the heat flux over time. The net heat flux at the surface is the summation of these three source/sink terms. The conduction from below was estimated within the model using the gradient between the prescribed boundary node and the first node immediately above this boundary. The heat stored as sensible heat was calculated using the specific heat, mass of waste and temperature difference within the domain. The heat generated within the aerobic and anaerobic zones was tracked in the model. The latent

heat for phase change was calculated using the above terms and assuming energy conservation. This was then checked using the temperatures in a calculation similar to that used to calculate the sensible heat and good agreement was found.

During Period 1, there was a net heat loss to the atmosphere as heat was generated via aerobic conditions in the top 1 m of waste. The remaining heat generated via aerobic biodegradation, anaerobic zone heat generation, and heat gained from below the landfill were stored as sensible heat and latent heat. During Period 2, there was no biological heat generated because the temperature of the waste never reached the minimum required temperature of 10°C (see Figure 10). Heat was lost to the atmosphere as this 45 day simulation period was in December 2010 and January 2011. Period 3 included the summer months and led to a net heat gain at the surface due to solar radiation. During Period 4, heat generation was the largest due to the increased aerobic heat generation rate applied at the top of this layer (see Figure 8). The high temperatures at the surface also led to the largest heat lost to the atmosphere. Period 5 reflects the longest simulation period. Heat generated in the aerobic and anaerobic zones was lost to the atmosphere and for the first time, there was a net heat flux out of the base of the landfill. The heat generated due to aerobic conditions in the upper 1 m depth of waste is lower in comparison to the fourth simulation period as the aerobic biodegradation rate was assumed to be lower similar to periods 1, 2, and 3. The heat generated within the anaerobic zone is significantly larger because the thickness of the anaerobic zone is large during this simulation period (23 m), the simulation period is longer, and the temperatures are above 10°C for a larger portion of the simulation period (See Figure 10).

The remaining heat was stored as latent and sensible heat. The heat profile in Figure 10 at the end of Period 4 (14-Mar-12) indicates that a frozen layer of waste remained and hence during Period 5, heat was still stored as latent heat to thaw this frozen layer.

In summary, convection, incident solar radiation, and long wave radiation impact the top boundary conditions of the model. Solar radiation increases the heat flux into the domain while long wave radiation and convection transfer heat out of the domain. At the bottom of the landfill heat can be transferred from and to the soil below. It was observed that a positive heat flux into the domain was observed in the first 4 simulation periods. However, as the temperature of the waste increased with time, the temperature gradient and corresponding heat flux were reversed. Based on the heat budget calculations, some energy is still required after 2-3 years of initial placement, to thaw the frozen sections of waste. Heat generated from aerobic degradation (occurring only in the top 1 m of the waste profile) generated  $761 \text{ MJ/m}^2$ . Heat generated within the anaerobic zone accounted for  $595 \text{ MJ/m}^2$  over the simulation period. Aerobic and anaerobic heat generation contributed to 56% and 44% of the total heat generation.

#### **4.1.6 Conclusion and Future Work**

The Ste. Sophie LFGTE facility was instrumented with bundles containing sensors which measure a variety of important parameters to better understand the waste stabilization process. Twelve instrument bundles were successfully installed within the waste column between January 2010 and March 2012 and valuable data are still being collected to date. A comprehensive heat transfer model was developed for five waste lifts which were sequentially placed within a waste cell at the Ste. Sophie LFGTE facility. The calibrated

model was able to simulate the temperatures measured to date within the instrumented waste profile at the site. The model was used to evaluate an energy/heat budget for the waste profile. The model simulations and heat budget provide a better understanding the heat transfer processes occurring within the landfill and the relative impact of the various heat source/sink and storage terms. Aerobic biodegradation appears to play an important role in the overall heat budget at this site. In simulating the placement of five waste lifts during a five year period, aerobic biodegradation in the top 1 m generated 56% of the total heat generation.

This model can be used to illustrate the impact of different waste placement strategies and operational practices on the waste temperatures in LFGTE facilities operating in northern climates. Optimizing operations at a site to reduce the length of time needed for the waste to reach 10°C will lead to increased waste stabilization prior to final cover placement resulting in more efficient use of the approved landfill airspace. Future work should include a more comprehensive analysis of the heat budget at the surface including the impact of interim cover soils on the diffusion of oxygen into the waste and the corresponding aerobic heat generation rate. The model would benefit from the development of a more complex heat generation model for both aerobic and anaerobic zones.

## **5 Model Application**

The 1-D finite element heat transfer model presented in the previous section was used to conduct a limited sensitivity analysis to see how sensitive the model simulation was to variations in the thermal properties of the waste ( $k$  and  $C_p$ ). The model was also used to simulate a scenario in which the second waste lift was placed in the summer months rather than the winter months to illustrate the impact of altering the waste placement sequence. The model results illustrate the impact on the temperature profile within the waste which would in turn, impact the degree of waste stabilization prior to the placement of the final cover.

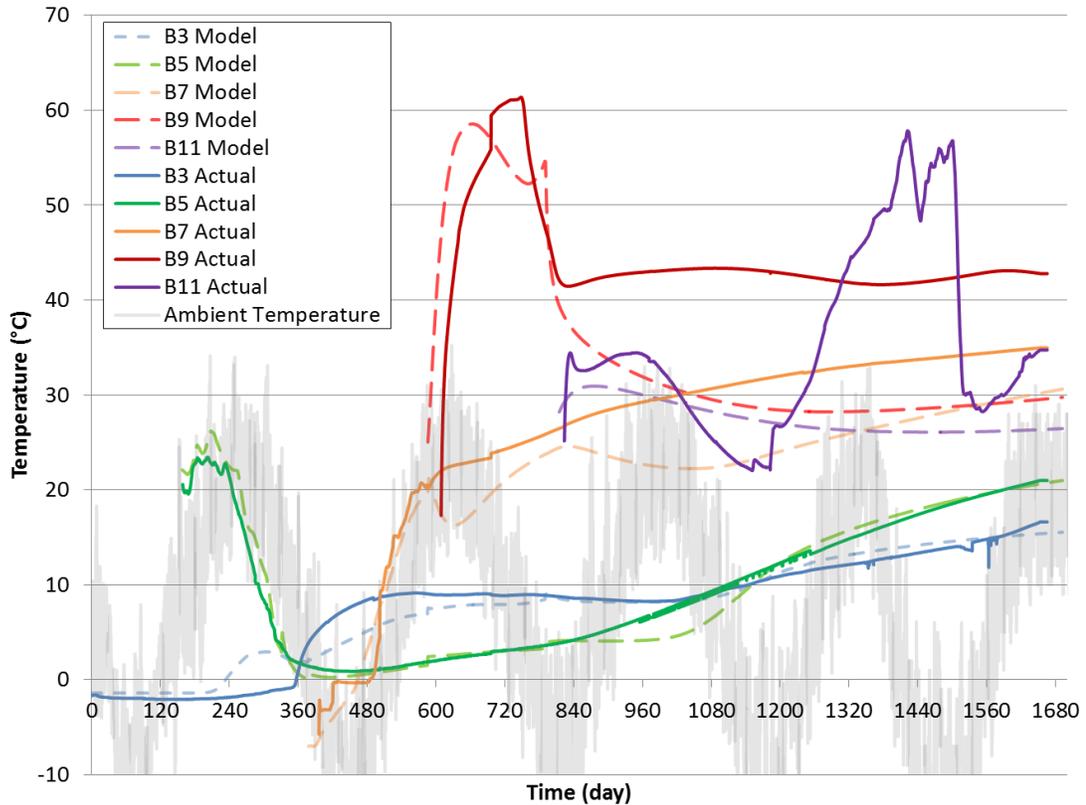
### **5.1 Sensitivity Analysis**

In the developed model, as discussed in section 4, the final specific heat and thermal conductivity used in the model were 800 J/kgK and 0.67 W/mK respectively (the top 1 m was assigned a thermal conductivity of 0.3 W/mK). Although the model simulates the field temperatures well, it is not a unique solution. To better understand the effect of changing the thermal conductivity and specific heat on the temperature, a brief sensitivity analysis composed of 2 model runs was conducted: (1) increasing  $C_p$  from 800 J/kgK to 1200 J/kgK, and (2) decreasing  $k$  from 0.67 W/mK to 0.3W/mK.

#### **5.1.1 Specific Heat Capacity**

To determine the sensitivity of the simulated temperatures to the value of the specific heat capacity, the model was run with an increased specific heat capacity of 1200 J/kgK. Increasing the specific heat capacity means a larger amount of energy is required to

change the waste mass temperature by 1 degree. This means that a smaller observed temperature change should be evident with a larger specific heat capacity.



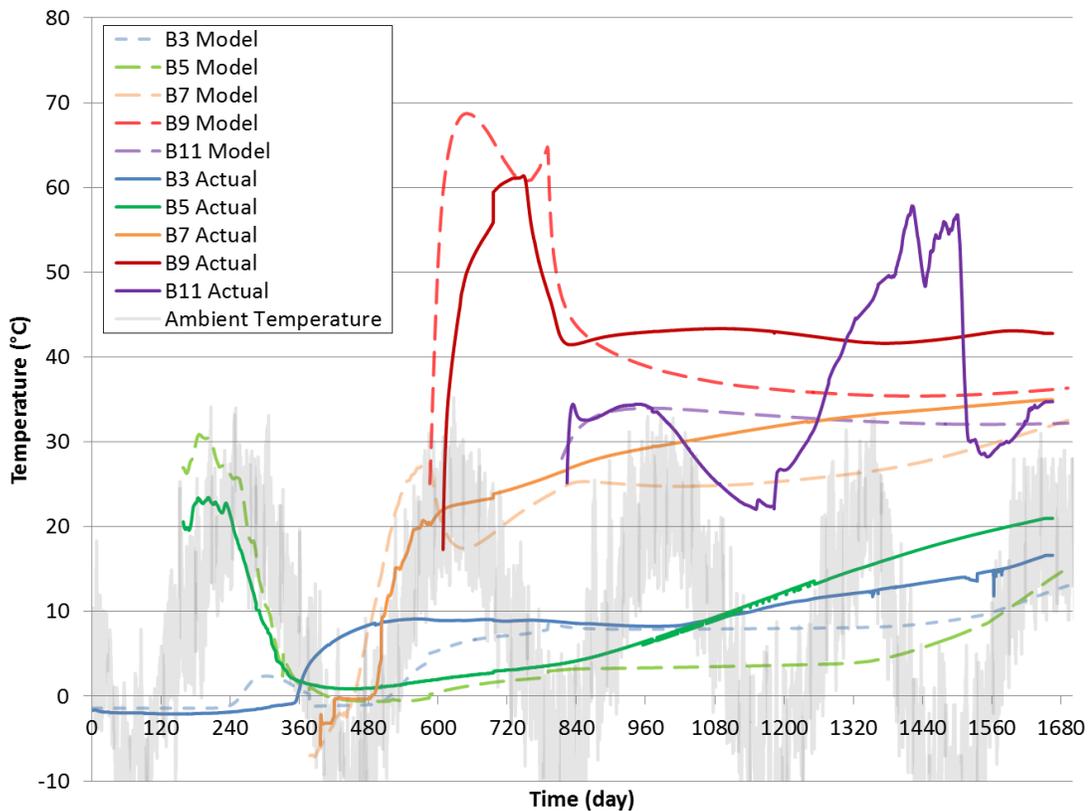
**Figure 11 Measured and simulated temperatures from bundles 3, 5, 7, 9 and 11 with  $C_p = 1200 \text{ J/kgK}$**

Figure 11 shows simulated temperatures to be in good agreement with measured temperatures at bundles 3 and 5 which are placed in the first 6 m waste lift. The simulated temperatures from the original model (see Figure 9) which had a lower  $C_p$  value, simulated temperatures which are higher than the measured values for bundles 3 and 5 during the fifth simulation period. This shows that a higher specific heat value provides improved model results during the fifth simulation period for bundles 3 and 5.

However the simulated temperatures for bundle 7 were slightly underestimated by the model with a high  $C_p$  value compared to the original model predictions. Similarly, the simulated maximum temperature at bundle 9 doesn't reach the field values which increased above  $60^{\circ}\text{C}$ ; whereas the original model does. Although the specific heat value was increased by 1.5 times in this model run compared to the original model, the simulated temperatures followed the same trends and were only slightly different.

### 5.1.2 Thermal Conductivity

To determine the sensitivity of the model results to the thermal conductivity of the waste, the model was re-run with a thermal conductivity of  $0.3 \text{ W/mK}$  throughout the entire domain, keeping all other model parameters constant.



**Figure 12 Measured and simulated temperatures from bundles 3, 5, 7, 9 and 11 with  $k= 0.3 \text{ W/mK}$**

During the first simulation time period, there was a smaller heat increase at bundle 3 (heat transferred from below the base of the landfill). Bundle 5 is overestimated reaching above 30°C. This is likely due to the low thermal conductivity which does not allow heat generated at the surface to be transferred as quickly into the surrounding waste. Similar to bundle 5, bundle 7 (at the top of lift 3) was overestimated. During the fourth simulation period, bundle 9 reached close to 70°C. Due to the aerobic heat generation rate applied at the top 1 m and low thermal conductivity of 0.3 W/mK applied throughout the entire domain, this heat was not transferred as quickly to the underlying waste leading to elevated temperatures at bundle 9. However, simulated temperatures for bundle 7 during the fourth and fifth simulation periods were lower than the original model. This is probably because the low thermal conductivity inhibits the transfer of heat from the top of lift 4 (with the high aerobic heat generation rate) to the waste lifts below. During the fifth simulation period bundles 3 and 5 simulated temperatures were much lower than the measured values because heat would be transferred at a slower rate from the overlaying waste or from the soil below due to the lower thermal conductivity.

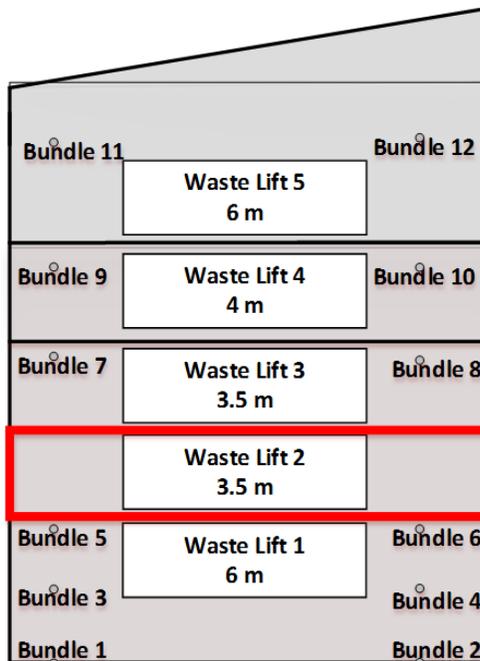
## **5.2 Effect of waste placement sequencing on the temperature profile in a LFGTE facility**

The model developed in section 4 of this thesis can be used to consider different landfill operating strategies to enhance waste stabilization leading to improved airspace utilization and increased landfill gas generation rates. Initial waste placement temperatures were shown to be directly correlated to long term temperatures of the waste (Hanson et al., 2010). Vingerhoeds et al. (2011) suggests avoiding consecutive placement of frozen waste lifts would help reduce the time periods for waste to thaw and

biodegradation within the warm waste lift would help heat adjacent lifts, leading to improved waste stabilization. Hanson et al. (2006) analyzed a landfill in Alaska and their model results show placement of a lift greater than 3 m thick would retard waste stabilization; the research recommended thinner waste lifts during the winter.

### 5.2.1 Model Structure

The model presented in section 4.1 (conceptual and numerical heat transfer model of a landfill in a northern climate) was used to determine the effect of sequencing waste lift placements in alternating seasons (i.e. winter, summer etc.). The model was used as a tool to illustrate how a different waste placement strategy would affect the temperature profile in the waste at the Ste. Sophie LFGTE facility. The original model (base case) simulated the waste lifts as they were placed by Waste Management (section 4.1). The first three waste lifts were placed during the winter months, the fourth waste lift was placed in the summer and the final waste lift was placed in the spring/summer.



**Figure 13 Second waste lift (3.5 m) placed in the summer rather than the winter**

Another model (scenario case) was developed where the second waste lift was placed in the summer instead of the winter; alternating the waste placement of the waste lifts as illustrated in Figure 13. All waste lifts were kept at the same waste depths and the same

thermal properties were used as in the base case. The main difference between the scenario model and the base model was the duration of the first and second simulation time periods as shown in Table 9. Instead of having 13 m of waste placed in a largely frozen state during the winter months, the second waste lift was placed in June 2010 rather than December 2010. In the base case, the first and second simulation periods were 331 and 45 days respectively. In the scenario case, the first simulation period was decreased to 152 days and the second simulation period was extended to 224 days.

**Table 9 Simulation time periods for base case and scenario simulation for the five waste lifts in Ste. Sophie**

Waste Lift	Simulation Time Period	
	Base Case	Scenario Simulation
1	Jan 16, 2010 – Dec 12, 2010 (Winter)	Jan 16, 2010 – Jun 16, 2010 (Winter)
2	Dec 13, 2010 – Jan 27, 2011 (Winter)	Jun 17, 2010 – Jan 27, 2011 (Summer)
3	Jan 28, 2011 – Aug 22, 2011 (Winter)	Jan 28, 2011 – Aug 22, 2011 (Winter)
4	Aug 23, 2011 – Mar 14, 2012 (Summer)	Aug 23, 2011 – Mar 14, 2012 (Summer)
5	Mar 15, 2012 – Aug 31, 2014 (Spring/summer)	Mar 15, 2012 – Aug 31, 2014 (Spring/summer)

### 5.2.2 Model Results of Scenario Case

The first waste lift was placed at a sub-zero temperature as per the base case simulation. Prior to the placement of the second waste lift in June 2010 in the scenario case (as seen in the dark blue line in Figure 14a), the simulated temperature at the upper section of the first waste lift reached temperatures higher than 45°C. This is due to solar radiation and heat generation due to aerobic biodegradation in the top 1 m of the waste lift. In the scenario case, the second waste lift was placed at an initial temperature of 25°C. This temperature value was a reasonable estimate of typical waste placement temperatures

during the summer (i.e. waste lifts 4 and 5 which were measured values). At the end of the second simulation period (after 224 days), in January 2011, the temperature profile for waste lifts 1 and 2 (9.5 m) indicates that the temperatures are largely above 0°C, with the exception of the waste at the surface, and all of the first waste lift (6 m) is above 5°C. In the base case, after the second and third simulation periods the entire second waste lift remained below 0°C.

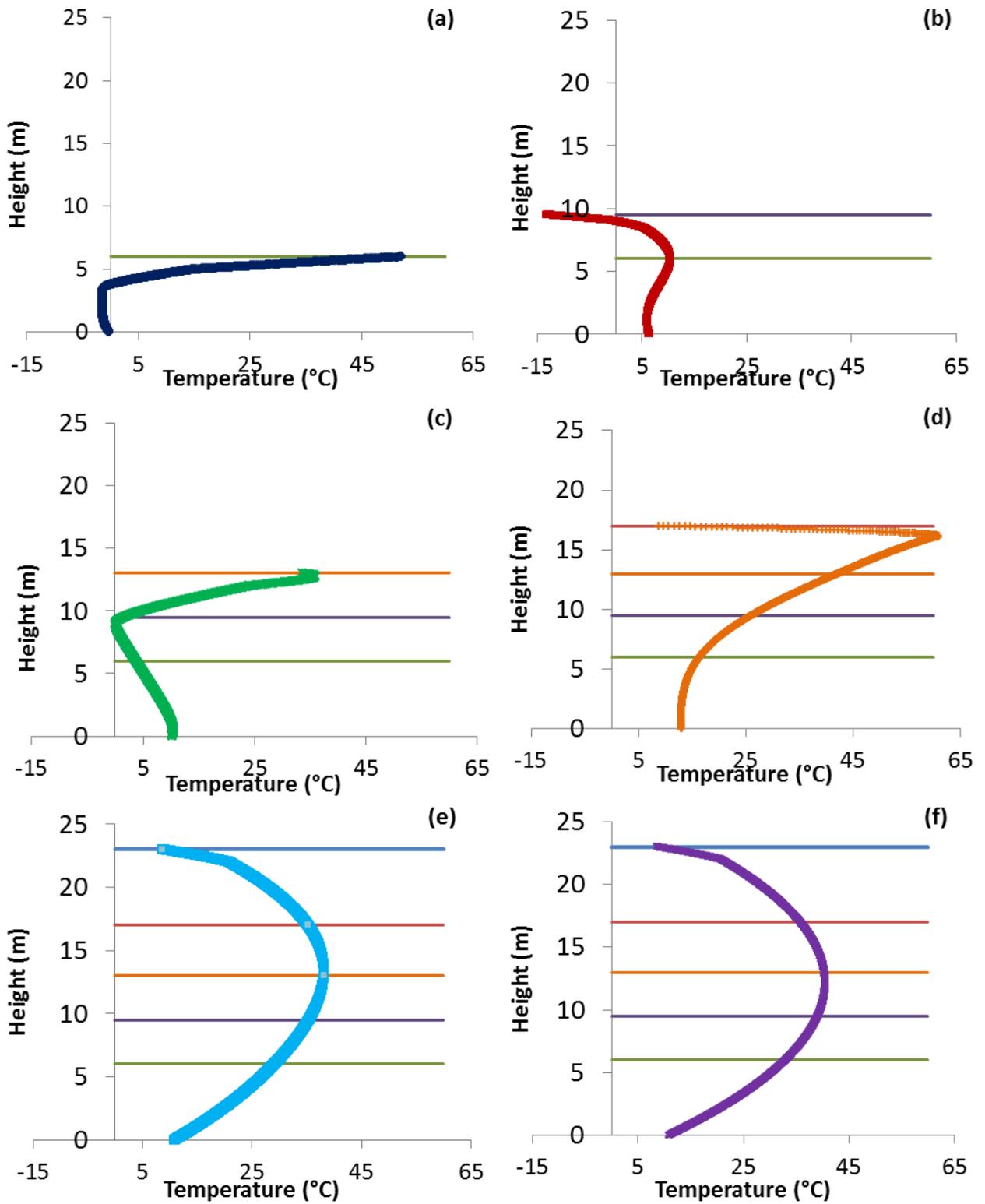
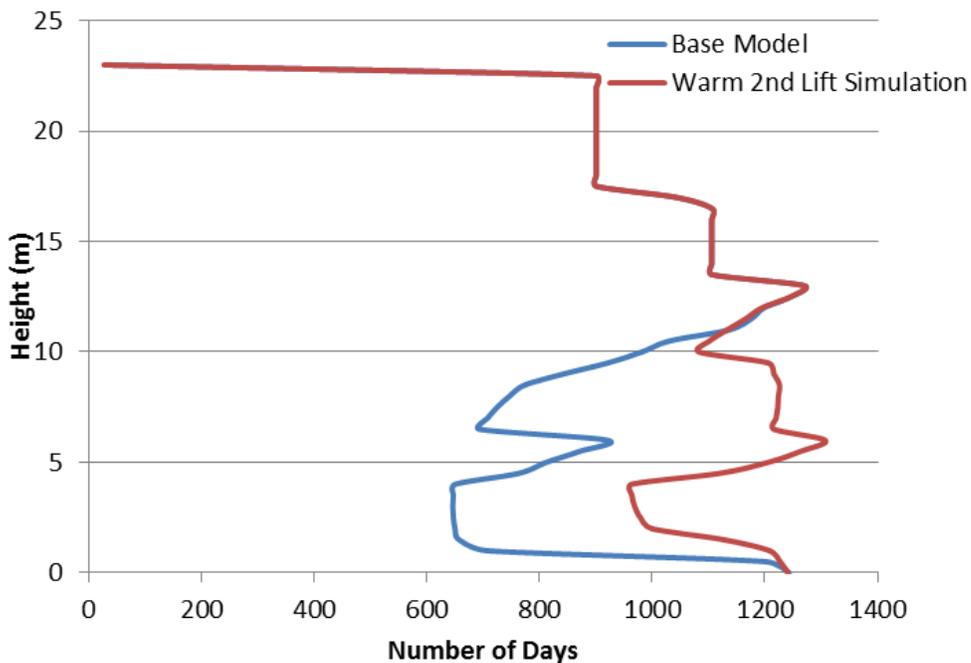


Figure 14 Temperature profile within waste lifts in Ste. Sophie at if second waste lift is placed in the summer at the end of a) Jun 16, 2010 , b) Jan 27, 2011, c) August 22, 2011, d) March 14, 2012, and e) January 9, 2013, f) May 23, 2014

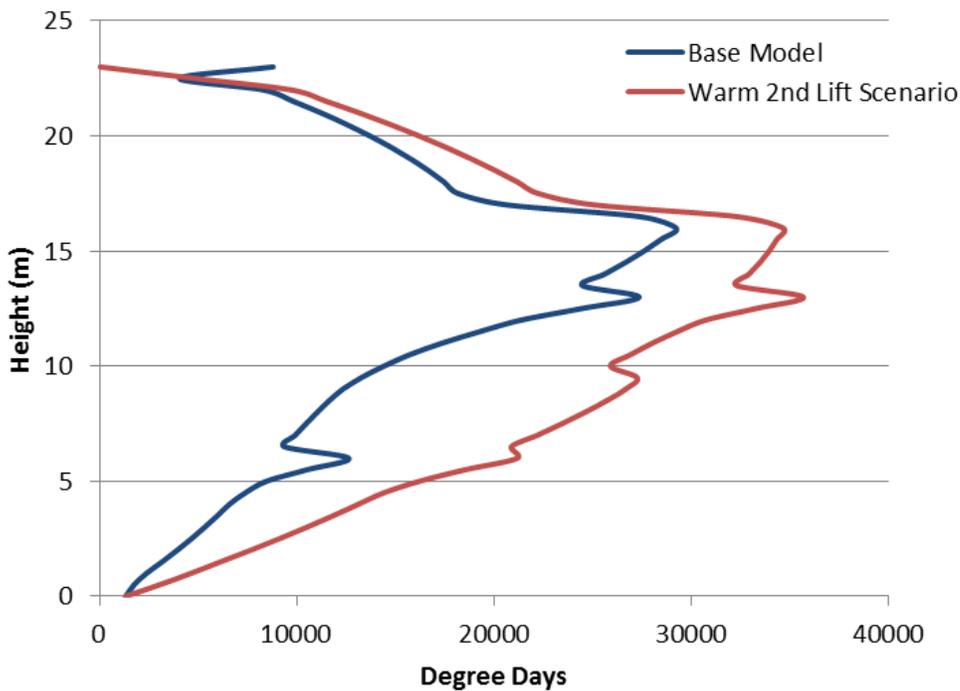
The remaining waste lifts were placed in the same time periods as the base case. Lifts 4 and 5 follow similar trends as the base case however the final temperature profile at the end of the fifth simulation period illustrates higher temperatures throughout the waste profile. It is important to note that this is a conservative because the bottom temperature was prescribed to be the temperature at bundle 1, while in reality this bottom temperature would likely have increased as a result of the increased heat initially within the second waste lift and due to the additional heat generated due to biodegradation given the warmer temperatures of the second waste lift.

To quantify the effect of varying the waste placement on the temperature profile of the waste, the total number of days the waste was above 10°C during the simulation was calculated for the base and scenario cases as seen in Figure 15.



**Figure 15 Effect of waste placement pattern on total number of days where biodegradation may occur**

This is important because no anaerobic biodegradation will occur at temperatures below 10°C. Providing the optimum temperatures for mesophilic bacteria to thrive will enhance waste stabilization, improve LFG generation, and regain airspace before the final cover is added. The total number of days above 10°C is almost 400 days more in the scenario case compared to the base model (at 5 m vertical height).



**Figure 16 Comparing the effect of lift sequencing patterns on the number of degree days reached in Ste. Sophie LFGTE facility**

The number of degree days is the cumulative number of degrees which are above 10°C.

The blue line in Figure 16 shows the cumulative degree days for the base model (second waste lift placed in December) and the red line shows the cumulative degree days for the scenario model (second waste lift placed in June instead of December). The warm second lift helps warm up the waste below and above it. As noted earlier, this is a conservative estimate given the lower boundary condition.

## 6 Conclusions and Future Work

The Ste. Sophie landfill was instrumented with 12 instrument bundles measuring several parameters including airspace oxygen concentration and temperature. A complete dataset of oxygen and temperature data were collected throughout the vertical profile of the waste from November 2009 to October 2014. The oxygen data were used to support the argument of heat generation via aerobic biodegradation. Conceptual and numerical models were developed to simulate temperatures in the landfill. A 1-D finite element heat transfer model was formulated based on continuous temperature and oxygen data measured in each waste lift. The heat transfer model was used to better understand the impact of different thermal processes and parameters within the landfill on the temperature profile. The model was used to successfully simulate the temperatures observed in the field. The goal of the model is to help landfill operators better manage landfill operations to enhance waste stabilization and landfill gas production, increase settlement, and create more air space to allow the addition of more waste per unit area of the landfill.

Data indicated that temperatures as high as 60°C were attained in the top one metre of waste when the interim cover allowed sufficient oxygen diffusion to support aerobic degradation. This was supported by the oxygen concentrations measured in the field. An aerobic heat generation rate similar to values measured in compost piles was needed to simulate these elevated temperatures near the surface. The vertical temperature profile within the waste showed that the heat generated within the top 1 m of waste due to aerobic activity can increase temperatures of the surrounding waste to temperatures

required to initiate anaerobic biodegradation. The heat budget of the waste shows that energy was still required after 2-3 years of initial placement, to thaw the frozen sections of waste. The energy budget indicates that aerobic biodegradation plays an important role on the overall heat budget for landfills operated in northern climates. The aerobic heat generation within the one metre aerobic zone accounted for 56% of the total heat generation, while the heat generated within the anaerobic zone accounted for 44% of the total heat generated.

A brief sensitivity analysis was completed to better understand the effect of specific heat ( $C_p$ ) and thermal conductivity ( $k$ ) on the model results. It was observed that the model was not very sensitive to changes in specific heat. However, different values of  $C_p$  provided better agreement for simulated temperatures at certain locations in the vertical waste profile while reducing the agreement between simulated and measured data at other locations within the waste profile. A higher  $C_p$  value provided a better estimate of temperatures at the bottom of the waste column with time. For the upper two waste lifts in which biodegradation played a significant role, a lower  $C_p$  provided a better fit to field data. The model appeared to be more sensitive to changes in the thermal conductivity. A lower thermal conductivity meant that heat transfer was reduced causing elevated temperatures at certain depths (overestimating the field data) and lower temperatures at other depths (underestimating the field data).

The model was then used to investigate the effect of waste placement and sequencing on the temperature profile in a LFGTE facility. By alternating waste placement of the second

waste lift from winter to summer such that the first three waste lifts were placed sequentially in the winter, summer, and winter, the number of days above 10°C in the second waste lift increased by approximately 400 days in comparison to the field case when the first three lifts were placed in the winter months. This would lead to greater waste stabilization and improved airspace utilization prior to the placement of the final cover.

This model can be used as a tool to simulate other operational management scenarios and study their effect on the temperature profile in the waste. The model can be improved by performing a more extensive sensitivity analysis of the thermal properties used in the model. To better represent the thermal parameters, they should be allowed to vary with depth to accommodate the effect of settlement and compaction on the thermal properties of the waste. The approximation of the latent heat of fusion and the heat generation terms can be improved. Incorporating oxygen diffusion within the interim cover and waste and coupling the heat generation rate to oxygen consumption can be of great value for the model.

## 7 Bibliography

- Ahring, B. K. (2003). Perspectives for Anaerobic Digestion. *Advances in biochemical engineering/biotechnology*, 81, 1-30.
- Angelidaki, I., Ellegaard, L., & Ahring, B. K. (2003). Applications of the anaerobic digestion process. *Advances in biochemical engineering/biotechnology*, 82, 1-33.
- Bareither, C. A., Wolfe, G. L., McMahon, K. D., & Benson, C. H. (2013). Microbial diversity and dynamics during methane production from municipal solid waste. *Waste Management*, 33(10), 1982-1992.
- Bonany, J. (2012) Heat Budget for an Anaerobic Bioreactor Landfill in Sainte-Sophie , Quebec , Canada. M.A.Sc. Thesis, Ottawa, Canada.
- Bonany, J. E., Van Geel, P. J., Gunay, B. H., & Isgor, B. (2013a). Heat budget for a waste lift placed under freezing conditions at a landfill operated in a northern climate. *Waste Management*, 33(5), 1-14.
- Bonany, J. E., Van Geel, P. J., Gunay, B. H., & Isgor, B. O. (2013b). Simulating waste temperatures in an operating landfill in Québec, Canada. *Waste Management & Research*, 31(7), 692-699.
- Cossu, R., Christensen, T., & Stegmann, R. (1992). *Landfilling of waste: leachate*. New York: Elsevier Applied Science.
- Davies, D., & Colbran, C. (2010). Sustainable Landfill Biocell: An Innovative Technology to Biostabilize Organic Fraction of Municipal Solid Waste. *Proceedings of Remediation Technologies Symposium*. Banff, AB.
- Donoso-Bravo, A., Mailier, J., Martin, C., Rodriguez, J., Aceves-Lara, C. A., & Wouwera, A. V. (2011). Model selection, identification and validation in anaerobic digestion: a review. *Water Research*, 45(17), 5347-5364.
- Duffie, J. A., & Beckman, W. A. (2006). *Solar Engineering of Thermal Processes*. Hoboken, N.J: Wiley.
- El-Fadel, M. (1999). Simulating Temperature Variations in Landfills. *Journal of Solid Waste Technology and Management*, 26(2), 78-86.
- El-Fadel, M., Angelos, N., Findikakis, & Leckie, J. O. (1996a). Estimating and enhancing methane yield from municipal solid waste. *Hazardous Waste & Hazardous Materials*, 13(3), 309-331.
- El-Fadel, M., Findikakis, A. N., & Leckie, J. O. (1996b). Numerical Modelling of Generation and Transport of Gas and Heat in Sanitary Landfills II. Model Application. *Waste Management & Research*, 14(6), 537-551.

- El-Fadel, M., Findikakis, A. N., & Leckie, J. O. (1997). Numerical Modelling of Generation and Transport of Gas and Heat in Sanitary Landfills III. Sensitivity Analysis. *Waste Management & Research*, 15(1), 87-102.
- El-Fadel, M., Findikakis, A., & Leckie, J. O. (1996c). Biochemical and Physical Processes in Landfills. *Journal of Solid Waste Technology and Management*, 23(3), 131-143.
- El-Fadel, M., Leckie, J. O., & Findikakis, A. N. (1996d). Numerical Modelling of Generation and Transport of Gas and Heat in Landfills I. Model Formulation. *Waste Management & Research*, 14(5), 483-504.
- Faitli, J., Magyar, T., Erdelyi, A., & Muranyi, A. (2014). Characterization of thermal properties of municipal solid waste landfills. *Waste Management*.
- Farouki, O. T. (1981). *Thermal properties of soil*. Hanover, New Hampshire: Cold Regions Research and Engineering Laboratory.
- Gawande, N. A., Reinhart, D. R., Thomas, P. A., McCreanor, P. T., & Townsend, T. G. (2003). Municipal solid waste in situ moisture content measurement using an electrical resistance sensor. *Waste Management*, 23(7), 667-674.
- Genivar. (2008) Figure 4, Configuration du réseau de captage du biogaz zone IV. L.E.S. de Sainte-Sophie. Project number Q110532. Prepared for: Waste Management
- Gholamifard, S., Robert, E., & Duquennoi, C. (2008). Modeling anaerobic bioreactor landfills in methanogenic phase: long term and short term behaviors. *Water Research*, 42(20), 5061-5071.
- Government of Canada. (2014). Retrieved from [https://weather.gc.ca/almanac/almanac\\_e.html?id=7035290](https://weather.gc.ca/almanac/almanac_e.html?id=7035290)
- Haarstrick, A., Hempel, D. C., Ostermann, L., Ahrens, H., & Dinkler, D. (2001). Modelling of the biodegradation of organic matter in municipal landfills. *Waste management & research*, 19(4), 320-331.
- Hanson, J. L., Edil, T. B., & Yesiller, N. (2000). Thermal properties of high water content materials. *ASTM Special Technical Publication 1374 Geotechnics of High Water Content Materials*, (pp. 137-151). West Conshohocken, PA.
- Hanson, J. L., Liu, W.-L., & Yesiller, N. (2008). Analytical and Numerical Methodology for Modeling Temperatures in Landfills. *Selected Sessions of GeoCongress 08: Geotechnics of Waste Management and Remediation*, (pp. 1-8). New Orleans, Louisiana.
- Hanson, J. L., Oettle, N. K., & Yesiller, N. (2010). Spatial and Temporal Temperature Distributions in Municipal Solid Waste Landfills. *Journal of Environmental Engineering*, 136(8), 804-815.

- Hanson, J. L., Yesiller, N., & Kendall, L. A. (2005). Integrated Temperature and Gas Analysis at a Municipal Solid Waste Landfill. *Proceedings of the 16th International Conference on Soil Mechanics & Geotechnical Engineering*, (pp. 2265-2268). Rotterdam, The Netherlands.
- Hanson, J. L., Yesiller, N., Howard, K. A., Liu, W. -L., & Cooper, S. P. (2006). Effects of Placement Conditions on Decomposition of Municipal Solid Wastes in Cold Regions. *Proceedings of the 13th International Conference on Cold Regions Engineering*.
- Hanson, J. L., Yesiller, N., Onnen, M. T., Liu, W.-L., Oettle, N. K., & Marinos, J. A. (2013). Development of numerical model for predicting heat generation and temperatures in MSW landfills. *Waste Management*, 33(10), 1967-2144.
- Houi, D., Paul, E., and Couturier, C. (1997). Heat and mass transfer in landfills and biogas recovery. *Proceedings of the sixth International Waste Management and Landfill Symposium*. Sardinia, Italy: CISA.
- Hudgins, M., & Harper, S. (1999). Operational characteristics of two aerobic landfill systems. *Proceedings of the the seventh International Waste Management and Landfill Symposium*, (pp. 1-8). Sardinia, Italy: CISA.
- Hunte, C., Hettiaratchi, J. P., & Megooda, J. H. (2011). Performance of a Waste Cell in Cold Climate Operated as an Anaerobic Landfill Bioreactor. *Geo-Fronteirs*, 1276-1286.
- Kallel, A., Matsuto, T., & Tanaka, N. (2003). Determination of Oxygen Consumption for Landfilled Municipal Solid Wastes. *Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA*, 21(4), 346-55.
- Karthikeyan, O. P., & Joseph, K. (2007). Bioreactor Landfills For Sustainable Solid Waste Management. *Proceedings of the National Conference on Sustainable Energy and Waste Management*, (pp. 112-123). Coimbatore, India.
- Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., & Christensen, T. H. (2002). Present and long-term composition of MSW landfill leachate: a review. *Environmental Science and Technology*, 32(4), 297-336.
- Koerner, G. R., & Koerner, R. M. (2006). Long-term temperature monitoring of geomembranes at dry and wet landfills. *Geotextiles and Geomembranes*, 24(1), 72-77.
- Lanini, S., Houi, D., Aguilar, O., & Lefebvre, X. (2001). The role of aerobic activity on refuse temperature rise: II. Experimental and numerical modelling. *Waste Management & Research*, 19(1), 58-69.
- Lee, G. F., & Jones-Lee, A. (1996). Dry Tomb Landfills. *MSW Management*, 6(1), 82-89.
- Lefebvre, X., Lanini, S., & Houi, D. (2000). The role of aerobic activity on refuse temperature rise, I. Landfill experimental study. *Waste Management & Research*, 18(5), 444-452.

- Mata-Alvarez, J., & Martinez-Viturtia, A. (1986). Laboratory Simulation of Municipal Solid Waste Fermentation with Leachate Recycle. *Journal of Chemical Technology and Biotechnology*, 36, 547-556.
- McAdams, W. H. (1954). *Heat Transmission* (3rd ed.). New York: McGraw-Hill.
- McBean, E. A., Rovers, F. A., & Farquhar, G. J. (1995). *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, N.J: Prentice-Hall.
- Megalla, D., VanGeel, P.J., Gladish, A., and Gunay, B. (2014). Impacts of aerobic and anaerobic biodegradation on the heat budget for landfills operating in northern climates. *Proceedings of the Fifth International Symposium on Energy from Biomass and Waste*. San Servolo, Venice, Italy: CISA.
- Ministry of Environment. (2010). *Landfill Standards: A Guideline on the Regulatory and Approval Requirements for New or Expanding Landfilling Sites*. Ontario Ministry of the Environment.
- Nelson, M. I., Balakrishnan, E., & Chen, X. D. (2003). A semenov model of self-heating in compost piles. *Trans IChemE*, 81(September), 375-383.
- Neusinger, R., Drach, V., Ebert, H. -P., & Fricke, J. (2005). Computer Simulations that Illustrate the Heat Balance of Landfills. *International Journal of Thermophysics*, 26(2), 519-530.
- Nopharatana, A., Pullammanappallil, P. C., & Clarke, W. P. (2007). Kinetics and dynamic modelling of batch anaerobic digestion of municipal solid waste in a stirred reactor. *Waste Management*, 27(5), 595-603.
- Onnen, M. (2014) Thermal Numerical Analysis of Vertical Heat Extraction Systems in Landfills. M.A.Sc. Thesis, San Luis Obispo, United States of America.
- Pacey, J., Augenstein, D., Morek, R., Reinhart, D., & Yazdani, R. (1999). The Bioreactor Landfill- An Innovation in Solid Waste Management. *SWANA*, (pp. 1-14). Silver Springs, Maryland.
- Pirt, S. J. (1978). Aerobic and anaerobic microbial digestion in waste reclamation. *Journal of Chemical Technology & Biotechnology*, 28(4), 232-236.
- Pommier, S., Chenu, D., Quintard, M., & Lefebvre, X. (2007). A Logistic Model for the Prediction of the Influence of Water on the Solid Waste Methanization in Landfills. *Biotechnology and Bioengineering*, 97(3), 473-482.
- Rees, J. F. (1980). Optimisation of Methane Production and Refuse Decomposition in Landfills by Temperature Control. *Journal of Chemical Technology and Biotechnology*, 30(2), 458-465.
- Reinhart, D. (1996). Full-Scale Experiences With Leachate Recirculating Landfills: Case Studies. *Waste Management & Research*, 14(4), 347-365.

- Rodriguez, J., Premier, G. C., Guwy, A. J., & Dinsdale, R. (2009). Metabolic Models to Investigate Energy Limited Anaerobic Ecosystems. *Water Science and Technology*, 60(7), 1669-1675.
- Rowe, R. K. (1990). Containment Impact Assessment and the Contaminating Lifespan of Landfills. *Canadian Journal of Civil Engineering*, 18, 244-253.
- Rowe, R. K., & Islam, M. Z. (2009). Impact of landfill liner time-temperature history on the service life of HDPE geomembranes. *Waste Management*, 29(10), 2689-2699.
- Rowe, R. K., Hoor, A., & Pollard, A. (2010). Numerical Examination of a Method for Reducing the Temperature of Municipal Solid Waste Landfill Liners. *Journal of Environmental Engineering*, 136(8), 794-804.
- Stams, A. J., Oude Elferink, S. J., & Westermann, P. (2003). Metabolic Interactions Between Methanogenic Consortia and Anaerobic Respiring Bacteria. *Advances in biochemical engineering/biotechnology*, 81.
- Statistics Canada. (2010). *Waste Management Industry Survey: Business and Government Sectors*. Ottawa: Statistics Canada.
- Statistics Canada. (2011). *Human Activity and the Environment: Detailed Statistics*. Ottawa.
- Swati, M., & Joseph, K. (2005). Bioreactor Landfills– A global vista on the emerging technology for sustainable management of municipal solid waste. *Prithvi 2005: Global Ecomeet*, (pp. 63-76).
- Swinbank, W. C. (1963). Long-wave Radiation From Clear Skies. *Quarterly Journal of the Royal Meteorological Society*, 89.
- The Hinkley Center For Solid and Hazardous Waste Management. (2008). *Florida Bioreactor Landfill Demonstration Project*.
- Tittlebaum, M. E. (1982). Organic Carbon Content Stabilization through Landfill Leachate Recirculation. *Water Pollution Control Federation*, 54(5), 428-433.
- Townsend, T. G., Kumar, D., & Ko, J. (2008). *Bioreactor Landfill Operation: A Guide For Development, Implementation and Monitoring: version 1.0 (July1, 2008)*. Gainesville, FL.
- United States Environmental Protection Agency. (2014). *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*. Washington, DC.
- Vingerhoeds, E. (2011) Instrument Installation and Preliminary Data in a Full-Scale Anaerobic Bioreactor Landfill, Sainte-Sophie, Quebec, Canada. M.A.Sc. Thesis, Ottawa, Canada.
- Ward, R. F. (1983). Temperature Effects: Methane Generation From landfill Samples. *Journal of Environmental Engineering*, 109, 979-981.

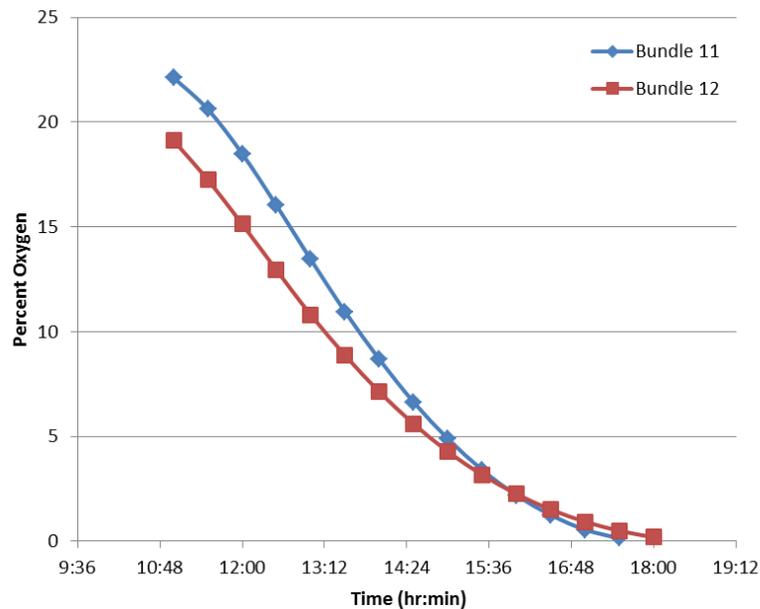
- Warith, M. (2002). Bioreactor landfills: experimental and field results. *Waste Management*, 22(1), 7-17.
- Warith, M. (2003). Solid Waste Management: New Trends in Landfill Design. *Emirates Journal for Engineering Research*, 8(1), 61-70.
- Watmuff, J. H., Charters, W. W., & Proctor, D. (1977). *Solar and Wind Induced External Coefficients - Solar Collectors*. Cooperation Méditerranéenne pour l'Energie Solaire, Revue Internationale d'Héliotechnique, 2nd Quarter.
- Yesiller, N., Hanson, J., & Liu, W. (2005). Heat Generation in Municipal Solid Waste Landfills. *Journal of Geotechnical and Geoenvironmental engineering*, 131(11), 1330-1344.
- Yoshida, H., & Rowe, R. (2003). Consideration of landfill liner temperature. *Proceedings of the Ninth International Waste Management and Landfill Symposium* (pp. 1-9). Cagliari, Italy: CISA.
- Yoshida, H., Tanaka, N., and Hozumi, H. (1997). Theoretical study on heat transport phenomena in a sanitary landfill. *Proceedings of the Sixth International Waste Management and Landfill Symposium*. Sardinia, Italy: CISA.
- Zambra, C. E., Moraga, N. O., & Escudey, M. (2011). Heat and mass transfer in unsaturated porous media: Moisture effects in compost piles self-heating. *International Journal of Heat and Mass Transfer*, 54(13-14), 2801-2810.
- Zanetti, M.C., Manna, L., Genon, G. (1997). Biogas production evaluation by means of thermal balances. *Sixth International Waste Management and Landfill Symposium*. Italy: CISA.
- Zhao, X., Musleh, R., Maher, S., Khire, M. V., Voice, T. C., & Hashsham, S. A. (2008). Start-up performance of a full-scale bioreactor landfill cell under cold-climate conditions. *Waste Management*, 28(12), 2623-2634.

## Appendix A- Field Data

Temperatures are discussed in detail in the paper; the moisture sensors failed after a few months from installation; the spikes in the oxygen are due to pumping; the TEPC overestimate the overburden pressures and are a topic of another MASc student's thesis; and the analysis of the settlement data was recently initiated by a summer USRA student.

### Oxygen Data

During the final installation of bundles 11 and 12, the initial oxygen content measured was about 21%. As seen in Figure A1, the oxygen in bundles 11 and 12 declined to 0% in less than a day. The oxygen concentration declined immediately during the installation of bundles 11 and 12 and the temperature during installation was greater than 20°C indicating aerobic microbial activity which would be responsible for consuming the oxygen.



**Figure A1 Oxygen consumption in bundles 11 and 12 upon installation in final waste lift (May 24, 2012)**

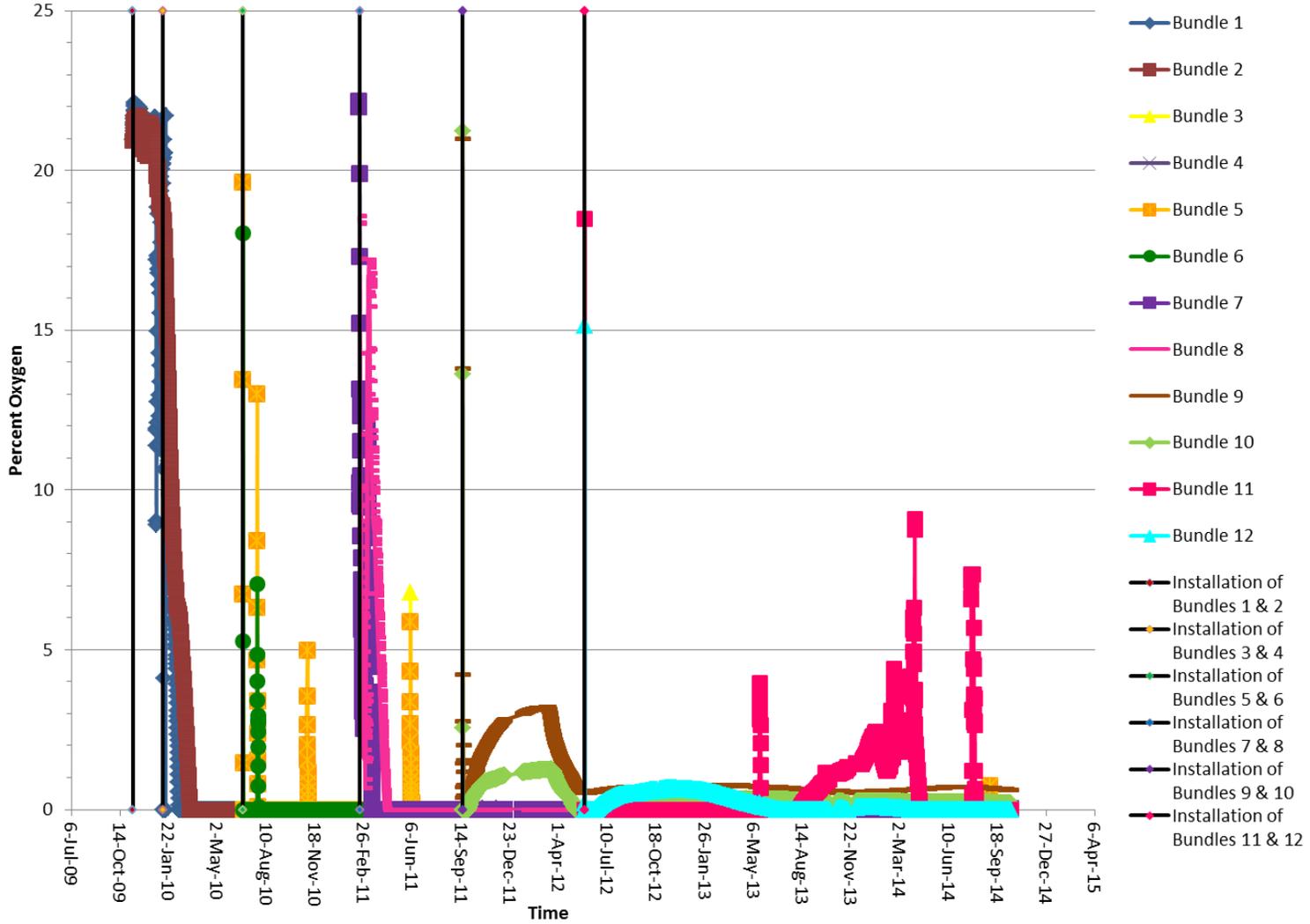


Figure A2 Oxygen concentration in bundles 1 to 12 from November 2009 to October 2014 and bundle installation times

## Settlement data

Figure A3 shows the settlement of the 12 instrument bundles since the installation until September 2014.

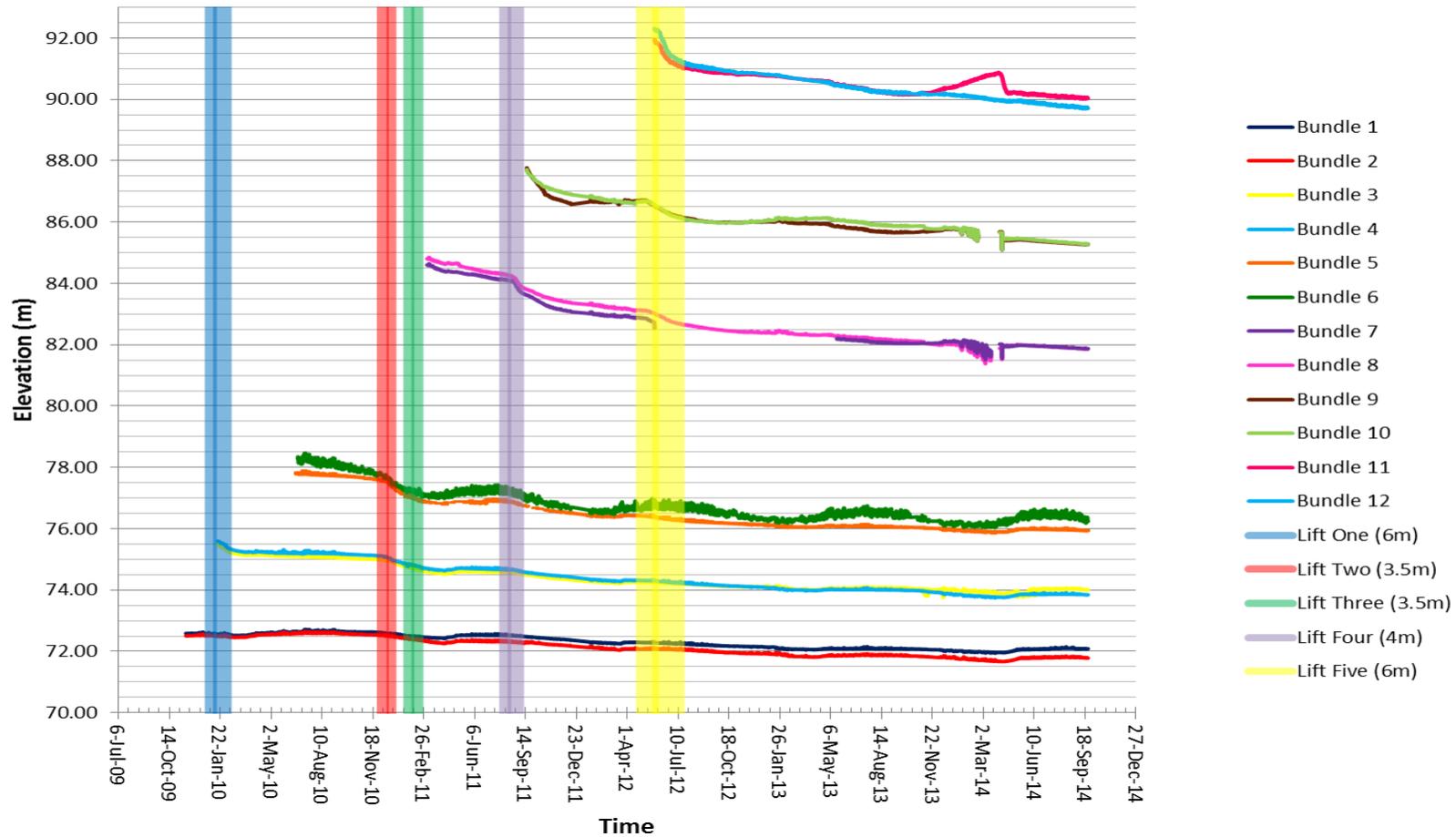


Figure A3 Total settlement for bundles 1 to 12 from November 2010 to September 2014 and time of placement of five waste lifts in Ste. Sophie LFGTE facility

As seen in Figure A3, settlement data for bundle 7 was missing for approximately a year starting from May 24, 2012. This was due to a wiring problem which was fixed to May 17, 2013. There is also missing data for bundles 7-10 for a few weeks in April 2014 which was due to pressures above the range of the pressure transducers for the settlement system. The problem was solved by releasing some of the liquid in the tubing from the accumulator in the instrument shed; this in turn reduced the pressures at the transducer in the instrument and at the transducer at the instrument bundle.

Table A1 summarizes the location and total settlement of each bundle. It is important to note that bundles at the bottom of the landfill settle due to consolidation of the clay unit below the landfill but bundles which are placed within the waste lifts settle due to mechanical and biological settlement.

**Table A10 Surveyed locations of bundles and elevations during installation and total settlement as of September 2014**

Bundle	Northing	Easting	Elevation - As placed (masl)	Distance from landfill bottom as placed (m)	Elevation as of 23/9/2014 (m)	Total Settlement as of 23/9/2014 (m)
1	5070938	273056.7	72.58	0	72.09	0.49
2	5070925	273045.4	72.47	0	71.78	0.69
3	5070938	273056.7	75.46	2.88	74.00	1.46
4	5070925	273044.9	75.63	3.16	73.85	1.78
5	5070939	273057.3	77.79	5.21	75.94	1.85
6	5070925	273044.9	78.31	5.84	76.24	2.07
7	5070938	273056.4	84.57	11.99	81.88	2.69
8	5070925	273045.1	84.76	12.29	81.86	2.90
9	5070938	273056.5	87.71	15.13	85.28	2.43
10	5070925	273044.3	87.77	15.3	85.28	2.49
11	5070940	273051.1	91.918	19.338	90.03	1.88
12	5070930	273036.5	92.272	19.802	89.71	2.56

## Total Earth Pressure Cell Data

Figure A4 shows that the total earth pressure increases as the overburden pressure increases.

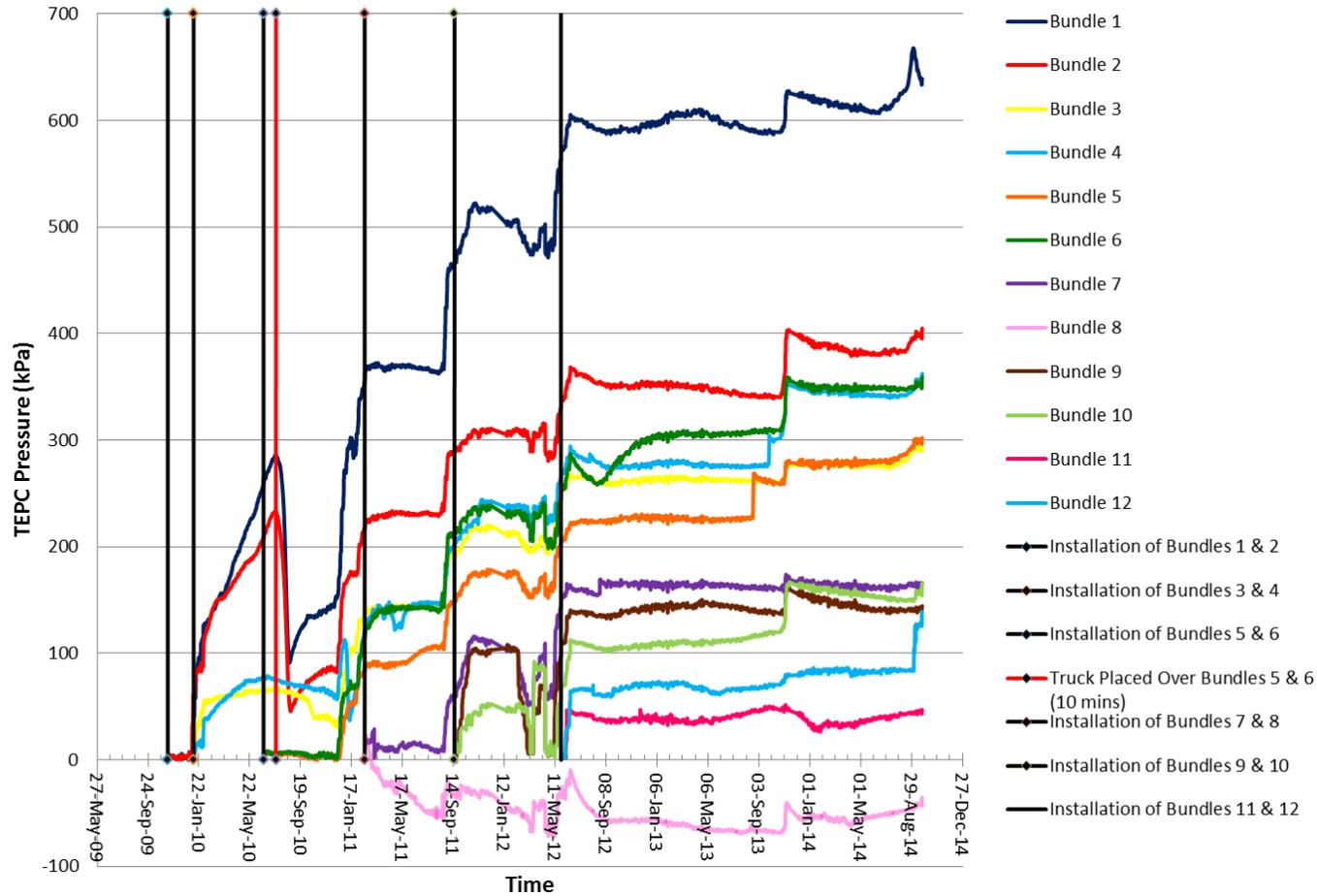


Figure A4 Total earth pressure for bundles 1 to 12 from November 2010 to September 2014 and time of bundle installations in Ste. Sophie LFGTE facility

## Piezometer

Figure A5 shows mounding of leachate at the bottom four bundles installed in the Ste. Sophie LFGTE facility.

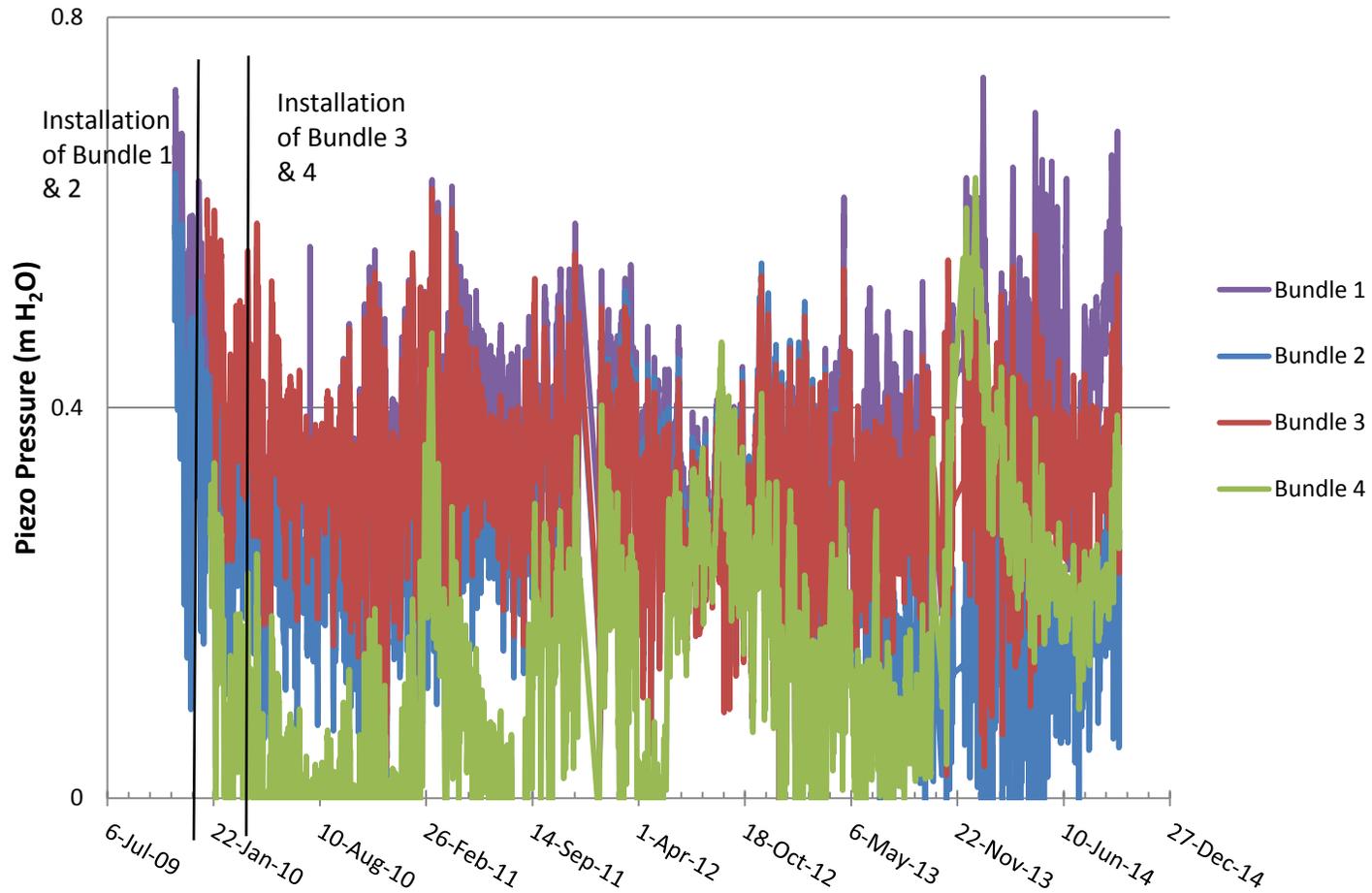


Figure A5 Piezometric pressure for bundles 1-4 November 2010 to September 2014