A FEASIBILITY STUDY OF MUNICIPAL WASTE-TO-ENERGY MANAGEMENT: MEASUREMENT OF LANDFILL GAS QUALITY AT BRADY ROAD LANDFILL IN CANADA

By

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A Thesis Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The purpose of this study was to evaluate the feasibility of landfill gas utilization at Brady Road landfill. Five gas monitoring probes were installed to monitor landfill gas quality and the chemical and physical characteristics of landfill gas over time. Analysis of several gas contaminants, including vinyl chloride, hydrogen sulfide and siloxanes, was carried out to determine for the need for pre-treatment of the gas to protect turbines and equipment from corrosion. The average concentration of vinyl chloride was 0.28 ± 0.21 part per million by volume, while the corresponding value of hydrogen sulfide was 11,800 ± 1,800 part per million by volume. Estimates of landfill gas generation potential and greenhouse gas reductions were calculated to recommend the viable gas utilization options for Brady Road landfill.

The evidence of high and stable concentrations of methane (56.0% ± 2.6% by volume) and carbon dioxide (39.1% ± 3.1% by volume) at Brady Road landfill reflect the waste, at the sampling location, being two years old and in its stable methane fermentation stage. The landfill gas temperature (15.1 ± 1.8°C) at 10 meters below ground level was relatively constant in comparison to the ambient temperature (26°C to -20°C) and atmospheric pressure (101.7 kPa to 104.1 kPa). The high relative humidity (75.7% ± 10.0%) indicated a need for moisture removal treatment, particularly for upgrading to natural gas pipeline quality. For all gas contaminants investigated, concentrations were at low levels; thereby no contaminant filtering is required for direct combustion and boiler use.

The site-specific landfill gas generation estimates show that Brady Road landfill has great potential to harvest biogas through methane recovery as landfill gas generation rates could be as high as 3,300 standard cubic feet per minute in 2050. If recovered, it could potentially reduce approximately 168,000 tonnes of carbon dioxide equivalent per year, and create annual revenue of approximately $335,000 from greenhouse gas credits and much more from energy use. Based upon this study, the combined direct uses (i.e. direct combustion and boilers) and leachate evaporation are the two most favourable options for the future gas utilization at Brady Road landfill. These offer the most cost-effective and practical methane usage suitable for a large landfill capacity like Brady Road landfill that has a landfilling projection of over a next century.

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ABBREVIATIONS

AP-42 – Compilation of Air Pollution Emission Factors

BTU – British Thermal Unit

CAA – Clear Air Act

CH_4 – Methane

CO_2 – Carbon Dioxide

DOC – Degradable Organic Carbon

EC – Environment Canada

E-VAP – Leachate Evaporation

ft^3 – Cubic Feet

ft^3/lb – Cubic Feet of Methane Per Tonnes of Waste

GC – Gas Chromatography

GHG – Greenhouse Gas

H_2S – Hydrogen Sulfide

IC – Internal Combustion

K – Decay Rate Constant

kg – Kilogram

kPa – Kilo Pascal

lb – Pound

LFG – Landfill Gas

Lo – Methane Generation Potential

MSW – Municipal Solid Waste

Mt – Million Tonnes

N_2 – Nitrogen

O_2 – Oxygen

ppm – Part Per Million (by volume – ppm v/v)

PVC – Polyvinyl Chloride

RH – Relative Humidity

SCF – Standard Cubic Feet

SCFM – Standard Cubic Feet Per Minute

CHAPTER 1
INTRODUCTION

1.0 Background

Solid waste management requires that new concerns and constraints of climate change be considered. In December 1997, Canada and more than 160 other countries met in Kyoto, Japan, and agreed to reduce greenhouse gas (GHG) emissions. Canada's target is to reduce its GHG emissions to 6% below 1990 levels by the period between 2008 and 2012. In September 2001, the Manitoba government announced its intention to meet and exceed the targets of the Kyoto Protocol. Manitoba anticipates to reduce GHG by up to 18% below 1990 levels by 2010, and by up to 23% below 1990 levels by 2012 (Manitoba Government, 2002).

In Manitoba the largest single point source of GHG is the landfill gas at the Brady Road Landfill in Winnipeg. If recovered, it could potentially reduce GHG emissions of 0.4 megatonnes carbon dioxide equivalent (eCO_2) and create about 6.7 megawatts of electricity per year (Manitoba Government, 2002). Landfill gas is typically generated during a 30-50 year period as waste decomposes, and continues after the closure of the landfill, which in the case of Brady Road landfill is a long time, as it is expected to remain open until 2150 (Environment Canada, 1999). Generation of electricity from landfill gas provides a source of environmentally friendly renewable power that would otherwise be wasted and become a liability due to fire and explosion risks.

In addition to GHG reductions, the capture and use of landfill gas provides the ancillary benefits of limiting odours, controlling damage to vegetation, reducing owner liability, risk from explosions, fires and asphyxiation, and smog while providing a potential source of revenue and profit. Forty one landfills in Canada presently capture methane resulting in a reduction of GHG emissions of more than 7 megatonnes per year of CO_2 equivalents annually (Conestoga Rovers and Associates, 1999). An estimated 70% of the captured gas in Canada is used for energy generation at 13 facilities (Pembina Institute, 2003) of which six generate electricity to sell to the grid (e.g., Keele St., Toronto) and seven use the gas directly as an industrial process fuel. The state-of-the-art composting and landfill gas recovery facility in Edmonton demonstrates the efficacy of multi-faceted environmental systems for waste management (Environment Canada, 1999).

Currently, utilization of landfill gas in several countries, such as the United States, has shown a revenue stream that can offset some of the costs associated with building, operating, and maintaining a landfill. Production of electricity power and use of landfill gas as a heating fuel (natural gas replacement or supplement) are two landfill gas utilization approaches that have been widely applied. Landfill gas has proven to be a reliable fuel resource. The alternative that is best suited for a specific site is dependent on many factors including: 1) projected landfill gas availability; 2) presence and location of a suitable market; 3) market price for end products; 4) environmental and regulatory factors; and 5) economics of utilization, including processing, transporting energy, and generation requirements.

Typical landfill gas in North America consists of 50% methane (CH_4), 48% carbon dioxide (CO_2), and small amounts of hydrogen, oxygen, nitrogen and trace amounts of non-organic compounds and volatile organic compounds (Gardner et al., 1993). After the refuse has been placed in the landfill, aerobic decomposition of the organic waste begins. In particular, other greenhouse gases, like CO_2, are also produced during aerobic decomposition process. Once the oxygen becomes depleted, then anaerobic micro-organisms become dominant and produce the greenhouse gases (i.e. CH_4 and CO_2) in landfill sites (Schumacher, 1983). Methane emissions from landfills vary considerably depending on the waste characteristics (composition, density, particle size, moisture content, nutrients, microbes, stage of decay and pH) and the site-specific environment (depth of waste, oxygen content and temperature) (El-Fadel, 1998). Data from field studies conducted worldwide indicate that landfill methane production may range over six orders of magnitude (between 0.003-3000 $g/m^2/day$) (Bogner et al., 1995). Not all landfill methane is emitted into the air; some is stored in the landfill and part is oxidized to CO_2.

1.1 Purpose and Objectives

The purpose of this study was to investigate the energy potential of Winnipeg's Brady Road landfill and the quality of landfill gas production. The study also estimates the quantity of landfill gas production, although this is not the focus of this thesis. The specific objectives of this study were to determine:

1) Chemical composition of landfill gas including trace components,
2) Seasonal variability of the physical characteristics,
3) Heating value of the landfill gas,
4) Site specific methane generation rate values,
5) Estimated potential of greenhouse gas reductions, and
6) Management implications for Brady Road landfill.

1.2 Significance of Research

Methane from landfills is a global warming potential released into the atmosphere, if not recovered. This may result in odour nuisance, explosive danger and health hazards associated with trace gases. The study of landfill gas quality is essential in reducing GHG emissions and creating alternative resource energy.

1.3 Organization

This thesis consists of five chapters. This chapter introduces the landfill gas issue and its impacts to the environment, establishes the purpose and objectives and significance of the research. Chapter 2 reviews the related literature, followed by the details of the methodology in Chapter 3. In Chapter 4, the study results are interpreted and discussed in relation to the objectives. At last, the conclusions and recommendations are provided in Chapter 5.

CHAPTER 2
SOLID WASTE MANAGEMENT AND LANDFILL GAS

2.0 Introduction

Recently, global climate change, due to human-made greenhouse gases, caused by activities such as burning fossil fuels, has become one of the most important issues in environmental awareness around the world. Anthropogenic activities include the methane emissions from landfill, which accounts for about 12.6% of Canada's CO_2 equivalent GHG emissions with almost one quarter (24%) from landfills (Casto-Wunsch and Ng-Grondin, 2002). However, carbon dioxide generated by the landfills is not counted into the assessment of GHG emission inventories because if this gas is not recovered, it would eventually be produced through natural decomposition (USEPA, 2002). Brady Road landfill is considered to be both the largest single point source of GHG, in Manitoba and the largest landfill that is unmanaged for GHG in Canada. Therefore, Manitoba's GHG strategy requires consideration of waste management options, such as landfill gas recovery, to curb climate change as well as to create a new source of revenue.

The purpose of this chapter is to provide an overview of literature regarding solid waste management, landfill gas, and issues associated with landfill gas. It is organized into six sections.

1. Waste management overview in Canada and Manitoba,
2. Greenhouse gases,
3. Landfill gas characteristics,
4. Factors affecting landfill gas generation and enhancement of gas production,
5. Landfill gas utilization alternatives, and
6. Specific site information.

Several methods used for analysis of landfill gas quality in recent studies are also discussed in this chapter.

2.1 Provision of Solid Waste Management in Canada

Managing solid waste is divided amongst the three levels of government: federal, provincial, and municipal. The federal government is responsible for managing only its federal lands, including Indian reserves and national parks. The provincial government has the overall responsibility for solid waste management policy and the related general strategies, such as regulating the collection and the disposal of garbage. Municipalities develop plans for local programs and can also be responsible for their delivery (Statistics Canada, 1993). However, provincial government and municipalities usually share their responsibilities, such as garbage collection and recycling programming. In such cases, projects and strategies can be conducted either directly by or in conjunction with the Canadian Council of Ministers of the Environment (CCME) (Mackenzie, 1994)

2.1.2 Municipal Solid Waste Management in Manitoba

In Manitoba, the province's solid waste management policy provides a province-wide solid waste management system that is designed to minimize risk to human health and the environment, as well as to support the continued growth of the Manitoba economy. One of the greatest improvements to Manitoba's solid waste management system, since 1995, has been the establishment of alternative waste management facilities, such as reuse and recycling. The development of alternative waste management facilities has been stimulated in part by the support provided by Manitoba's product stewardship agencies, including the Manitoba Product Stewardship Corporation (MPSC) for multi-material recycling; Manitoba Association for Resource Recovery Corporation (MARRC) for used oil, filters and containers; Tire Stewardship Board (TSB) for used tires; and the Crop Protection Institute of Canada (CPIC) for pesticide containers (Manitoba Conservation, 1999).

However, the need for landfill gas management has been recently mentioned in the 2002 Manitoba Climate Change Action Plan without any financial commitment or new programming. This indicates a lack of incentives from the Provincial Government and political will to deal with the landfill gas issue. To control greenhouse gas emissions from landfills, the provincial government needs to promote landfill gas opportunities and establish policies and incentives to encourage recovery from landfill owners and municipalities. For example, government should increase greenhouse gas credits to build efforts to reduce greenhouse gas emissions.

Moreover, lack of regionalizing solid waste management in the province could create a lot of landfills in rural and small communities. Due to limited resources, individual and small communities have a hard time providing all the services for which they are responsible, from public works projects to municipal solid waste management. Regionalization, therefore, can be used as a strategy for neighbouring cities and towns to pool resources to address local challenges (USEPA, 1998). For example, regionalization can provide greater leverage in obtaining the financial resources needed for solid waste management planning and implementation activities (given priority to small communities when disbursing grant).

2.2 Greenhouse Gases

Many gases in the environment exhibit "greenhouse" properties, including those that occur naturally in the atmosphere, such as water vapour, carbon dioxide, methane, and nitrous oxide, and those that are human-made, such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (Environment Canada, 1999).

In general, Global Warming Potential (GWP) is widely used as a qualified measure of the globally averaged relative forcing impacts of a particular greenhouse gas (IPCC, 1996). GWP is also defined as the ratio of global warming from one unit mass of a greenhouse gas to one unit mass of carbon dioxide over a period of time (USEPA, 2002). In other words, it is a measure of the potential for global warming per unit mass of carbon dioxide. For example, carbon dioxide has a GWP of exactly 1 (since it is the baseline unit to which all other greenhouse gases are compared) and methane has a GWP of 21 (measured relatively to GWP of carbon dioxide over 100 year time horizon). Therefore, GWP values allow policy makers to compare the impacts of emissions and reductions of different gases.

Many chemical compounds, found in the Earth's atmosphere, act as "greenhouse gases" including carbon dioxide, methane, chlorofluorocarbon, and nitrous oxide. These gases allow sunlight, which is radiated in the visible and ultraviolet spectra, to enter the atmosphere unimpeded. When sunlight strikes the Earth's surface, some of the sunlight is reflected as infrared radiation (heat). Greenhouse gases tend to absorb this infrared radiation as it is reflected back towards space, trapping the heat in the atmosphere (Environment Canada, 2001).

In addition, this phenomenon can be explained in term of earth's energy imbalance when the outgoing heat from the earth does not equal the incoming energy from the sun (see Figure 2.1). Although human-made aerosols (fine particle in the air generated by the burning of fossil fuel) increase reflection of sunlight by the earth, this reflection is more than offset by the trapping of heat radiation by greenhouse gases. The excess energy, therefore, warms up the ocean and melts the ice (Scientific American, 2004).

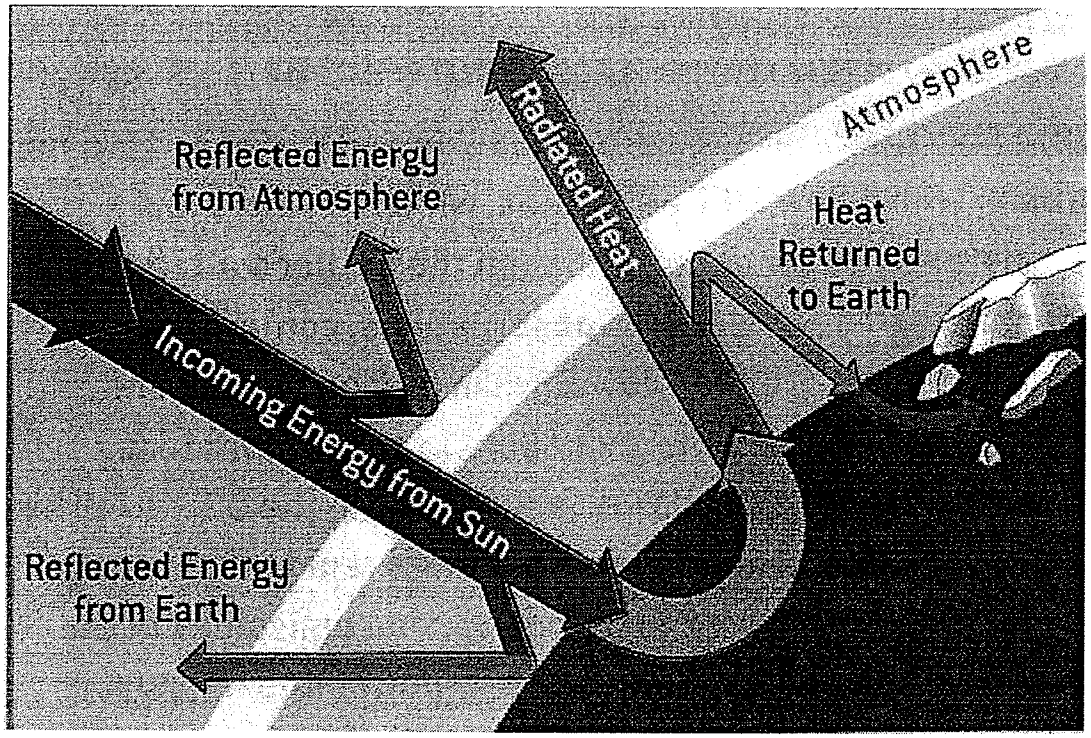

Figure 2.1 Earth's energy imbalance (Scientific American, 2004, page 47).

Based on Manitoba greenhouse gas emissions estimate in 1999, waste disposal accounts for 2.8% eCO_2 (carbon dioxide equivalent) of overall greenhouse gas emission in Manitoba. The largest amount of greenhouse gas emissions comes from energy use (61.3%), such as vehicle transportation. Although the proportion of greenhouse gas emissions from waste disposal is small, impact of its contribution to the environment is significant, as biogas from waste disposal contains a large proportion of powerful greenhouse gases (i.e. > 50% of methane). Therefore, concerns and awareness should be addressed on this matter to examine challenges and opportunities for Manitoba posed by climate change.

2.2.1 Alternate Greenhouse Gas Revenue Streams

The Kyoto Protocol is serving to change business conditions by characterizing greenhouse gas as a commodity that poses a cost to those who generate it and a value to those who can reduce it. Therefore, the Kyoto Protocol creates a new source of revenue called greenhouse gas credits.

2.2.1.1 Greenhouse Gas Credits

The sale of greenhouse gas credits is a relatively new means to generate revenue. Companies can obtain greenhouse gas credits through reducing greenhouse gas emissions. Greenhouse gas credits can be sold through a local market to other companies who are required to reduce their own emissions. However, the value of the greenhouse gas credits varies over time. The \$1.68 CAD/tonne of eCO_2 reduction is assigned as a constant value for the 20 to 50 year term (i.e. 2000-2020) to estimate greenhouse gas credits for sites across Canada (Environment Canada, 1999). Generally, greenhouse gas credits range from \$1.00 to \$2.00 per tonnes of eCO_2 for sites with existing capture and flaring systems and range from \$2.00 to \$3.00 for sites without recovery systems (Environment Canada, 1999).

2.2.1.2 Green Power

Green power is a special variation of electrical power revenue based upon deregulation of the electrical power industry. It is based on the idea that a percentage of the population will pay a premium to source their electricity purchase from a renewable or green producer (Environment Canada, 1999). A credit potential of 5 cents/kWhr is currently used in Canada. Recently, the Government of Canada invested $7.2 million to help develop key enabling technologies for sustainable and clean electrical energy sources (Industry Canada, 2004). This would assist Canada to achieve a goal for emission reduction target under Kyoto Protocol.

2.3 Climate Change Implications

Climate change can affect our life and environment in many ways, such as extreme weather, human health, endangered ecosystem, and economic risks. Impacts of climate change have already been observed around the world. These include receding glaciers, thawing of the permafrost, late freezing and early break-up of ice on rivers and lakes, declines of some plants and animal populations, earlier flowering of trees, and earlier emergence of insects and egg-laying in birds (USEAP, 2002). Preliminary evidence has also shown climate change impact to human lifestyle with recent increases in floods, droughts, and storms. These consequently create significant economic losses (USEPA, 2002). According to the Manitoba government study (2002), the 2001 prairie drought cost the Canadian economy over $5 billion in agricultural losses.

Air pollution caused by fossil fuels is already a health concern. The effects of climate change will make the smog more intense and thereby lead to higher rates of asthma and heart disease (USEPA, 2002). Moreover, climate change is changing the patterns of animal life and unbalancing the ecosystem. For example, climate change is one of the causes of a dramatic drop in Pacific salmon populations along the west coast of North America (USEPA, 2002). In Manitoba, the Manitoba climate change action plan was established in 2002 to cope with climate change problems and try to achieve Canada's Kyoto Protocol targets. One of the proposed actions in this plan is to reduce and capture greenhouse gas emissions from Brady Road landfill.

2.4 Overview of Landfill Gas-to-Energy Opportunities in Canada

Landfill gas produced from municipal solid waste landfills is one of the most significant sources of methane emission. In Canada, methane emissions account for about 12.6% of Canada's CO_2 equivalent greenhouse gas emissions. Of these emissions 23.5% come from landfills (Casto-Wunsch and Ng-Grondin, 2002). Landfill gas recovery can play an important role to convert a harmful emission into a reliable environmentally-sustainable energy source. The recovery and utilization of landfill gas is a win-win situation which provides the benefits of: 1) reducing the release of greenhouse gases that contribute to global warming; 2) limiting odours; 3) controlling damage to vegetation; 4) reducing risks from explosions and fires; 5) converting a harmful emission into a reliable energy source; and 6) creating a potential source of revenue and profit (Wheless and Wiltsee, 2001).

There were approximately one million tonnes of methane emitted from Canadian landfills in 1990. Of that amount, it is estimated that 20% are captured and combusted (Sawell et al., 1996). Emissions are predicted to rise to approximately 1.3 million tonnes by 2020. The technical feasible level of emission recovery from landfill is about 63% of total emissions (Hickling, 1994).

A recent Environment Canada report (2003), as shown in Table 2.1, provides an overview of different landfill projects in terms of landfill gas recovery and utilization. It also shows that Brady Road landfill is potentially the largest emitter. In Canada, over 18 different landfills currently employ landfill gas to generate electricity and sell to the electricity grid (Cover Bar, Keele Valley, Waterloo, Optigaz etc.). Moreover, these landfills significantly reduce greenhouse gas emissions by more than 7 million tonnes per year (Mt/year). In particular, Brady Road landfill is expected to reduce a significant amount of emissions, being as high as 0.4 Mt/year (Province of Manitoba Climate Change Action Plan, 2002).

Table 2.1 Summary of landfill gas (LFG) recovery projects in Canada (Environment Canada, 2003).

Name of Landfill	*Landfill Capacity (tonnes)*	*CH_4 Captured (m^3)*	*eCO_2 Reduced Per Year (tonne/yr)*	*Estimated % CH_4 in LFG*	*Energy Generation (kW-hr)*
Port Mann, BC	4,000,000	1,522,000	23,379	57	16,000,000
Jackman, BC	400,000	310,000	4,689	45	3,255,600
Saint Michel, QC	33,000,000	74,700,000	1,123,562	38	208,200,000
Lachenaie, QC	10,800,000	33,000,000	554,664	58.5	31,200,000
Cambridge, ON	2,650,000	4,800,000	75,732	52	45,754,400
Waterloo, ON	12,000,000	9,500,000	142,435	53	28,600,000
Beare Road, ON	9,000,000	9,400,000	140,133	45	26,600,000
Brock West, ON	18,000,000	40,600,000	611,425	39	43,500,000
Keele Valley, ON	25,000,000	119,000,000	1,789,481	47	274,800,000
Clover Bar, AB	13,200,000	12,500,000	188,726	51	41,300,000
Brady Road, MB	50,000,000	0	167,489**	56	>200,000,000*

*Estimated Value, ** Potential

Tanapat et al. (2003) and Tanapat et al. (2004) found that landfill gas generation from Brady Road landfill can produce between 3,800 to 5,800 standard cubic feet per minute in 2050. As a result of this finding, gas generation from Brady Road landfill would be sufficient for landfill gas recovery. Table 2.2 demonstrates different landfill gas-to-energy operations and their associated costs.

Table 2.2 Summary of Landfill Gas-to-Energy Operations in Canada (Environment Canada, 2001: Environment Canada, 1999)

Name of Landfill	*LFG-to-Energy System*	*Electricity (MW) or Heat Production (BTU/yr)*	*Collection System*	*Gas Treatment*	*Estimated Capital Cost ($ million)*
Port Mann, BC	Direct use	35,000 million (BTU/yr)	110 vertical wells	Dehydration using ethylene glycol	1.4
Jackman, BC	Direct use	4,689 million (BTU/yr)	40 vertical wells	None	N/A
Saint Michel, QC	Steam turbines	25 MW	360 wells	Condensate trap	N/A
Lachenaie, QC	4 Engines	4 MW	N/A	Condensate trap	N/A
Cambridge, ON	Direct use	155,000 million (BTU/yr)	44 vertical, 5 horizontal wells	None	1.3
Waterloo, ON	Engine	3.7 MW	73 vertical wells	Moisture & particular removed	5.7
Beare Road, ON	7 Reciprocating engines	3.2 MW	100 vertical wells	Condensate trap, water scrubber, cooling and reheating	N/A
Brock West, ON	Steam engine	8.5 MW	21 trenches and 110 wells	Condensate trap	N/A
Keele Valley, ON	Steam turbine	33 MW	N/A	Condensate trap	N/A
Clover Bar, AB	Steam turbine	5 MW	75 vertical wells (120 existing)	Diethylene glycol	1.4

In general, environmental benefits from collecting and combusting landfill gas include odour reduction, landfill gas emission reductions, and energy recovery. Collecting and burning landfill gas significantly reduces greenhouse gas emissions due to the conversion of methane to carbon dioxide. However, carbon dioxide generated by landfills or through the combustion of landfill gas is not counted as a greenhouse gas emission because if carbon dioxide were not emitted from landfills, it would be produced through natural decomposition (USEPA, 2002). The net increase of carbon dioxide, therefore, is zero.

On the other hand, methane is counted as an anthropogenic greenhouse gas because even though methane is derived from biogenic sources, such as yard trimmings and paper, composting would not result in methane emission, if not for deposition in landfills in anaerobic conditions (USEPA, 2002). In other words, methane generation from landfills results from the influence of human beings.

2.5 Landfill Gas Composition and Characteristics

Landfill gas is the product of solid waste decomposition. The quantity and the composition depend on the types of solid wastes that are decomposing. A waste with a large fraction of easily biodegradable organic material will produce more gas than one consisting largely of ash and construction debris. The rate of gas production is governed by the rate at which decomposition is occurring in the wastes. When decomposition ceases, gas production also ends. Gas production begins almost immediately after the solid waste is placed in a landfill. Willumsen (1990) noted that the most significant gas production usually begins 200 days after solid waste is disposed of in a landfill.

Landfill gas evolves from the breakdown of biodegradable materials in a landfill. The composition of the gas varies according to the type and phase of breakdown which occurs within the site at specific time. Schumacher (1983) noted that after the refuse has been placed in the landfill, aerobic decomposition of the organic waste begins and a small amount of greenhouse gas, i.e. CO_2, is produced. Once the oxygen has been depleted, the anaerobic microorganisms become dominant and produce the greenhouse gases in landfill sites. In particular, anaerobic decomposition is a two-stage process as shown in Figure 2.2. In the first stage, complex organics are converted by a group of facultative and anaerobic bacteria commonly termed the "acid formers" into organic fatty acids. In this stage, there is no methane production as the organic matter is mostly depleted by acid-forming bacteria as an energy source, and thereafter the organic matter is placed in a form suitable for the second stage of decomposition.

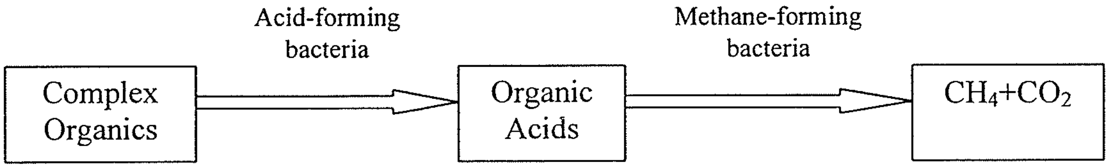

Figure 2.2 Two stages of anaerobic decomposition of complex organic waste (Emcon Associates, 1980)

During the second stage of methane fermentation, the organic acids are consumed by a special group of methanogenic bacteria and converted into methane and carbon dioxide (EMCON, 1980). It is believed that the anaerobic process in a typical landfill occurs between 180 and 500 days after landfilling, depending on the waste composition, moisture content, temperature, pH, nutrients and refuse density (Boyle, 1977). Figure 2.3 demonstrates a typical landfill gas composition.

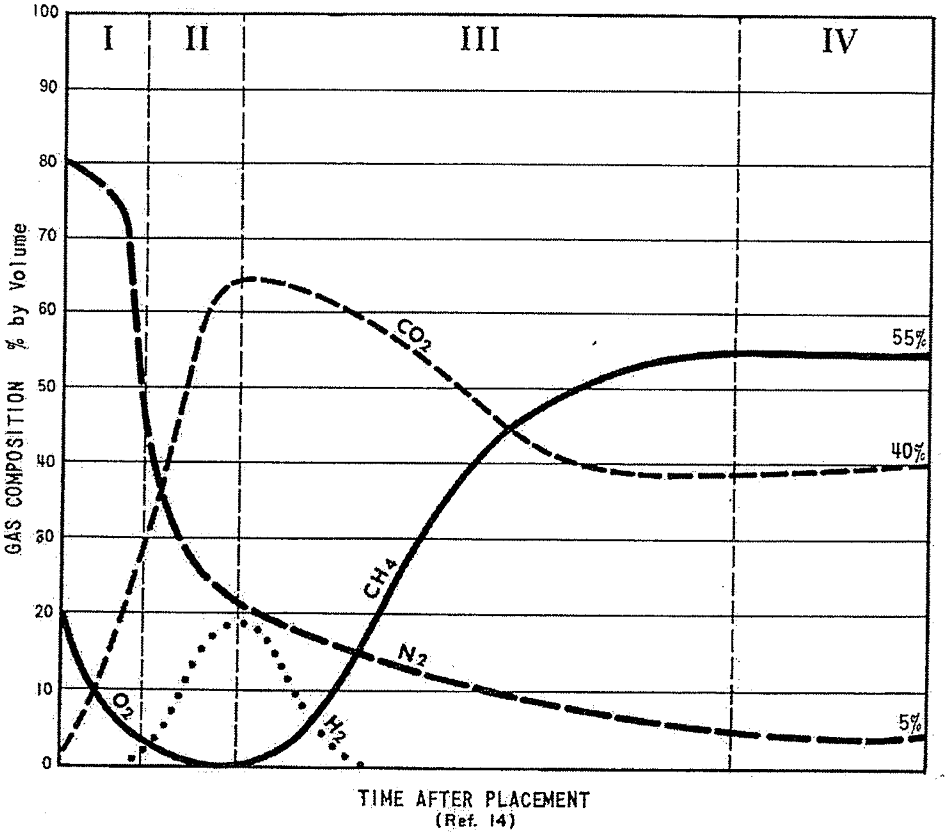

Figure 2.3 Landfill gas composition transition from the time of waste emplacement until stable methane generation (EMCON, 1980).

There are four metabolic stages that can be distinguished in the anaerobic solid waste fermentation as follows (Veeken et al., 2000):

1. Hydrolysis – complex insoluble organic material is solubilized by enzymes excreted by hydrolytic microorganisms.
2. Acidogenesis – soluble organic components including the products of hydrolysis are converted into organic acids, alcohols, hydrogen, and carbon dioxide.
3. Acetogenesis – the products of the acidogenesis are converted into acetic acid, hydrogen, and carbon dioxide.
4. Methanogenesis – methane is produced from acetic acid, hydrogen, and carbon dioxide as well as directly from other substrates of which formic acid and methanol are the most important.

In general, landfill gas composition depends on the composition of the waste, but it will generally contain almost 40-60% methane (CH_4), 40-50% carbon dioxide (CO_2), small amounts of 0.2-1% oxygen, 2-5% nitrogen, 0-1% hydrogen and other trace components such as hydrogen sulfide (0.0017-0.91%) and vinyl chloride (< 0.0001%) (Senior, 1990). Table 2.3 shows the typical landfill gas composition and characteristics.

Table 2.3 Typical landfill gas composition and characteristics (Ham, 1979).

Component	*Component %* *(dry volume basis)*
Methane	47.5
Carbon Dioxide	47.0
Nitrogen	3.7
Oxygen	0.8
Paraffin Hydro carbons	0.1
Aromatic & Cyclic Hydrocarbons	0.2
Hydrogen	0.1
Hydrogen Sulfide	0.01
Carbon Monoxide	0.1
Trace compounds[1]	0.5
Characteristic	**Value**
Temperature (at source)	41°C
Specific Gravity	1.04

A large landfill may produce gas for a period in excess of 50 years and can result in a total yield of landfill gas in the range 0.06 m^3/kg up to 0.53 m^3/kg. Typically, the heating value of typical landfill gas is roughly 16.8 mega joule per cubic meter (450 BTU/ft^3) or approximately half the lower heating value of natural gas (David, 1997).

2.6 Factors Affecting Landfill Gas Generation

There are a number of factors affecting gas generation including: refuse deposits, pH, temperature, nutrients, moisture content, and site operational factors. These will be discussed in this section:

2.6.1 Refuse Deposits

Refuse high in organic matter, such as food waste, garden waste, and paper, will decompose more rapidly than inorganic materials such as demolition and construction rubble. In the United States, yard waste was reported to contribute methane gas up to 20% of the wastestream, while paper contribution ranges from 30% to 50% (Owens and

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[1] Trace compounds include sulfur dioxide, benzene, toluene, methylene chloride, perchlorethylene in concentration up to 50 ppm.

Chynoweth, 1992: U.S. Congress, 1989). Pacey (1986) reported that 60% or more of methane gas production derived from the biodegradation of paper waste components.

2.6.2 pH

Optimum pH values for anaerobic digestion range from 6.4 to 7.4. The pH values in landfills may be influenced by industrial waste discharges, alkalinity, and clear water infiltration (Boyle 1977). The average pH in a landfill does not drop below 6.2 when methane is produced (Rare Earth Research Conference, 1978).

2.6.3 Temperature

Temperature of the landfill will indicate which class of bacteria is functional. Mesophile bacteria grow best in the temperature range of 20 to 40°C, while thermophiles grow best above 45°C (Schumacher, 1983). EMCON Association (1980) reported that most landfills operate in the mesophilic range, which produces less methane gas than thermophilic digestion.

2.6.4 Nutrients

Sufficient nutrients are required for the growth of bacteria in the landfill. These primarily are carbon, hydrogen, oxygen, nitrogen, and phosphorus (EMCON Association, 1980).

2.6.5 Moisture Content

Rate of methane production increases with higher moisture content. The optimum moisture content should be approximately 40 to 45% (wet weight) for the maximum gas production (Pacey, 1986). Studies have shown, in addition, that gas production can increase after a heavy rainfall as recorded high moisture content as 80% (EMCON Association, 1980).

2.6.6 Site Operational and Characteristic Factors

Gas production increases with the reduction in particle size and the resultant increase in surface area. Pacey (1986) suggested that reduced particle size will expose a greater surface area of refuse to the key parameters: moisture, nutrients and bacteria. In addition, Gas production increases with the increment of refuse thickness. The designed refuse height of 40 metres (or more) is the standard landfill designed structure for landfill gas recovery.

2.7 Enhancement of Gas Production

Gas enhancement is a method to provide the optimal environment in the landfill for anaerobic digestion. Numerous experiments, including both laboratory-scale and field-scale studies, have been conducted, including changing the composition mix of the refuse by increasing the organic content and limiting the presence of toxic substances. According to Croft (1990), organic content can be enhanced by the addition of sewage sludge; manure or agricultural wastes; removal of ferrous and nonferrous metals; separation of heavy and light material; and use of less daily and intermediate cover soil. The toxic substances can be avoided by pre-screening types and amounts of wastes admitted to the landfill.

To prevent ambient air intrusion from the excessive gas extraction, the surface and perimeter of the landfill may be sealed with clays, synthetic materials, or paving. Refuse moisture content can be increased by the addition of waste or leachate recirculation (EMCON Association, 1980). Leachate recirculation favours methanogenic bacteria for the acceleration of waste stabilization and reintroduces nutrients and inoculums. In a recent study, utilization of buffer solutions, such as KOH and Na_2CO_3, together with leachate recirculation was formed to further enhance waste stabilization and prevents possible acid inhabitation (Erses and Onay, 2004). Environmental pH, alkalinity, and nutrient availability, in addition, can be improved by the addition of chemical during refuse placement.

2.8 Estimate of Landfill Gas Production Rate

The Scholl Canyon model (see below for equations and inputs) will be employed for the purpose of evaluating landfill gas production rates over time. This approach assumes that after a lag time of negligible duration, during which anaerobic conditions are established and the microbial biomass is built up and stabilized, the gas production rate is at its peak

(Schumacher, 1983). Therefore, the gas production rate is assumed to decrease as the organic fraction of the refuse diminishes. The equation governing the model is:

Equation (2.1)

$$dL/dt = KLo \sum_{i=1}^{n} r_i \, e_i^{-Ki\,ti}$$

where:

L is amount of gas left to generate per unit weight of refuse (ft^3/lb);

Lo is total volume of methane ultimately to be produced (ft^3/lb);

n is number of years considered;

t_i is time from placement year 2000 as i to (years);

K_i is greenhouse gas production constant applied to each year; and,

r_i is a ratio of the tonnage of all previous years accumulated to the landfill's maximum capacity of landfill[2].

Table 2.4 summarizes the default parameters.

Table 2.4 Input parameters used in landfill gas model (USEPA, 2001; Environment Canada, 1991).

K (year^{-1})				*Lo (m^3 CH$_4$/tonne)*				*Waste Tonnages (metric tonnes)*			
EC	High CAA	Low (wet) AP-42	Low (dry) AP-42	EC	High CAA	Low(wet) AP-42	Low(dry) AP-42	1973 opens	2000	2025	2050
0.006	0.05	0.04	0.02	165	170	100	100	30000	375000	450000	450000

Note: CAA = Clean Air Act, AP-42 = Compilation of air pollution emission factors, Volume II: mobile source, EC = Environment Canada

It should be noted that the United States Environmental Protection Agency (USEPA) default parameters provide the upper boundary of what is considered typical and the Environment Canada (EC) default parameters provide the lower boundary, including a specific value for use with Manitoba landfills. However, site specific inputs were

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[2] The expected total site capacity was estimated at about 50 million tonnes of total waste. A fraction of total landfilled refuse (r_i) was obtained from the amount of refuse deposit each year between 1973 and 2000 divided by the expected site capacity of 50 million tones (i.e. $r_{(1973)}$ 30,000/50,000,000).

employed to estimate the actual K (decay constant rate) and Lo (methane generation potential). IPCC (1996) indicated that a variation of Lo is between 100 to 200 m^3 of CH_4 per tonne of waste, while a variation of K is between 0.03 (half-life of 23 years, dry condition) to 0.2 (half-life of 3 years, high temperature and a humidity condition). These values are based mainly on European waste.

2.9 Effect of Organic Waste Diversion on Landfill Gas Utilization

Public interest in minimizing wasting resources in a landfill is growing rapidly. As a result there is currently a strong focus on consideration of waste management activities and technologies that avoid or reduce the quantity of waste that is ultimately landfilled. For several years, communities across Canada have been actively involved in waste reduction and recycling programs to assist with meeting this objective. Recently, there has been an increasing diversion of organic materials, such as food and yard wastes, across Canada. This will significantly reduce the amount of methane generation, particularly if government and community support result in significant diversion rates (Earth Tech Canada Inc., 2001). Although waste diversion programs, such as bluebox recycling for paper and cardboard, are in place, significant amount of paper waste enters the landfill as shown in the decline recovery rate in 2000 (34%), 1998 (41%), and 1996 (42%) (Earthbound Environmental Inc., 2000). Tanapat et al. (2003) estimated that even if the waste diversion is as high as 50% or 75%, methane generation is sufficient to warrant landfill gas recovery from Brady Road landfill.

2.10 Gas Quality and Uses

In the typical landfill producing gas containing 50 to 55% methane and 45 to 50% carbon dioxide the energy value is 500-550 British Thermal Unit (BTU) per standard cubic foot (SCF) (Schumacher, 1983). Gas with this energy, called medium quality gas, can be used directly in boilers, space heaters, internal combustion engines, etc. Corrosion, pitting and excess wear of combustion chambers may result from the contaminants present in the gas. Wheless and Wiltsee (2001) revealed that siloxane (cosmetic by-products expected to be found in Brady Road landfill) can erode turbine nozzle vanes in microturbine and cause severe and expensive damages. Therefore, this compound has to be removed prior to the operation.

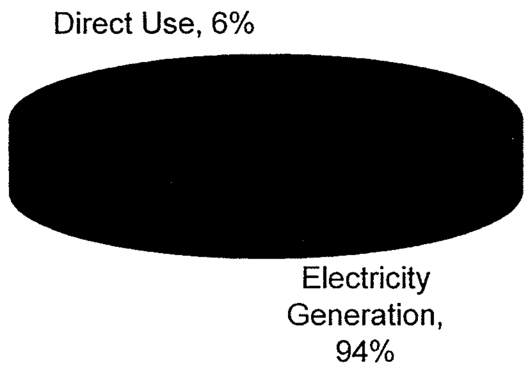
The gas can be treated to remove the impurities and be upgraded to 1,000 BTU/SCF. This gas is called pipeline quality gas. It may be injected into existing distribution systems, converted into fertilizer or liquefied. The need to upgrade landfill gas to pipeline quality heating value is necessary only when the customer does not accept a lower value gas into the pipeline system. About 1000 BTU/SCF is the maximum heating value achievable for processed landfill gas (Sawell et al., 1996). Some have allowed a 960 BTU/SCF heating value gas to be delivered into their pipeline systems. The energy options for landfill gas can be broadly classified into three main areas as shown in Table 2.5.

Table 2.5 Energy options for landfill gas (Sawell et al., 1996).

Low BTU Gas (<450 BTU/SCF)	**Medium BTU Gas (450-600 BTU/SCF)**	**High BTU GAS (960-1000 BTU/SCF)**	**Generation of Electricity**
The low BTU gas is viable for a few applications such as space and process heating applications, and as boiler fuel for production of steam for heating or electricity generation using stream turbine.	A processed, medium BTU is essentially landfill gas containing carbon dioxide as its major dilutant. The landfill gas has to be processed to meet sales-gas specification such as water and trace hydrocarbon contents.	High BTU gas is processed landfill gas with the majority of carbon dioxide removed. High BTU is usually sold to gas utility companies and is blended with their natural gas in pipeline transmission systems.	A processed medium BTU gas is used as the primary fuel for a returning gas engine or gas turbine driving an electrical power generator. This is the least thermally efficient of all landfill gas options.

Based on the 2001 analysis of utilization landfill methane in Canada (Environment Canada, 2001), approximately 94% of overall methane gas captured was utilized for electricity generation, while 6% was used for direct heating buildings (as shown in Figure 2.4).

Figure 2.4 Analysis of Utilized Landfill Methane in Canada



2.11 Landfill Gas Utilization Alternatives

In this section, the overview of current landfill gas conversion technologies is presented, including performance characteristics and associated initial capital cost.

2.11.1 Electrical Power Generation

In general, electrical power generation is one of the most prevalent in North America. The normal plant sizes with gas engine are between 350 and 1200 kW power per engine. In larger plants, dual-fuel engines plant can be used, as combined heat and power. Compared with only power production, dual-fuel engines create more efficient system for utilizing the energy from landfills. The energy flows of dual-fuel engines can make up about 3% power output and 53% heat output, which has only a 12% energy loss.

In general, there are two common types of engines for electrical generation project (between 500 Kilo Watts (kW) and 50 Mega Watts (MW) of power plants), internal combustion reciprocating engines (ICRE) and gas turbines. Table 2.6 shows the performance characteristics and associated capital costs of ICRE and gas turbine.

Table 2.6 Performance characteristics of ICRE and gas turbine (SCS, 1997).

Type	**ICRE**	**Gas turbine**
Engines/Generator Reference	Caterpillar 3516 SITA and Waukesha 7100GL	Centaur and Solar turbine
Efficiency (%)	33	28
Engine Capability (MW)	1-3	3-10
Heating Rate (BTU/kWh)	10,400	12,200
Electrical Generating Capacity (kW)	1,000 to 3,000	≥3,000
Estimated Initial Capital Cost (based on USD value in 1997)	1000 kW Plant ~ \$1.2 M 3000 kW Plant ~ \$3.45 M	1000 kW unit ~ \$1.5 M 3000 kW unit ~ \$4.54 M

In addition, microturbines are relatively new to the landfill gas operations, but these small turbine sets are the new economic opportunities for small landfill owners, especially a young or closed landfill with low landfill gas generation rates. Moreover, the microturbines can be used to provide both onsite power needs and power to electrical grids. They also can be equipped with options that allow the user to recover waste heat as heating water, greenhouses, or office space (EMCON, 2004). The capacity size of the microturbines ranges between 25 to 250 kilowatts costing between \$35,500 to \$250,000, based on 2004 USD value (Global Microturbine, 2004). The high cost associated with the contaminant removals (i.e. siloxane) from the landfill gas is an important issue that makes this technology less interesting.

In Canada, price of electricity varies from province to province. The estimated Manitoba's electrical price is currently at 3.0 cents/kWh (Environment Canada, 1999). Moreover, Manitoba has a surplus of electrical power with a continuation of its surplus in the foreseeable future. Utilizing landfill gas to generate electricity, as a business-as-usual scenario, may not be economically viable for this province.

2.11.2 Boiler and Direct Combustions

Landfill gas may be used directly as an energy source as heating fuel for industrial boilers, dryers, kilns or gas furnaces. The ideal end users should be located close to the landfill (less than 10 kilometres) (Environment Canada, 2001). In general, the pipeline length ranges from 0.6 to 5 kilometres, but less than 3 kilometres is the most feasible for utilization. In Canada, there are six landfill projects for direct use of landfill gas, such as West Edmonton, Vancouver, Glenridge, Mohawk, St-Etienne-Des-Gres, and Spadina landfills. These projects have the average distance-to-site end-user of less than 3 kilometres (Environment Canada, 1999).

The capital cost ($800,000 to $1,200,000 based on USD value in 1998) of direct-use of landfill gas includes the cost of the landfill gas collection system, landfill gas treatment, landfill gas compressor, burner conversion, and transmission pipeline (Reinhart, 1994). This estimate considers the amount of landfill gas generation and the end user's energy demand. Moreover, additional cost consideration includes the pipeline distance, and the gas quality and quantity. The ideal situation would be a user located within a 3 kilometre radius of the landfill, which could accept all of the gas generated on a continuous basis (Reinhart, 1994). According to Environment Canada (1991), the price paid for landfill gas by potential end-users in Manitoba is assumed to be 3.0 cents/m^3. It is less than the natural gas price due to the landfill gas's lower heat value and to provide additional saving incentives provided to the end-user.

2.11.2.1 Leachate Evaporation

Leachate evaporation is one of the most practical direct uses of landfill gas when off-site leachate disposal and treatment are present. Leachate evaporation would reduce the long-term costs of transportation of leachate and associated liability costs. The principle of the leachate evaporation system is the use of landfill gas collected at the site as an energy source to evaporate water and combust the organic compounds in the leachate (Roe et al., 1998). The common systems currently used are Technair and Vaporator systems, with the initial installation costs of approximately $300,000 to 500,000 USD (based on the USD value in 1998). Leachate evaporation also can be collaborated with other landfill gas utilization programs, such as direct combustions and fuel cells.

Leachate evaporator system (E-VAP) is a proven technology that provides integrated long-term control of regulated landfill by-products in a reliable process. In the standard E-VAP system, volatile organic carbon and odorous compounds found within the leachate feed are stripped into the exhaust vapour of the evaporation process and thermally treated with an enclosed landfill gas flare (EMCON, 2004). Often, the air stream (or off-gas) is treated before it is emitted to the atmosphere, thereby reducing toxic emissions being emitted to the atmosphere. In particular, E-VAP process reduces more than 97% of the volume of typical leachate. Trace metals and salts remain with the residual that is continuously removed from the bottom of the E-VAP. This treated non-hazardous residue can be re-circulated to the landfill or solidified for landfill disposal. In the low fuel ratio E-VAP system, volatile organic carbon and other odorous compounds are removed from the leachate feed by an integrated pre-treatment system and thermally treated within the E-VAP burner. Clean exhaust from the low fuel ratio E-VAP is discharged directly to atmosphere (EMCON, 2004).

In 2003, the City of Winnipeg transported approximately 11,400 kilolitres of leachate from Brady Road landfill to the North End Water Pollution Control Centre (NEWPCC). The total cost of transportation, based on 2003 value, was approximately $58,000 CAD, excluding the operation cost. In addition, municipal wastewater treatment facilities like NEWPCC are not designed to remove the leachate contaminants (i.e. heavy metal). Many of these contaminants in leachate eventually end up in the biosolids, which are applied to agricultural land.

2.11.2.2 Landfill Gas as a Supply of Heat and CO_2 for Greenhouse

The exhaust gas from the boilers can be used as a fuel supply for heating a greenhouse. This principle of this process is to dilute the exhaust gas (CO_2) from the boilers and inject into greenhouse to enrich the CO_2 concentration for promoting plant growth. In particular, the exhaust gas normally contains approximately 99,000 ppm of CO_2. As only

1,000 ppm of CO_2 is required in the greenhouse, significant dilution of exhaust gas is necessary (Roe et al., 1998). The initial capital cost of this technology is unconfirmed.

2.11.3 Upgrading to Natural Gas Quality

Landfill gas can be upgraded into high quality gas (> 980 BTU/SFC) and injected into a natural gas pipeline. As compared with other power generation alternatives, the capital cost for sale of upgraded pipeline quality gas is high ($4,000,000 to $10,000,000 based on USD in 1994) (USEPA, 1998), because treatment systems that are used to remove CO_2 and impurities are required. Also, upgraded gas needs a significant amount of compression to conform to the pipelines pressure at the interconnect point (Reinhart, 1994). However, the benefit of pipeline quality gas technology is that all the gas produced can be utilized (Environment Canada, 1999). In the United States, there have been approximately 10 plants of this kind, however; only 5 of these continue to be in operation.

2.11.4 Vehicle Fuels

The technology for using compressed natural gas (CNG) as an alternative for motor vehicles has been demonstrated for many years, especially in Europe and South America. The reasons of the major constraints using CNG in motor vehicles are: 1) the driving range of vehicles is limited because of fuel storage capacity constraints; and 2) the availability of fuel dispensing facilities (Roe et al., 1998). These constraints are limited to only vehicles that return to the same location each day.

Processes of landfill gas to produce compressed landfill gas (CLG), equivalent to CNG, include extraction, purification, and compression. The special gas collection system, so-called cryogenic separation, is required to remove the ambient air to be drawn into the landfill (air intrusion) during landfill gas collection process. However, this process is very complex and expensive, in order to achieve a high efficiency gas collection system. The initial capital cost for compressed landfill gas production facility, based on the USD value in 1992, was estimated at $1,100,000 (USD) and estimated power usage was at 5.0 cents per kWh (Roe et al., 1998). Due to the expensive initial costs, as well as the operating and maintenance costs, this option is not profitable and attractive, compared to the other options, and requires a major incentive from government to subsidize the technology.

2.11.5 Fuel Cells

Fuel cells may be compared to large electrical batteries which convert the chemical bonding energy of a chemical substance directly into electricity. A simplified schematic of hydrogen-oxygen fuel cell is demonstrated in Figure 2.5.

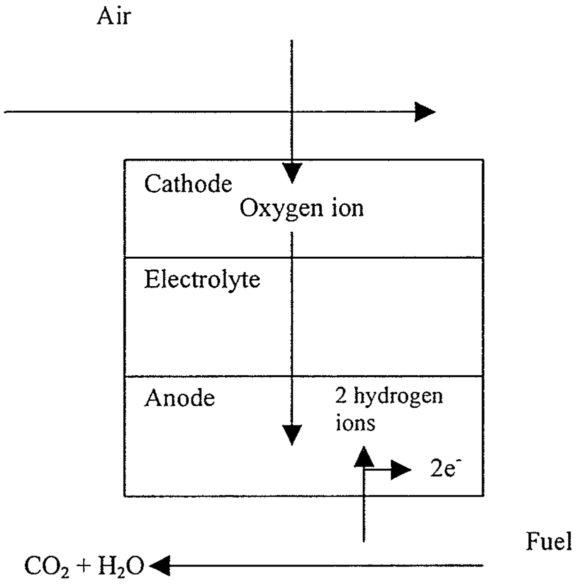


Figure 2.5 Simplified schematic of a hydrogen-oxygen fuel cell (Roe, et al., 1998).

In a fuel cell, fresh reactants (fuel) are continuously supplied to the cell. Oxygen ions (from air) pass from the cathode, through an electrolyte (which allows passage of oxygen ions but not electrons), and combine with hydrogen ions and carbon at the anode (derived from a hydrogen-rich fuel) to form water (as stream) and CO_2 (Roe et al., 1998). Currently, phosphoric acid fuel cell (PAFC) is one of the technologies with the most potential available in the market. Commercial PAFC uses hydrogen gas or reformed methanol as its fuel sources to produce electricity. The hydrogen gas may be bought in purified form for small scale applications, or it may be obtained via conversion from a hydrogen containing fuel, such as natural gas, landfill gas, or alcohols (Roe et al., 1998). Yet, PAFC has not been demonstrated on landfill gas.

Expected electrical conversion efficiency of a fuel cell is between 50 to 60%, which is much higher than the traditional power generation technologies. Estimated initial capital costs based on 2001 (USD) value were between $1,500,000 to 3,500,000 (USEPA, 2001).

2.11.6 By-product Carbon Dioxide Utilization

Apart from methane utilization, the by-product of carbon dioxide from biogas separation could be utilized in many ways, such as a carbon source for methanol synthesis and trace contaminant removals. The key process of the proposed technology is to convert raw landfill gas to a high pressure mixture of contaminant-free methane and carbon dioxide to produce methanol synthesis feedstock. The absorber temperature and pressure are selected to provide a product gas containing methane and carbon dioxide in the desired ratio (2.3 CH_4 per CO_2) for reforming to methanol synthesis gas. In turn, the contaminant-free methane-carbon dioxide recovered from landfill gas is produced as feedstock for methanol synthesis (Cook et al., 1997). In separate processing, liquid carbon dioxide is produced by a fluid continuously condensed directly from landfill gas. However, a pilot scale synthesis of liquid carbon dioxide to absorb landfill gas contaminants is underdeveloped and some results are unconfirmed.

2.11.7 Aerobic and Anaerobic Bioreactor

Bioreactor landfills are a new sustainable alternative to promote waste decomposition. The US Environmental Protection Agency defines a bioreactor landfill as a cell where liquid or air, in addition to landfill leachate and gas condensate, is added in a controlled fashion into waste mass in order to increase the stabilization of the waste (Powell, 2004; US EPA, 2000). Other strategies of this approach include waste shredding, pH adjustment, nutrient addition, waste pre-disposal and post-disposal conditioning, and temperature management (County of Yolo, 1996). The aerobic bioreactor approach, large expenses for air injection blower and its operation are necessary. An aerobic bioreactor, however, may have the advantage of reducing the need for a gas collection system or flare in comparison to anaerobic approach. An economic analysis may be required to evaluate the most favourable option towards an individual landfill site. The initial capital cost of construction for an anaerobic bioreactor was estimated to be between $100,000 and $400,000 USD per acre, based on USD value in 1996, while a corresponding aerobic bioreactor was more at between 500,000 to 700,000 USD per acre (County of Yolo, 1996).

2.12 Analytical Methodologies

A sampling program in this study will be conducted to identify and quantify the constituents in the landfill site. Conventional gas chromatography techniques will be utilized for the landfill gas analysis.

2.12.1 Gas Chromatography Analysis

Gas chromatography (GC) is a highly versatile instrumental method of analysis which was first developed in 1951. Furthermore, Gibson (1984) concluded that GC is a routine separation technique with a large variety of instrumentation available commercially. GC technologies include Flame Ionization Detector (gas composition analysis) and Mass Spectrometry (siloxane analysis).

2.12.1.1 GC – Flame Ionization Detector (FID)

GC – Flame Ionization Detector (FID) is a common method for detecting organic constituents in the effluent from a gas chromatography column (Sawyer et al., 1994 Tanapat, 2001). According to Poole and Poole (1991), FID responds to the presence of nearly all organic compounds in gas chromatography effluent and is considered to be a general detector.

Sawyer et al. (1994) explained the principle of GC-FID as follows. Organic compounds yield ions and electrons when burned in a flame. This principle can be applied by measuring the current by charged particles (ions) when a potential of a few hundred volts is applied across the burner. A collector electrode is eluted from the chromatographic column and burned. Very small concentrations of methane (mg/l) can be measured by using this detector (Distler, 1991).

2.12.1.2 GC – Mass Spectrometry (MS)

MS is a powerful method for studying a sample at the molecular level. It can be applied to detect very low levels of specific compounds and elements, such as siloxanes. Moreover, it can provide the determination of masses with its high sensitivity and accuracy and provide more specific information per given amount of material than any other analytical technique (Encyclopaedia of Physical Science and Technology, 1987; Tanapat, 2001).

A GC – mass spectrometer is an instrument that will separate charged gas molecules or ions. The analyzed substance is vaporized and converted to positive ions by bombardment with rapidly moving electrons. The ions formed are pulled from the gas stream by an electrical field. These ions are accelerated depending on the type of instrument and are separated by their mass-to-charge ratio (Sawyer et al., 1994).

2.13 Site Description – Brady Road Landfill

Winnipeg's Brady Road landfill is selected for this case study as it is Canada's largest and most cost-effective remaining site for capturing methane (Province of Manitoba Climate Change Action Plan, 2002). The Brady Road landfill is located 3 kilometres south of the Perimeter Highway, Southwest of Winnipeg. The radius from nearby households is approximately 5 kilometres. The landfill is a municipal solid waste landfill and is owned and operated by the City of Winnipeg. It has operated since 1973 and currently holds approximately 5 million metric tonnes of waste under class 1 (i.e. domestic refuse, commercial and industrial refuse) waste disposal grounds facility (City of Winnipeg, Water and Waste Department, 2001). The current filling rate is at 500,000 tonnes per year. At this rate, the Brady Road landfill is expected to remain open until 2150. There are two active dumping areas in the landfill, one for commercial waste and the other for residential.

The total available capacity of the landfill is approximately 8 km^2. The landfill serves over 650,000 residents and associated businesses in the nearby area. The average thickness of refuse is approximately 6 meters deep (City of Winnipeg, Water and Waste Department, 2001). Maximum refuse density is approximately 700 kg/m^3. Based on the waste composition study in 2000, organic materials make up more than 50% of overall wastestream with compostable food waste accounting for 20%, while yard waste and paper waste account for 17% and 18% respectively. The estimated per capita weighted average waste generation rate for the City of Winnipeg in 2000 was 252 kg/capita/year.

In addition, leachate from landfills in Winnipeg is removed and transported to the North End Pollution Control Centre (NEWPCC) by truck. Leachate volumes from Brady Road landfill have significantly decreased from 5900 m^3 in 1997 to 1840 m^3 in 2000. This is due to a smaller amount of precipitation in Manitoba between 1997 and 2000 (Hombach, 2002).

2.14 Summary

Landfills are the major source of greenhouse gas emissions currently fuelling climate change. Landfill gas, which consists mainly of potent greenhouse gas methane, is produced from the anaerobic process of organic materials, such as food waste and yard waste, in the landfill. Without recovery, landfill gas can create fire and explosion risks to the nearby areas and liability for the landfill owners. Landfill gas utilization, therefore, is a win-win solution as it creates new sources of energy and revenue while diminishing greenhouse gas emissions. At present, Brady Road landfill is operating without composting (except yard waste composting), flaring of methane or landfill gas captured. Moreover, Brady Road landfill is the largest single point source of greenhouse gas emissions in Manitoba, based on the site capacity. This calls for the Provincial Government and Municipalities to take serious action at Brady Road landfill to reduce the greenhouse gas emissions.

Currently, the Scholl Canyon model is widely used in many counties to evaluate landfill gas production. In this model, several default values have been introduced, by US EPA and Environment Canada, for the initial landfill gas utilization assessment, but site-specific values are the most accurate for landfill gas generation estimate. In addition, prediction of landfill gas generation potential has brought up political and economic concerns due to government, greenhouse gas credits and incentive of landfill gas utilization. Innovative regulations and positive findings could also support the decision-making course of action.

Several landfill gas conversion technologies (as shown in Table 2.7) offer the beneficial landfill gas utilization practices for Brady Road landfill. However, advanced technologies (i.e. fuel cell, vehicle fuel) have high capital costs. It may be wise to allow these innovative technologies to develop further prior to implementation.

Table 2.7 A summary of current landfill gas-to-energy technologies

Landfill gas technology	**Efficiency (%)**	**Estimated Capital cost (million in USD)**	**Specification**
Electrical Power	ICRE = 33 Gas Turbine = 28 Microturbine = 27	\$1.2 to \$4.5 (ICRE and Gas turbine) \$1.3 (microturbine)	Average electrical potential for ICRE and gas turbine between 500 kW to 50 mW; Microturbine between 25 to 250 kW
Boiler and direct combustions	30 to 35	\$0.8 to \$1.2	End user of 3 kilometres (or less) is the most feasible
Leachate evaporation	25 to 30 (OWT)	\$0.3 to \$0.5	97% volume of leachate removal; off-gas treatment is required.
Natural gas	N/A	\$4.0 to \$ 10.0	Upgrading to high quality gas > 980 BTU/SFC
Vehicle fuels	N/A	\$1.1 to \$8.0	Popular fuel technology is compressed landfill gas (CLG)
Fuel cells	50 to 60	\$1.5 to \$3.5	Popular technology is phosphoric acid fuel cells (PAFC)
By-product CO_2	N/A	N/A	Liquid CO_2 is used to absorb landfill gas contaminants
Aerobic and Anaerobic bioreactors	N/A	\$ 0.1 to \$0.4 (anaerobic) \$ 0.5 to \$0.7 (aerobic)	Additional cost of air blowers is applied to aerobic bioreactor

Note: OWT = Organic Waste Technology Inc.; N/A = not available. Source: County of Yolo (1996); EMCON (2004); Reinhart (1994); Roe et al. (1998); SCS (1997); USEPA (1998); and USEPA (1998).

Chapter 3 provides an overview of site-specific monitoring study to evaluate quality of landfill gas production as well as to estimate landfill gas generation by using site-specific information.

CHAPTER 3
MATERIALS AND METHODS

The purpose of this chapter is to provide specific information on the materials and methods used in this study. This methodology section is divided into two parts, consisting of the methods describing: 1) site-specific landfill gas monitoring; and 2) estimation of landfill gas generation using site-specific information.

3.0 Area of Study

The preliminary survey was conducted in May 2003 for the initial investigation prior to landfill gas quality testing. The actual study area was located near the leachate collection manhole #31 and #32 (see Figure 3.1) on Charrette Road which is about one kilometre west of the main entrance. This area was selected for the following reasons: 1) it has the most active sites for gas generation; 2) the site is representative of the landfill surface area geography throughout Brady Road landfill; 3) the waste contained at this location is all two-years-old waste; and 4) there is no nearby operation occurring at that location that might impede the routine sampling.

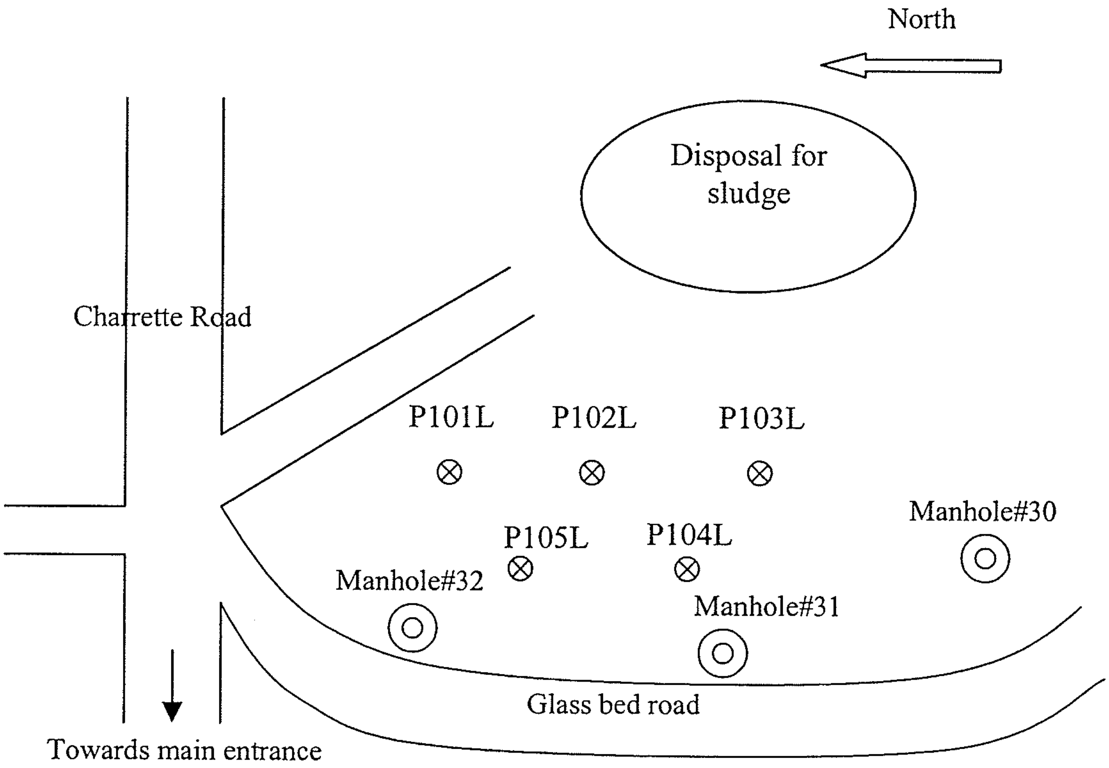


Figure 3.1 Location of the five sampling probes at Brady Road landfill in the study area.

3.1 Gas Monitoring Probe Installation

On June 20th, 2003, five (approximately 12 meters deep by two-inch-diameter) sampling probes were installed for landfill gas quality monitoring (see Figure 3.2). To capture the methane from the cell the probe's polyvinyl chloride (PVC) pipe was perforated for two meters at the bottom end and capped. The pipe was perforated to allow the air in and to avoid excessive pressure which could unduly weaken the pipe.

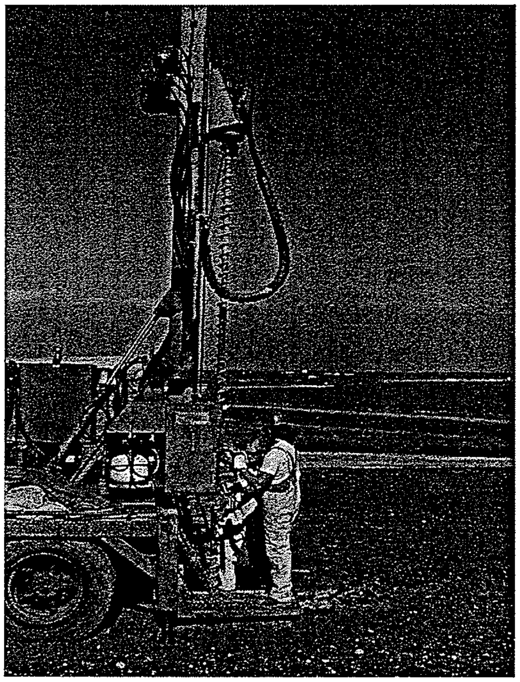


Figure 3.2 Gas monitoring probe installation on June 20th, 2003 at Brady Road landfill

3.2 Materials

3.2.1 Field Equipments

Figure 3.3 shows the gas monitoring probe configuration.

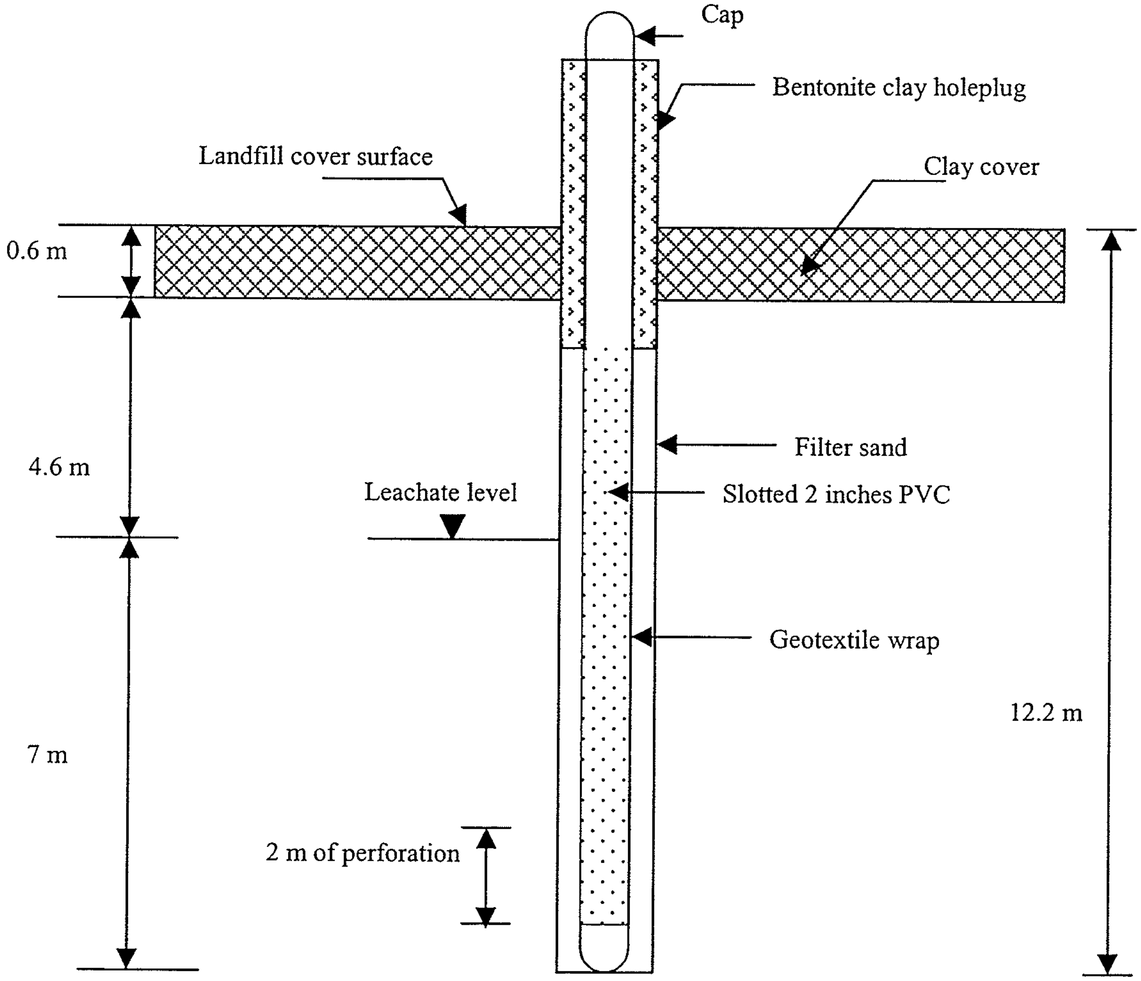


Figure 3.3 Schematic of gas sampling probe for determination of landfill gases at Brady Road landfill.

A Polyvinyl Chloride, three metres long and two inches in diameter, (PVC) pipe with perforation along its bottom for two metres was installed to monitor landfill gas (see Figure 3.3). The sample probe was capped at the bottom end and had a sampling port attachment at the top. To allow for sampling, each probe was capped with a plastic fitting that allowed for a tight seal over the probe and accessed for sample lines such as a vacuum pump and gas detector tube. The sampling probe went through the refuse to approximately 12.2 meters deep and extended the slot from the same probe down to the leachate level for the leachate collection. A sample of landfill gas was extracted with an evacuated cylinder.

3.2.2 Gas Sampling Equipments

Rubber stoppers and 30 millilitres of hypodermic glass and plastic syringes were purchased from Sigma-Aldrich Chemical Company (Milwaukee, WI). An air sampling pump equipped with filter connector was purchased from Cole-Parmer (Ontario, Canada). This equipment was used in landfill gas sampling.

For the relative humidity and temperature measurements, a portable thermalhygrometer was obtained from Hanna Instrument (Woonsocket, RI). The barometer was obtained from Thomas Scientific (Swedesboro, NJ). The manometer, pressure level, was obtained by the City of Winnipeg (Figure 3.4) using a handmade device capable of measuring from -6 to +6 kPa. These equipments were used to assess the physical characteristics of site-specific location.

Vinyl chloride detector tubes in the range of 0.1-3.0 ppm (tube number 132SC) and hydrogen sulphide detector tubes in the range of 0.05-1.2 % by volume (tube number 120SM) shown in Figure 3.5 were obtained from Sensidyne Inc. (Clearwater, FL). Gas detection pump (model AP-20S) was also obtained from Sensidyne Inc. (Clearwater, FL). Carbotrap tubes for siloxane analysis were obtained from EnviroTest Laboratory (Edmonton, Canada). The samples were sent to EnviroTest Laboratory for analysis by gas chromatography in the part per million (ppm) ranges. These supplies and equipment were used to analyze the trace compositions.

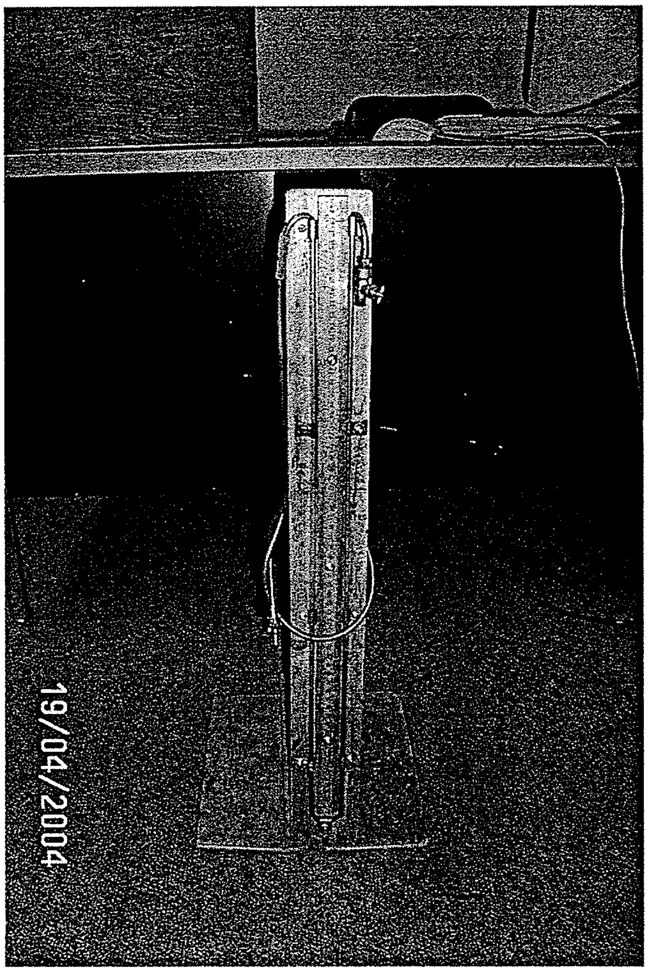


Figure 3.4 Pressure level used to measure the headspace pressure.

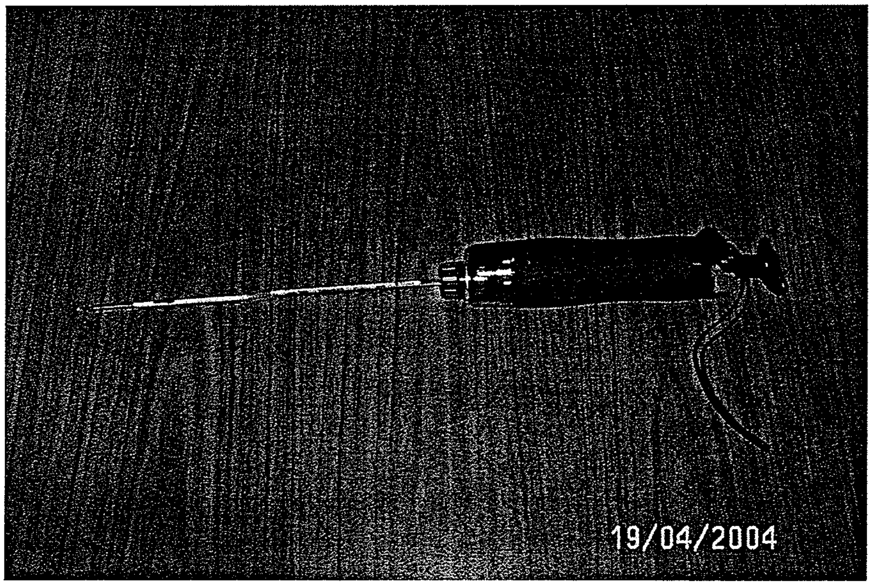


Figure 3.5 Trace contamination analyses: gas detection tubes and gas detection pump.

3.3 Experimental Methodology

3.3.1 Experimental Plan

In the preliminary test, 15 air samples were collected each week for eight weeks from July 2003 to August, 2003 to evaluate the gas production potential and to observe the consistency of gas compositions. The appropriate sampling program, thereafter, was collected at least once a month throughout the rest of experiment. Meteorological monitoring was also conducted to record temperature, moisture content, and barometric pressure throughout the sampling program. A total of 12 months of sampling program were conducted in this study, which included 20 different sampling periods.

Fifteen air samples were collected by both plastic and glass syringes by taking triplicates for quality control at each probe location. Triplicate samples were collected in the detention times of 5, 10 and 15 minutes to monitor the stabilization of gas concentration over time. The samples were taken by means of a syringe through a rubber septum and transported at ambient temperature from the site to the City of Winnipeg's laboratory. To avoid possible contamination, all samples were analyzed within 24 hours.

Trace contaminant monitoring of vinyl chloride (measuring range of 0.4-12.0 ppm) and hydrogen sulfide (measuring range of 0.05-0.6%) was conducted periodically by using the gas detection tubes. Five samples, one at each probe location, were drawn from the headspace through the gas detector tube for vinyl chloride and hydrogen sulfide testing. Vinyl chloride was selected as a representative of non-methane organic compounds. These compounds are toxic and corrosive to landfill gas-to-energy equipment. For siloxane monitoring, two landfill gas samples, one for each location at L103P and L104P, were collected on a Carbotrap tube (see Figure 3.6) at the sampling rate of 150-250 millilitre/minute for 1-5 minutes and transported to the EnviroTest laboratory for the specific analysis by GC/MS.

Figure 3.6 Siloxane sampling on April 22, 2004 at Brady Road landfill.

3.3.2 Gas Analytical Method

The determination of gas compositions (e.g. CH_4, CO_2, O_2, and N_2) were analyzed by gas chromatography with thermal conductivity detector GC/FID in the City of Winnipeg laboratory. A three-point calibration was made for pure methane gas before sample analysis, covering the range of 50, 60, and 70% methane content. At the same time, a three-point calibration of carbon dioxide was performed in a covering range of 30, 40, and 50% carbon dioxide. If samples are out of this range, additional calibration points were made as necessary.

Trace components, such as vinyl chloride, hydrogen sulfide and siloxanes, were analyzed by specific methods to determine toxic, corrosive and biological marker compounds as well as how these varied between different locations over time. In particular, the method of siloxanes analysis was analyzed by thermal desorption GC/MS. All mass spectra of the individual peaks in the chromatogram were identified to match the different siloxanes characteristic. Dimethyl siloxane was utilized as a standard in the appropriate range. The quantification would therefore be semi-quantitative calibrated against that single compound. Table 3.1 summarizes the sample collection and analysis methods used for determination of landfill gas production.

Table 3.1 Sample collection and analysis methods of determination of landfill gas.

Compound	*Collection & Analysis Method*	*Collection Media*	*Analytical Instrumentation*
CH_4, CO_2, N_2 & O_2	USEPA 3 (US EPA, 1998)	Syringe	GC/FID
Siloxanes	Semi-quantitative method	Carbotrap tube	Thermal desorption-GC/MS
H_2S & vinyl chloride	Calibrated direct reacting device	Gas detection pump	gas detection tubes
% moisture content	Calibrated direct reacting device	Not Applicable	Thermalhygrometer
Temperature	Calibrated direct reacting device	Not applicable	Thermalhygrometer
Pressure	Calibrated direct reacting device	Not applicable	Dial barometer

Note: GC/TCD = Gas Chromatograph/Thermal Conductivity Detector; GC/MS = Gas Chromatograph/ Mass Spectrometry

3.4 Estimate Methane Gas Generation Potential

The Scholl Canyon model was applied to estimate the energy potential of Brady Road landfill. This model is consistent with Environment Canada and IPCC climate change protocols for calculating greenhouse gas emissions inventories. Two steps were carried out to determine waste management options, that consisted of inputting: 1) field data to determine constants into Scholl Canyon model to determine gas generation under different waste management options for composting; and 2) accepted constants into model for comparison of results with field data.

To calculate landfill gas production, the different parameters were input into the model including greenhouse gas production constants from US EPA upper and lower limits for both wet and dry climates (US EPA, 2001); Environment Canada's parameters (Environment Canada, 1991); and Brady Road landfill site-specific parameters were applied. These compared the variation possible in landfill gas generation rates under two different waste management scenarios to investigate the impact of a composting program on gas generation.

3.4.1 Step 1: Site-Specific Inputs into Scholl Canyon Model

Although it is easy to input constants into this model in this step, it is much more demanding to input site and waste specific factors. Below the methane generation potential (Lo) was calculated by using % degradable organic compound and the decay rate constant (K) inputs to determine these site specific inputs.

3.4.1.1 Calculating Methane Generation Potential (Lo) of Brady Road Landfill

To determine the site-specific value of Lo the following equation was applied (IPCC, 1996):

Equation (3.1)

$$\text{Lo (m}^3\text{ of methane/tonne of Waste)}^{3} = \text{MCF x DOC x DOC}_F \text{ x } 16/12 \text{ x F}$$

where:

MCF = methane correction factor (1 = well managed landfill);

DOC = degradable organic carbon (fraction);

DOC_F = fraction DOC dissimilated; and

F = fraction of CH_4 in landfill gas (measurement at landfill has indicated a value of 56% CH_4 in biogas).

3.4.1.2 Determining Degradable Organic Carbon for Methane Generation Potential

The site-specific degradable organic carbon (DOC) is calculated based on IPCC (1996) formula:

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[3] Conversion factor: 1 (m^3/tonne) = 0.016 (ft^3/lb)

Equation (3.2)

$$\% \text{ DOC (by weight)} = 0.4(A) + 0.17(B) + 0.15(C) + 0.3(D)$$

where municipal solid waste consists of:

A = % paper and textiles;

B = % garden waste, park waste or other non-food organic putrescibles;

C = % food waste; and

D = % wood or straw.

The inputs, into degradable organic carbon (DOC) equation 3.2, from the Winnipeg waste stream are shown in Table 3.2.

Table 3.2 Percent Waste Streams in Municipal Solid Waste (MSW) in Winnipeg Waste (Earthbound Environmental, 2000)

Waste Stream	% MSW (by weight)
A: Paper and textiles	31
B: Garden and park wastes	6.6
C: Food waste	26.1
D: Wood and straw waste	2.3
% DOC (by weight)[4]	18.1

According to equation (3.2), DOC content value of 18.1% was obtained based on the composition of waste, calculated from a weighted average of the carbon content of various components of the waste stream as shown in Table 3.2. The biodegradable fraction was calculated by using equation (3.3) that considers the state of decomposition. The average volatile lignin content of 44.1% was employed in equation (3.3); this yields a figure of 0.82 dissimilated DOC.

DOC_F can be determined through the lignin content of the volatile solid (VS) (Tchobanoglous et al., 1993, pp. 88)

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[4] % DOC = (0.4x31%) + (0.7x6.6%) + (0.15x26.1%) + (0.3x2.3%) = 18.1%

Equation (3.3)

$$DOC_F = 0.83 - 0.028\ LC$$

0.83 = empirical constant;

0.028 = empirical constant; and

LC = lignin content of the VS expressed as a percent of dry weight from leachate sample.

Table 3.3 summarizes the results for the determination of methane gas potential (Lo)

Table 3.3 Input parameters used in landfill gas model

Category	**Inputs Parameters**				**Lo** (m^3 of methane/tonne of waste)
	MCF	DOC (%)	DOC_F	F (%)	
Result	1	0.18	0.82	0.56	111 ± 2.65

Using the equation (3.1) and data profiled in Table 3.3, the measured methane potential of 111±2.65 m^3 of CH_4 per tonne of waste (1.78 ft^3/lb) was obtained. This value is closest to the value (117 m^3 CH_4/tonne of waste or 1.87 ft^3/lb) recommended by Environment Canada, while it is different from the US EPA value (170 kg CH_4/tonne of waste or 2.72 ft^3/lb).

3.4.1.3 Determining Decay Rate Constant of Brady Road Landfill

The average of Environment Canada data (K=0.01) across Canada was chosen as the rate constant, rather than the value for Manitoba (K=0.006), which may reflect the smaller landfills in rural Manitoba but is inappropriately low for Winnipeg as Brady Road Landfill is the largest landfill size in the region (8 km^2) and is at the southern tip of the province. The organic waste in Brady Road landfill contains primarily food waste and yard waste, which decompose fairly rapidly. Methane generation from sampling data is not impacted by Winnipeg's extreme climate, which has temperatures dipping below 20 degrees in the winter, as the waste is covered in large cells that are 10 metres deep, which generate their own heat underground without impact by outside temperatures. In addition, the high humidity condition observed from sampling data at Brady Road landfill would be favourable to biodegradation kinetics. Although the limiting factors may be the relatively dry climate, as Winnipeg receives less than 635 millimetres (25 inches) precipitation in a year (Winnipeg Weather, 2003), this high humidity indicates the opposite. Also, the spring snow-melt, which resulted in landfill gas temperature drop for at least a week, reduced biodegradation kinetics for that period.

3.4.1.4 Step 2: Inputting Accepted Gas Constants

To contrast site specific constants for Lo and K with accepted constants, different parameters were input into the model. These parameters were compared to greenhouse gas production constants from US EPA upper and lower limits for both wet and dry climates (US EPA, 2001); Environment Canada's parameters (Environment Canada, 1991); and Brady Road Landfill's parameters. These constants allow comparisons to be made across the variation possible in landfill gas generation rates. Two different waste management scenarios are considered to add further variety. Table 3.4 summarizes the input parameters.

Table 3.4 Input parameters used in landfill gas model

Source	**Lo** (ft^3/lb)	**Lo** ($m^3/tonne$)	**K** ($year^{-1}$)
Brady Road	1.78	111	0.01
US EPA default Values (US EPA, 2001)			
CAA	2.72	170	0.05
AP-42 (wet)	1.6	100	0.04
AP-42 (dry)	1.6	100	0.02
Environment Canada default Values (Environment Canada, 1991)			
EC	1.87	117	0.006

Note: CAA (2001) = Clean Air Act, AP-42 (2001) = Compilation of air pollution emission factors, Volume II, EC (1991) = Environment Canada

IPCC (1996) default values for Lo are between 1.6 and 3.2 ft^3/lb (100-200 $m^3/tonne$), while K is between 0.03 and 0.2.

3.5 Estimating Greenhouse Gas Emission Reductions

According to Environment Canada (1991), greenhouse gas emission reduction can be calculated, in CO_2 equivalent (eCO_2), as

Equation (3.4)

$$r = 21\ \rho_s\, c\ V$$

r = greenhouse gas emission reduction (kg of eCO_2/year)
V = total volume of landfill gas in m^3/year[5]
ρ_s = density of methane in kg/m^3 ($\rho_s = 0.6557\ kg/m^3$)
c = average concentration of methane in landfill gas in % ($c_{Brady} = 56\%$)

In addition, r is multiplied by the destruction efficiency (in percent) to obtain the actual reductions. In this study, 75% collection system efficiency is employed based on the recommended value by Environment Canada (1999).

Chapter 4 presents the results and discussions of this research to determine chemical and physical characteristic of landfill gas production, as well as determination of landfill gas generation potential at Brady Road landfill associated with different waste management options.

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[5] V (m^3/year) = landfill gas flow (SCFM) x 0.02832 m^3/ft^3 x 525,600

CHAPTER 4

BRADY ROAD LANDFILL SITUATION

The gas compositions across the five gas monitoring probes remained relatively constant throughout the investigation. Results of this twelve-month field monitoring are presented and discussed in this chapter. Trace compositions at Brady Road landfill may require in a possible trace compound removal to meet the standards for gas utilization requirement. Results of estimating landfill gas generation potential associated with the site specific inputs are discussed as well as the effect of waste diversions. Several aspects of landfill gas utilization potentials are also discussed in this chapter.

4.0 Gas Composition Results

Triplicate gas samples taken from each gas monitoring probe showed that composition was consistent over a year as illustrated in Figure 4.1. Results of the 12 months of landfill gas compositions and metrological monitoring are compiled in Appendix A. The average gas chemical composition of methane and carbon dioxide were 56.04% ± 2.63% and 39.16% ± 3.09% by volume, while the corresponding values of nitrogen and oxygen were 2.95% ± 2.77% and 0.99% ± 0.71% by volume, respectively.

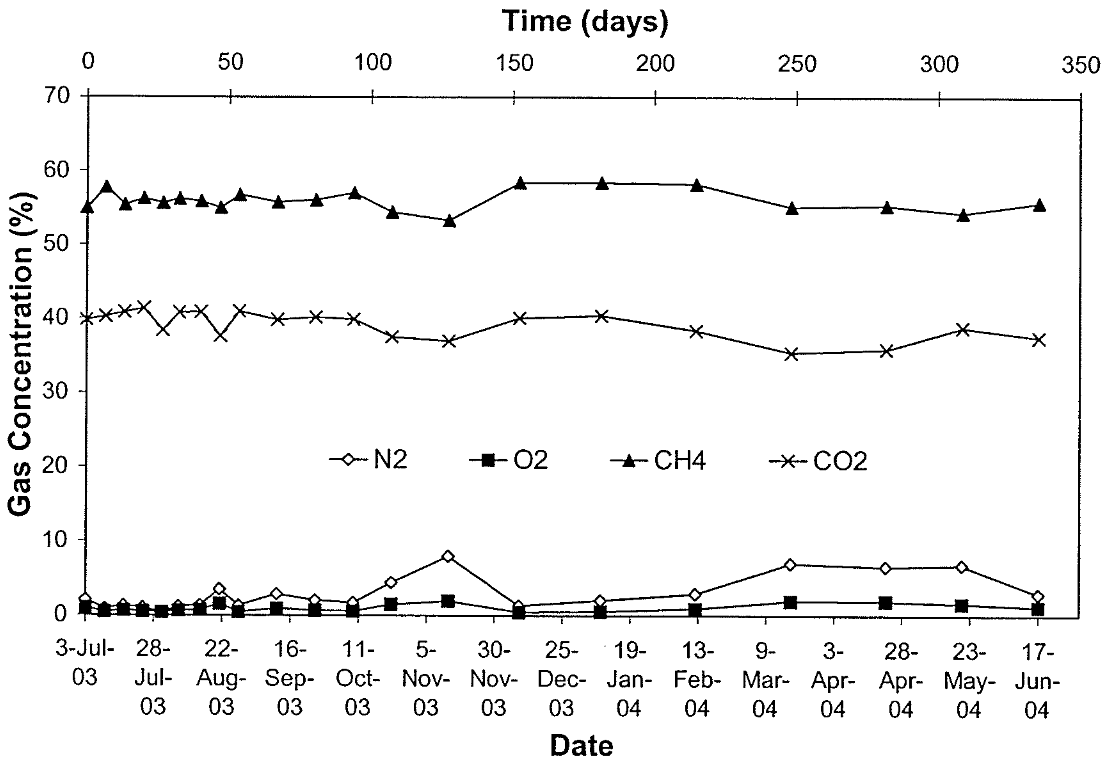


Figure 4.1 Results of average gas concentration at Brady Road landfill.

The findings of high and stable concentrations of methane and carbon dioxide at Brady Road landfill reflect the decomposition stage of the waste, at the sampling locations, being two years old and in its stable fermentation stage of anaerobic decomposition. This productive fermentation stage occurs over the initial five to ten years of waste decomposition, depending on the landfill size and environment. A minute concentration of oxygen and nitrogen was found, which demonstrates the validity of the sampling and testing process, being uncontaminated by outside air.

4.1 Physical Components Results

4.1.1 Atmospheric Pressure and Temperature

Seasonal changes in atmospheric pressure and temperature are shown in Figure 4.2

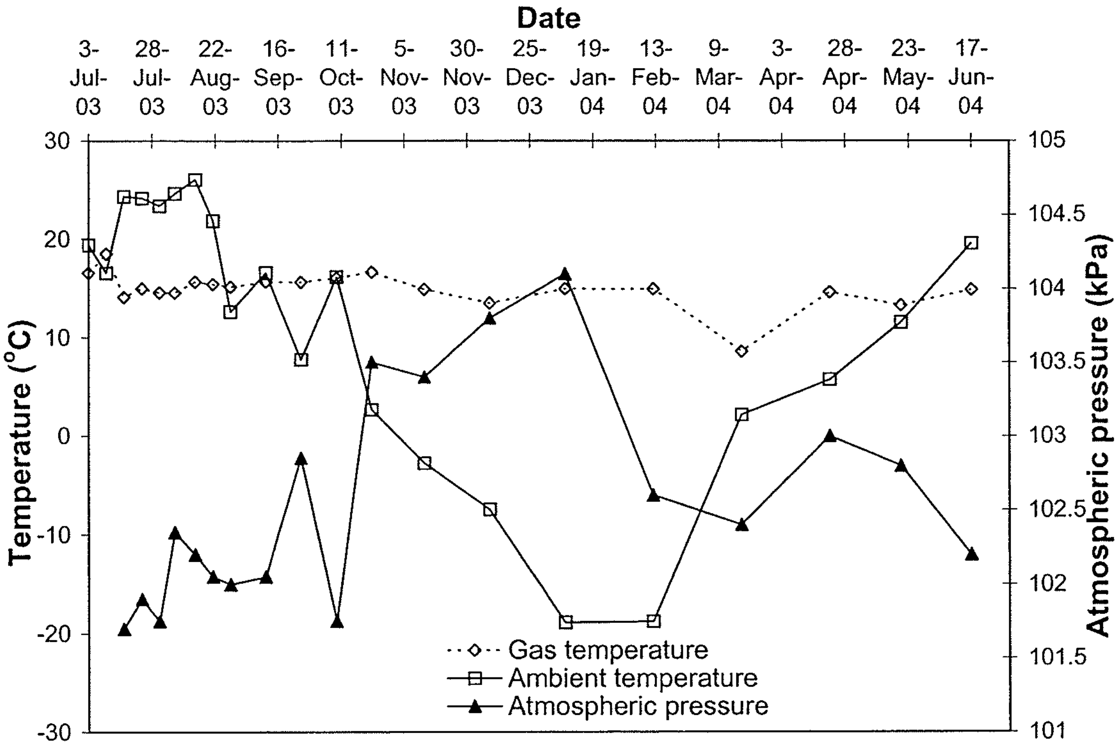


Figure 4.2 Seasonal changes in atmospheric pressure and temperature in contrast to landfill gas temperature

The landfill gas temperature was relatively constant (15.1°C ± 1.8°C) in comparison to the ambient temperature and atmospheric pressure, except for March, 2004 (day 236) as the spring snow-melt causing a temperature drop of 6°C. This evidence corresponds to the results demonstrated by Zeiss and Norstrom (2004) in their bioreactor landfills study in Edmonton. In this study, the spring snow-melt resulted in a gas temperature drop of as much as 9°C, increasing the moisture content of refuse by up to 5% for about three to five days. This moisture infiltration event upset the conditions in the bioreactor and thereby slowed down the transition from acid to stable methane fermentation (Zeiss and Norstrom, 2004).

4.1.2 Landfill Gas Pressure

Figure 4.3 shows the results of average landfill gas generation pressure at the headspace over a year.

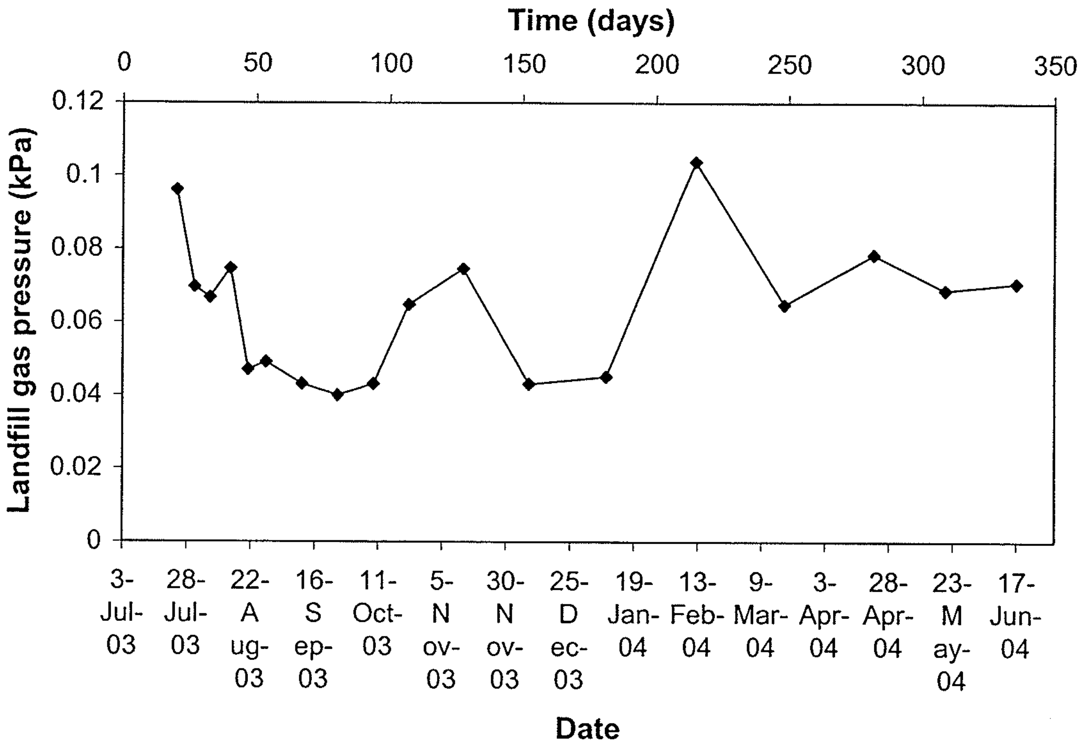


Figure 4.3 Landfill gas generation pressure at the headspace

Initial static testing to evaluate a site's physical characteristics at the five gas monitoring probes yielded very low landfill gas generation pressure, which is a typical occurrence in MSW landfill sites as previously indicated in three landfill sites in Calgary: East Calgary, Spyhill and Shepard (Wyton and Smith, 2002). Increases in barometer pressures cause decreases in actual gauge pressure measurements, while decreases in site barometric pressures result in increases in gauge pressure reading (Wyton and Smith, 2002). In response to problems, a powerful vacuum pump system may be required to draw the gas through the collection system or the specialized equipment available to take landfill gas that includes pumps.

4.1.3 Moisture Content

Figure 4.3 shows results of average percent relative humidity of biogas at Brady Road landfill.

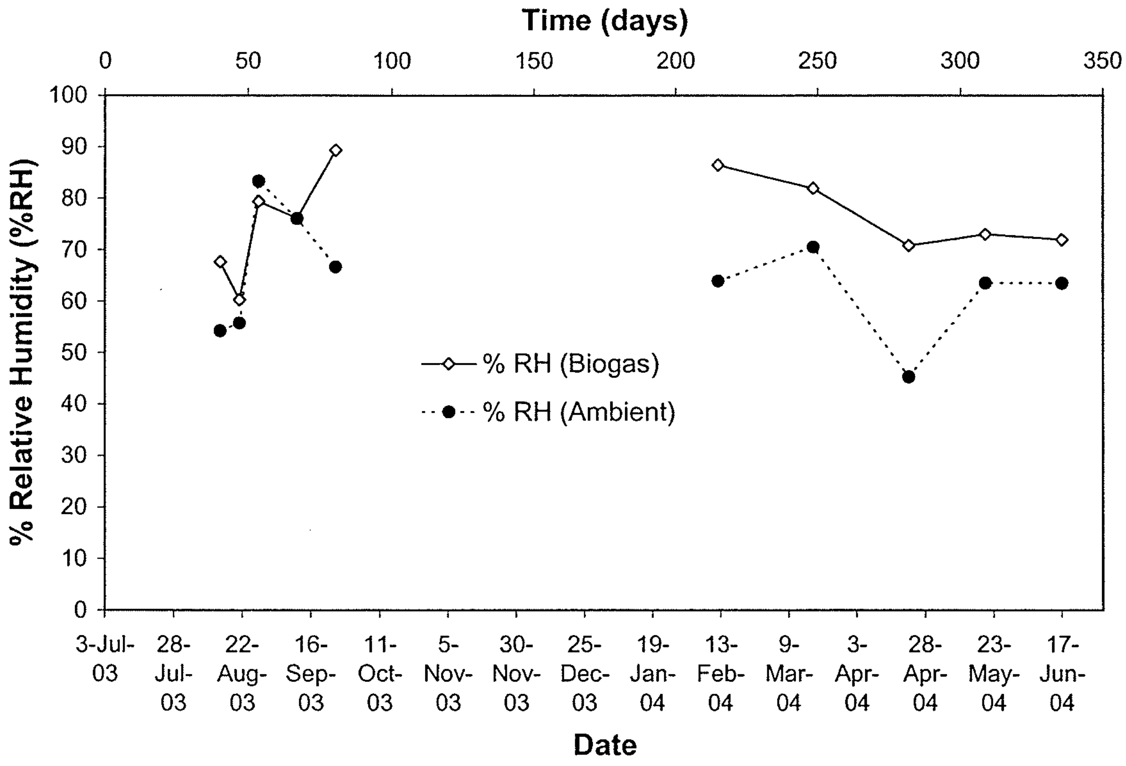


Figure 4.4 Average percent relative humidity of landfill gas.

The measurement of relative humidity (RH) was limited to days that the equipment was available which resulted in 10 measurements. The presence of relatively high % RH (75.7% ± 10.0%) of landfill gas in comparison to ambient environment (64.3% ± 11.0%) indicates a considerable amount of moisture contained in the landfill gas. Gas collection in different landfills in the United Kingdom were found to have % RH concentration between 60 and 80%, while others had zero liquid water (0% RH) approach dependent on landfill gas specifications of specific gas engine manufacturers (Environment Agency, 2002).

A high quantity of moisture content in the landfill gas may have a detrimental effect on the methane recovery as accumulation of water reduces the space available for gas flow, which results in large pressure losses (Environment Agency, 2002). Moreover, presence of contaminated water can also lead to deposit formation on the pipe wall which reduces the smoothness in the pipe (creating resistance to flow in the pipe) and additional increase of pressure loss. A procedure to meet zero liquid water specification is to upgrade landfill gas for natural gas pipeline specification. This can be done by chilling gas to 4°C followed by coalescing filter and then reheating to 29-35 °C (Reinhart, 1994). This method is widely used in many countries, including the United States and United Kingdom.

4.2 Landfill Gas Contaminants Results

Results of landfill gas contaminants can be found in Appendix B.

4.2.1 Hydrogen Sulfide and Vinyl Chloride

Table 4.1 showed the results of trace contaminant monitoring in five gas monitoring probes at Brady Road landfill.

Table 4.1 Results of trace contaminant monitoring in five gas monitoring probes at Brady Road landfill.

Location	**Hydrogen Sulfide (ppmv ± S.D)**	**Vinyl Chloride (ppmv ± S.D)**
L101P	<500 (n=3)	<0.05 (n=2)
L102P	<500 (n=3)	0.33 ± 0.21 (n=2)
L103P	11,800 ± 1,800 (n=3)	<0.05 (n=2)
L104P	<500 (n=3)	0.28 ± 0.28 (n=2)
L105P	<500 (n=3)	0.23 ± 0.16 (n=2)
Average	<500	0.28 ± 0.22

Note: n = number of total samples

The overall concentration of trace contaminants in the landfill gas measured at all five locations was generally low. The location of L103P, however, indicated a fairly high amount of hydrogen sulfide (11,800 ± 1,800 part per million by volume) in comparison to a typical range of 100-1,500 ppm (Environment Agency, 2002; Schumacher, 1983).

The specific location being sampled contains a significant amount of dry wall deposits, which the gypsum contained in the wall create a high concentration of hydrogen sulfide during the anaerobic fermentation stage. In some cases, hydrogen sulfide (H_2S) concentration was reported to be as high a concentration as 35,000 ppm due to different physical dimensions of the site, the types of waste and their input rates, moisture content, landfill pH and temperature. Moreover, previous work on the analysis of stained paint scrapings confirmed the presence of H_2S to be a major component in drywall staining (Natural Research Council Canada, 1992). In addition, H_2S is toxic and corrosive to landfill gas-to-energy equipment, and sulfate can competitively inhibit methane production.

Pre-treatment of this contaminant, therefore, is required prior to application for the future utilization. At present, several sulfide control technologies, such as throwaway liquids, throwaway solid, and re-generatable liquid, are widely used to remove H_2S from the gas. The concept of these treatment processes is to employ various chemical agents, like sodium hydroxide (NaOH) and iron sponge (Fe_2S_3), to transform H_2S into safe and stable forms of dithiazine and iron pyrite (Flynn, 1996).

The average range of vinyl chloride from biogas in the landfills in North America was approximately 0.03-2.20 ppm (Reinhart, 1994; Rachel, 1991), while the concentration of vinyl chloride at Brady Road landfill ranged from below detection limit to 0.28 ± 0.21 ppm. Under the Vinyl Chloride Release Regulation (1992), the vinyl chloride limit is 10 ppm (*Canadian Environmental Protection Act, 1999*). Concentrations of vinyl chloride emission at this specific location are well below regulated levels. However, the amount of vinyl chloride varies from location to location and depends on whether the landfill receives wastes containing these chemicals and whether chemical reactions are occurring which create or remove them.

4.2.2 Siloxane

Table 4.2 showed the results of siloxane monitoring in five gas monitoring probes at Brady Road landfill

Table 4.2 Results of siloxane monitoring in two gas monitoring probes at Brady Road landfill

Compound	**L103P Gas Concentration (ppbv)**		**L104P Gas Concentration (ppbv)**		**Average (ppbv)**
	30/04/04	**8/06/05**	**30/04/04**	**8/06/05**	
Trimethyl silanol	0.34	0.41	0.37	0.14	0.32 ± 0.12
Hexamethyl disiloxane	0.53	0.18	0.81	0.41	0.48 ± 0.26
Hexamethyl cyclotrisiloxane	0.29	0.07	0.08	0.06	0.13 ± 0.11
1,1,3,3,5,5 – Hexamethyl trisiloxane	0.29	0.95	0.38	0.52	0.54 ± 0.29

Note: The results are presented at only locations L103P and L104P as indicators.

Siloxane investigation at Brady Road landfill did not find a significant amount of its constituent in landfill gas production. For example, an average hexamethyl disiloxane concentration was found as low as 0.48 ± 0.26 part per billion by volume (ppbv). However, these results indicated in a specific cell, where constituents of siloxanes may not be adequately presented. Additional results of other locations should be investigated. At the present time, there is no consensus on the average range of this volatile organic compound found in landfill gas in Canada. It generally varies between >1 ppm and < 100 ppm by the volume of total organic silicon, based on the method of the analysis, such as gas chromatography – atomic emission detection (Environment Agency, 2002). It is believed that siloxanes are present in a landfill from many consumer products from household (detergent, hair care, skin care, deodorants, toothpaste), industrial sources (carrier oils), and building materials (impregnating oils). Siloxane deposits also severely reduce fuel internal combustion engines or turbines that drive electrical generator. Siloxane removal can be accomplished by a pre-treatment process but there is currently no standard method for treating landfill gas to eliminate or minimize siloxanes. Three proposed methods, shown in Table 4.3, are introduced as possible methods to remove siloxanes from landfill gas.

Table 4.3 Summary of the procedures and effectiveness of siloxane cleanup (Environment Agency, 2002; Prabucki et al., 2001).

Type	**Stage 1 (dry gas)**	**Cleanup efficiency[2]**	**Stage 2 (adsorbtion)**	**Siloxane level**	**Application range**
GRW[1]	Warm gas 35-40 °C	0%	Activated carbon	< 1 mg/m^3	Siloxane < 10 mg/m^3 Gas flow rate < 150 m^3/h
GRK[1]	Cool gas to 2 °C Post-warm up to 10 °C	Up to 25%	Activated carbon	<1 mg/m^3	Siloxane < 30 mg/m^3 Gas flow rate < 150 m^3/h
GRTK[1]	Cool gas to <-30°C Post-warm up to 10 °C	Up to 90%	Activated carbon	<1 mg/m^3	Siloxane > 30 to 1,000 mg/m^3

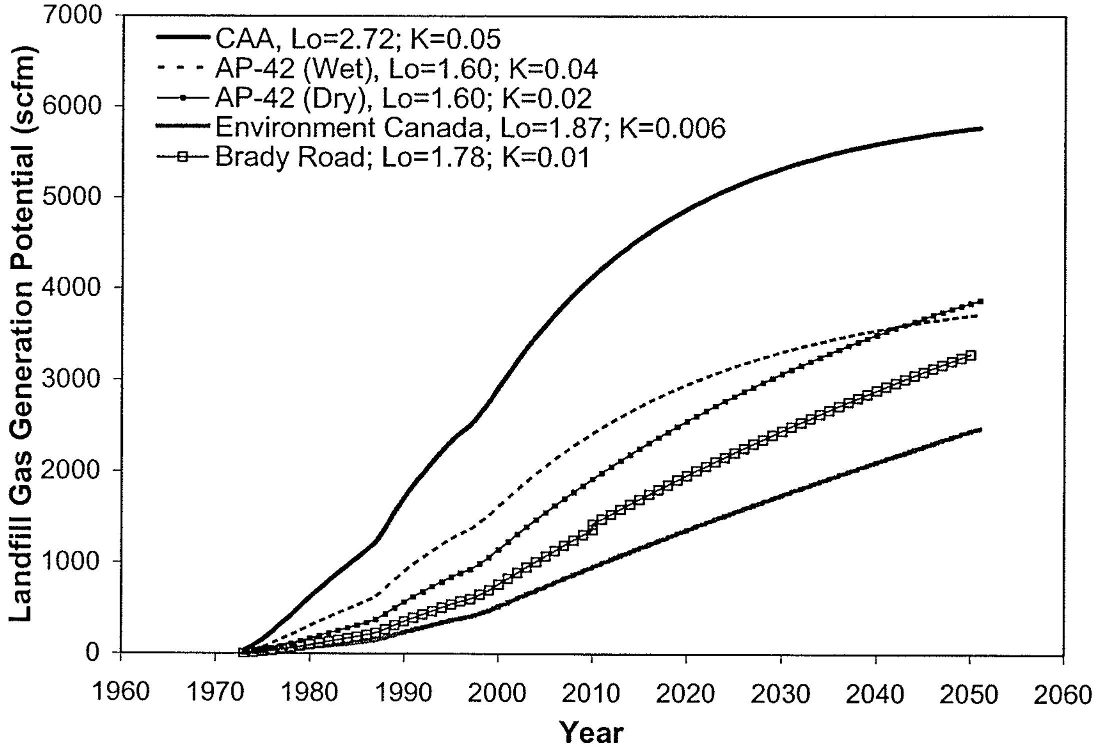
Note: [1]module names; [2]cleanup efficiency is dependant upon the type of siloxane within the gas

Basically, all three methods have the same approach at the inlet (stage 1) of drying the gas to prevent condensation of water vapour and blockage of the activated carbon sites. The purpose of cooling, except GRW type, in this stage is to produce a watery condensate containing up to 25% (GRK type) and 90% (GRTK type) of siloxanes, which also traps some hydrocarbon (olefins) increasing the useful life of the activated carbon. The gas later is heated up to increase siloxane loading capacity of the activated carbon. During the second stage, activated carbon is used as a filter to remove a significant amount of siloxane contaminants (Environment Agency 2002). It should be noted that the most important factor of these processes is to determine which type of treatment is the most economical and best fit to the inlet gases ranging in siloxane concentration. A full scale siloxane monitoring at a specific site, therefore, must be completed prior to this application.

4.3 Landfill Gas Generation Potential

Complete calculations of estimated landfill gas potential and different waste diversion applications are compiled in Appendix C. The estimate landfill gas generation rate is shown in Figure 4.5.

Figure 4.5 Estimated landfill gas generation potential at Brady Road landfill.



4.3.1 Waste Management Diversion Alternatives

There has been an increasing interest of the City of Winnipeg to upgrade the composting facilities, such as composting of yard waste and composting of kitchen food wastes. These activities significantly result in reducing the overall amount of organic materials disposed in Brady Road landfill. In this evaluation, these activities were assumed to be taking place in 2005. The following figures (Figure 4.6, 4.7, and 4.8) estimate landfill gas reductions that result from 25%, 50% and 75% diversions of organic wastes from landfill disposal.

Figure 4.6 Estimate landfill gas generation potential with 25% waste diversion.

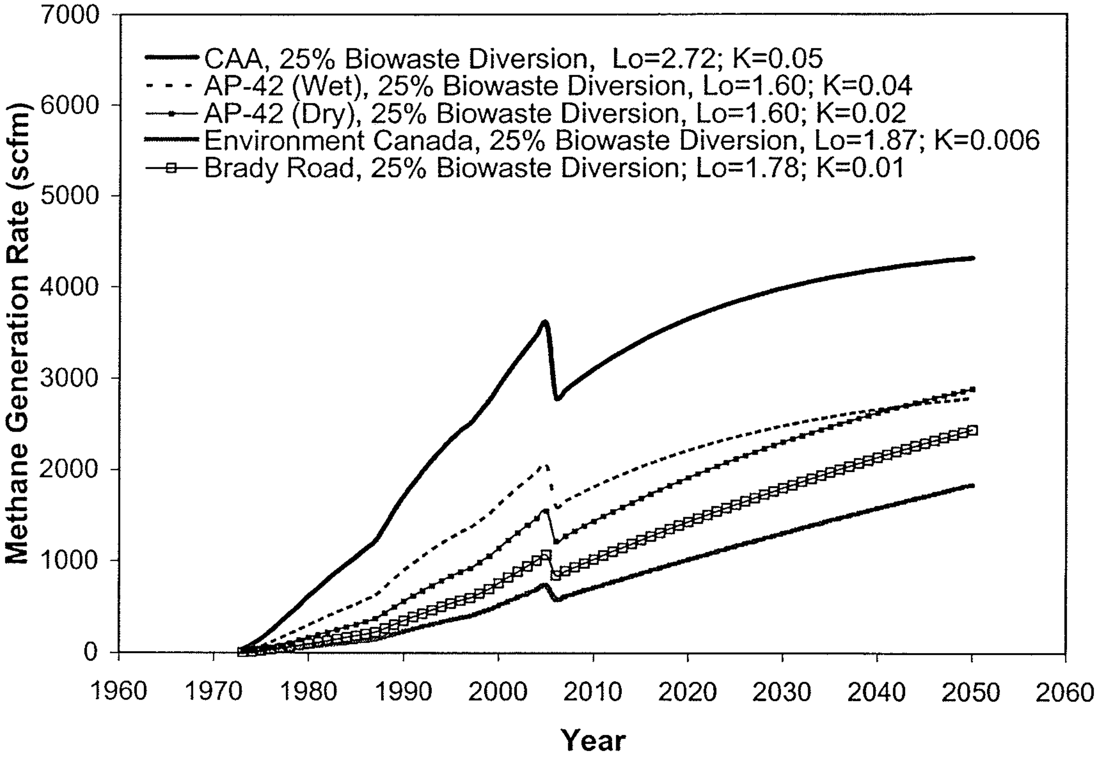


Figure 4.7 Estimate landfill gas generation potential with 50% waste diversion.

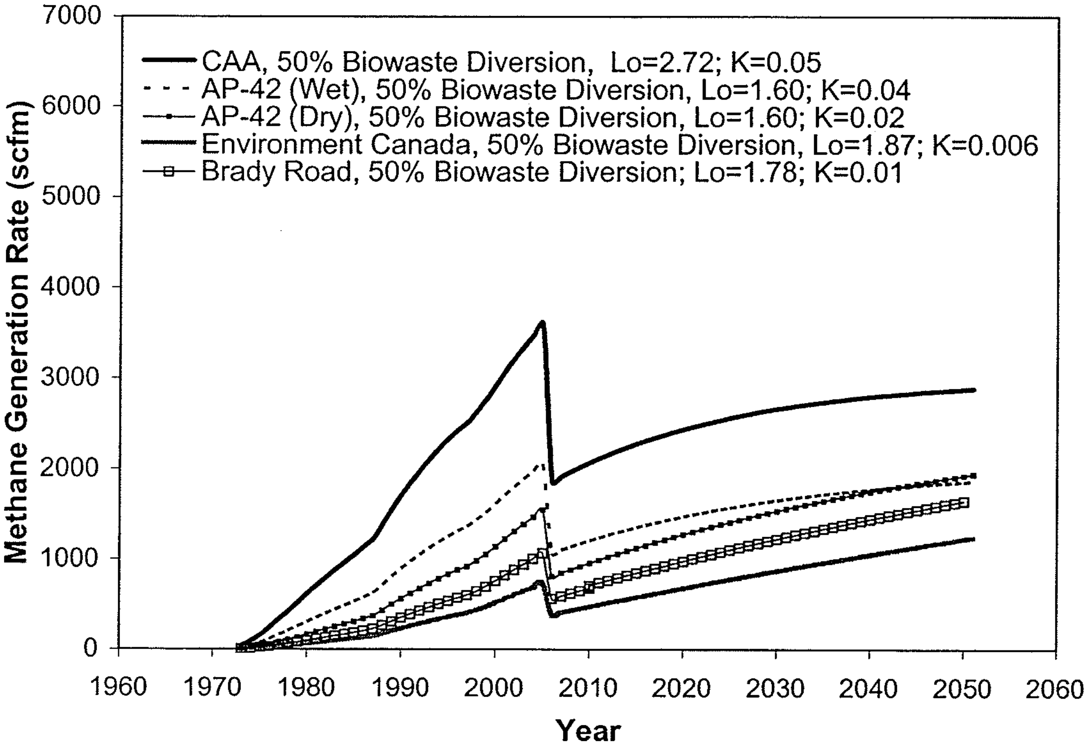
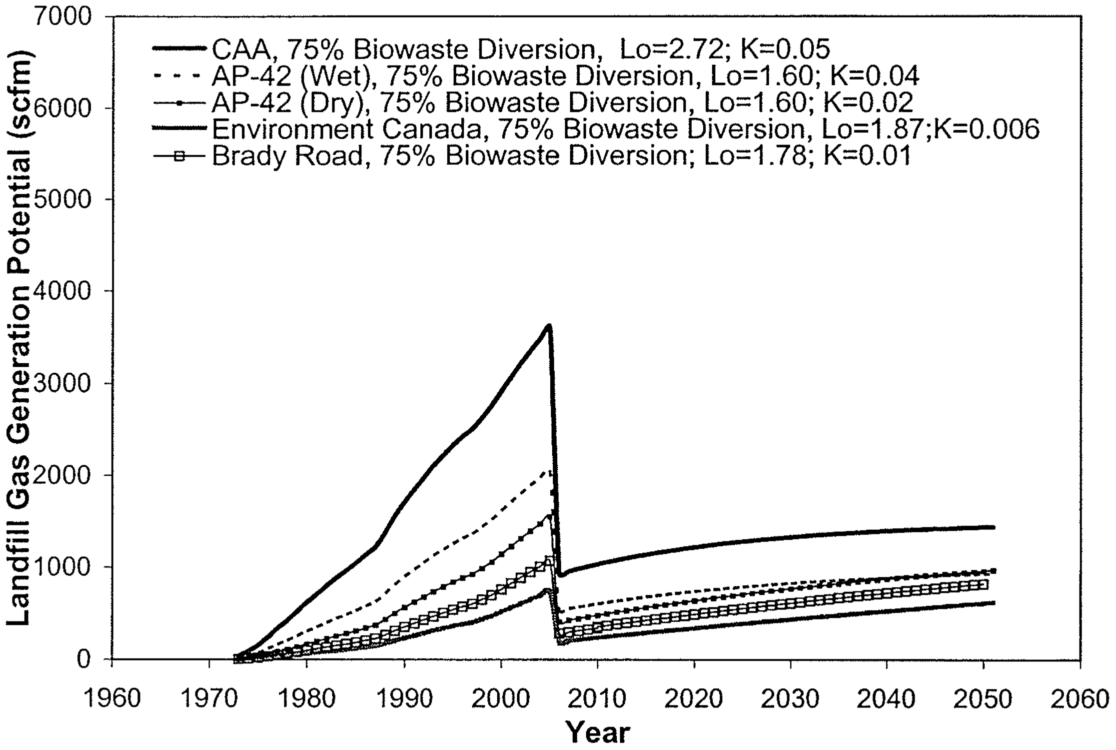


Figure 4.8 Estimate landfill gas generation potential with 75% waste diversion.



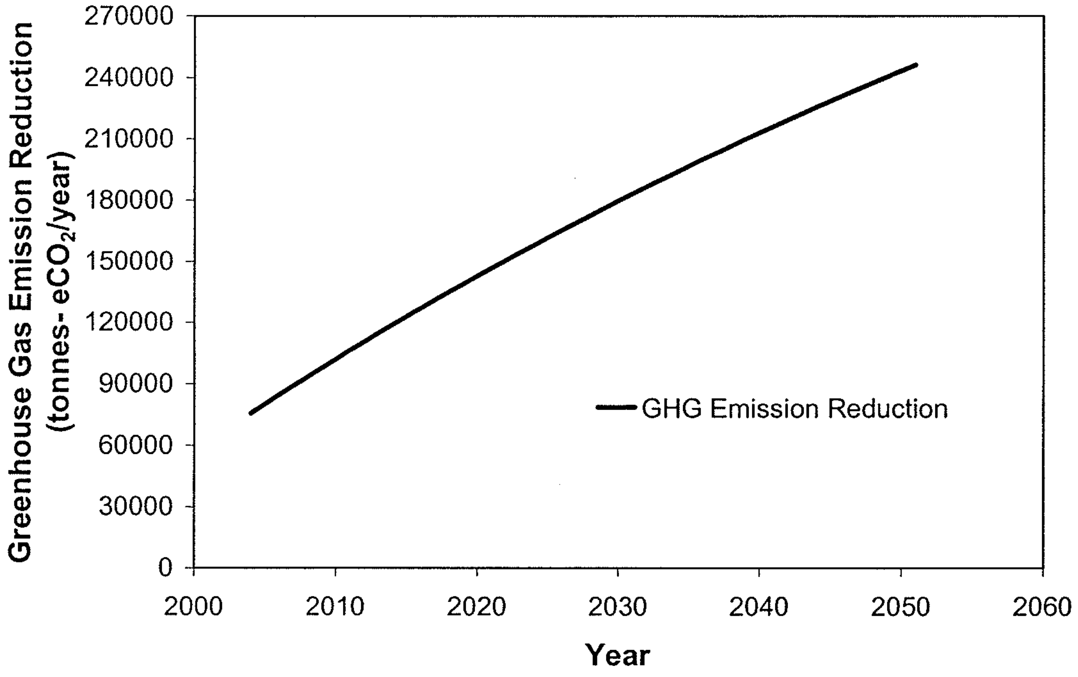
Landfill gas generation rates could be as high as 3300 standard cubic feet per minute (SCFM) according to Figure 4.5 or as low as 825 SCFM in Figure 4.8. In Figure 4.6 to 4.8 the graphs clearly show that composting programs would cause a dramatic decrease in methane, to as much as one-quarter the rate. In 2050 landfill gas production would rise to at least 825 SCFM/year, in the case that 75% of waste is diverted at the lowest range, to 3300 SCFM if no waste diversion occurs at upper range. As recycling rates of paper, which is easier to divert than compost, are presently only at 40% with blue box curb side pick-up it is expected that the diversion rate for composting would be at the lower rate of 25%.

Using the site-specific Brady Road decay rate constant (K) results in similar landfill gas generation rate to the accepted values, with a small range of difference of ±10% to both AP-42 (dry) and Environment Canada. However, inputting CAA parameters result in approximately twice the landfill gas generation rate due to the different site conditions, landfill properties, waste characteristics, moisture availability, and landfill structure. The differences on methane generation potential (Lo) from the default value of US EPA may result from different wastestream composition. Each wastestream has a different DOC content and thus a different methane generation potential. These differences can play an important role in the resulting emission estimate. Results of this finding, therefore, should be included in the landfill gas project assessment for estimating landfill gas generation in Canada especially for cold climate regions.

4.4 Greenhouse Gas Emission Reduction

Results of greenhouse gas emission reductions are compiled in Appendix D. Figure 4.9 demonstrates the estimated potential to reduce greenhouse gas emissions (2004-2050).

Figure 4.9 Estimated greenhouse gas emission reduction at Brady Road landfill (2004-2050).



The estimated global emission (average eCO_2 of 167,489 tonnes per year between the years of 2004 to 2050) indicates a major methane contribution to the atmosphere, if not recovered. Landfill gas collection and utilization, therefore, is a possible solution to diminish the adverse greenhouse gas emissions to the environment. The benefit of landfill gas utilization to the environment is that each mass unit used reduces the global warming potential by approximately 21 times the equivalent warming potential for each mass unit of CO_2 (Environment Canada, 1999). Besides, flaring landfill gas could give the same direct greenhouse gas reduction as landfill gas utilization option because a high temperature of flaring coverts the methane component of landfill gas to carbon dioxide and water, thereby reducing the global warming potential of emissions. Except that if energy was not applied to heat or electricity, energy from another source, with its greenhouse gas would have to be produced.

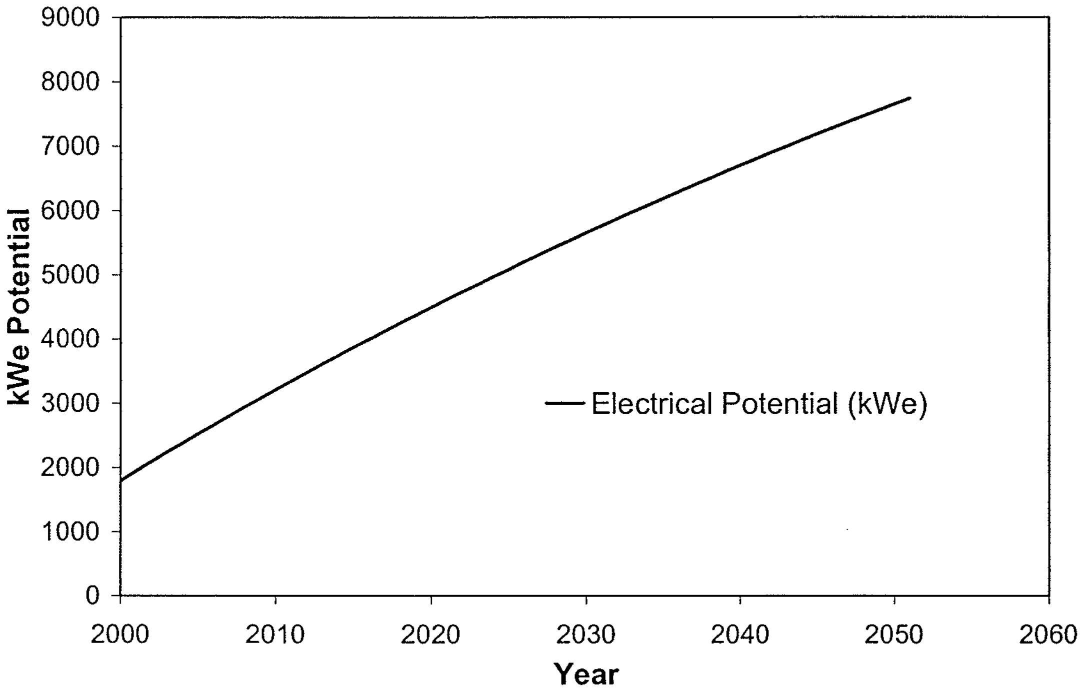
In Canada, landfill gas utilization represents one of the most cost effective means to reduce greenhouse gas emissions. Environment Canada (1999) reported that the range of greenhouse gas reduction prices (or greenhouse gas credits) is between \$1.00 and \$2.00 (CAD value based on 1999) per tonne of eCO_2 reduced. This would create annual revenue (167,489 tonnes of eCO_2 reduced x \$2 (optimum emission reduction credits)) of \$334,978, which can also be used to offset the cost of operating the landfill's gas control system, or the total revenue potential of over \$6 million within the next twenty years (2004-2024). However, the greenhouse gas reduction price varies significantly depending on the specific characteristics of the emission reductions and the motivations of the buyers. In addition, market economics for landfill gas are in a stage of transformation due to climate change regulations and policy directions, such as the Kyoto Protocol and Manitoba Climate Change Action Plan. These force the provincial government and municipalities to accept the non-traditional power and business relationships to increase opportunities for landfill gas recovery.

4.5 Calorific Value and Landfill Gas Energy Potential

The goal of this section is to determine the amount of site-specific heating value and electricity potential available in municipal solid waste at Brady Road landfill. The calorific value or heating value is normally determined by the percentage of methane present. Findings of landfill gas methane volume (56.10% ± 2.56% by volume) at Brady Road landfill indicates it is a medium quality gas, with an estimate energy value of about 560 British thermal unit (BTU) per standard cubic foot minute (SCFM).

To estimate the amount of electricity potential, a collection efficiency of 80% is assumed at a site specific heating value of 560 BTU/ft^3. Figure 4.10 demonstrates the estimated landfill gas potential at Brady Road landfill[6].

Figure 4.10 Electrical Potential Generation at Brady Road landfill



In 2050, electrical potential of 7742 kilo Watt electricity (kWe) or about 7.7 mega Watt electricity (MWe) (see Appendix E) indicates the electrical power generation opportunity for Brady Road landfill. This creates a sustainable renewable source of energy that replaces traditional power generation sources, such as fossil fuels. Brady Road landfill is also an active site with a lifespan of over a century, thereby ensuring a stable consistent source of energy to Manitoba.

The electrical potential (average of 5014 kWe/year, 2000 to 2050) indicates that Brady Road landfill is capable for both internal combustion engine and gas turbine options: its electrical generation exceeds the minimum engine requirement (1000 kWe) of these

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[6] Assumes landfill gas extracted from waste deposited in 2000

technologies. However, electricity prices are currently depressed due to the low prices from hydro – electricity generation, as Manitoba has a very competitive price compared to other provinces. Increased landfill gas recovery, therefore, depends on low cost conversion technologies capable of producing electricity at prices that electric utilities are willing to pay.

4.6 Landfill Gas Implications

The purpose of this section is to demonstrate the available technologies that are applicable to the findings for potential energy and greenhouse gas emission reduction. Advantages and disadvantages of each technology are also discussed.

Option #1 Electrical Power Generation

A number of proven technologies are easily adapted to landfill gas, along the highly developed and distributed transmission infrastructure. However, these are transmitted high capital costs. There are two major types of engines: internal combustion (IC) and gas turbine engine. Typical IC engines are used at sites capable of producing less than or equal to three Megawatts. Between three to five engines are employed in each project dependent on the landfill size.

For higher landfill gas quantity, turbine or conventional engines are recommended. They yield higher horsepower and performance, in comparison to IC engines, where gas quantity can support greater than three Megawatts (Thorneloe, 1992: Reinhart, 1994). In practical terms, electrical generation projects are normally set up according to perceived electrical generation capacity and number of generation units available.

To date, microturbines are applied in landfill gas-to-energy projects where the gas output is too low for larger engines and conventional turbines, or where excess gas or onsite energy needs exist (for example, microturbines could be used to power blowers in a gas collection system). Microturbines, therefore, are suited to relatively small applications (less than 1 Megawatt) and are designed to produce electricity for onsite energy needs and for end users close to the generation site. Table 4.4 demonstrates a summary of advantages and disadvantages of internal combustion engines, gas turbines, and microturbines.

Table 4.4 Advantages and Disadvantages – IC engines, gas turbines, and microturbines (SCS, 1997).

Type of Technology	Advantages	Disadvantages
IC engines	- high efficiency - utilize low pressure fuel gas compressor - adaptable to variable landfill gas supplies - suitable for moderate size landfill - lower capital cost	- higher emissions - more complex cooling system - more moving parts - high maintenance cost
Gas turbines	- low emissions - no cooling water required - simple lubrication system - few moving parts and wear points - exhaust can be utilized in cogeneration	- lower efficiency - high pressure fuel gas compressor required - high capital cost - not suitable for moderate size landfills - sensitive to varied landfill gas supply loads - sensitive to ambient air temperature variations
Microturbines	- low emissions - multiple fuel capacity - light weight/small size - does not require any pre-treatment of the fuel - lower maintenance costs	- low efficiency - has been tested for mostly natural gas applications

Installation of an electrical generation facility indicates a big investment cost (see Section 2.11.1) for landfill gas capture system, gas treatment, mechanical and electrical controls and electrical connections. Moreover, Manitoba's electrical power price (under market price of 3.0 cents/kWh) is very cheap, which may not be economically viable for business-as-usual clients. For this reason, electrical power generation may not be the attractive option for future utilization at Brady Road landfill compared to other options like direct uses.

Option #2 Boilers and Other Direct Combustion Applications

Direct combustion of landfill gas is considered to be the easiest reuse alternative. Direct use of landfill gas has successfully been demonstrated to replace or supplement coal, oil, propane, and natural gas. Various applications, such as boiler firing, space heating, cement and brick furnaces, and leachate drying and incineration, are commonly found in many industries because operation, maintenance gas and cleanup (including condensate removal and equipment and procedural modifications) costs are minimal. Direct use of landfill gas is the second most popular application in North America. This solution is not the most used options, as landfill gas-to-electricity (i.e. electrical generator) is more cost-effective and profitable than stream boilers in terms of price per kilowatt power and heat produced (Willumsen, 1999).

The most typical direct combustion use is a boiler fuel for stream production. The heat from some boiler systems is also used in greenhouses either by normal circulation of hot water or by heating of air blown into the greenhouse. However, corrosion problems have been reported, but may be solved by installing corrosion-resistant materials (Pacey et al., 1994; Reinhart, 1994). In industrial practice, landfills with medium heating value like Brady Road landfill (560 BTU/SCFM) are increasingly using landfill gas for co-firing, a supplemental gas for a waste-to-energy plant or other incinerator, due to the absence of cleanup requirements. Table 4.5 demonstrates a summary of advantages and disadvantages for direct gas utilization.

Table 4.5 Advantages and disadvantages – direct gas utilization (USEPA, 2001)

Type of Technology	Advantages	Disadvantages
Direct use (i.e. boiler)	- simple technology - minimal processing requirements - cost effective	- requires locating a customer near the landfill - local terrain not conducive to pipeline installation

At Brady Road landfill, direct uses, such as boilers, have a great potential for future landfill gas utilization over electrical power generation due to the cheap electricity price and surplus of electrical generation (i.e. Hydro and fossil fuel). The possible industries nearby Brady Road landfill that should be considered for the end-users are Canoco – Procor (Train Tankers), Brett Young, L-Bred, Pure-Bred, Turf-Bred, and Terraco (Esso). Moreover, this option has a relatively low capital cost of landfill gas treatment, landfill gas conversion, and collection system.

Option #3 Purification to Pipeline Quality Natural Gas

Landfill gas like Brady Road landfill has low BTU content, compared to natural gas, and needs upgrading to pipeline quality natural gas. The required gas cleanup is a very expensive and complex process, comparable to other alternatives such as boilers, which nearly complete all carbon dioxide removal ($CO_2 < 2\%$). Therefore, this option is not profitable. There are presently only five plants left in the United States, due to the big investment required and strict gas quality requirement issue. Prior to delivery of upgraded gas to the main natural gas distribution, the gas must be free of particles ($H_2S < 4ppm$) and liquid (moisture content < 4%).

The main step of upgrading also is the separation process of methane ($CH_4 > 99\%$) and carbon dioxide ($CO_2 < 2\%$) and can be summarized into three techniques: chemical absorption, pressure swing adsorption and membrane separation. The most cost-effective technique tends to be the membrane separation process. It has many advantages over other processes, including that a membrane process can easily be modified to handle unexpected variation in processing conditions, such as increases in flow or changes in gas composition. A membrane can easily be added or removed (Onu, 1999). Table 4.6 demonstrates a review of advantages and disadvantages of pipeline quality gas upgrade.

Table 4.6 Advantages and Disadvantages – pipeline quality gas upgrade (USEPA, 2001)

Type of Technology	Advantages	Disadvantages
Pipeline quality natural gas	- all gas recovered from landfill is used - cost effective for landfill with high volume of gas - beneficial in areas where natural gas prices are high	- extensive treatment of landfill gas - additional quality control requirement - higher capital cost - higher compression of gas

Option #4 Vehicle Fuel

Landfill gas for vehicle fuel is viable when the gas is upgraded to natural gas quality. The vehicles are modified to operate on some form of natural gas, and the refueling stations are equipped for dispensing natural gas. The technology of vehicle fuel is already established as liquefied natural gas (LNG) and compressed natural gas (CNG) for alternatively powered stationary internal combustion engines. The essential difference between LNG and CNG is the way in which the gas is stored. In the case of LNG the gas is liquefied and stored at a low temperature in a highly insulated container. The liquefaction and storage are high tech processes with high set-up costs. In the case of CNG the gas is compressed and then stored in high pressure cylinders. These are relatively expensive but the technology of compression and storage are within the reach of all countries. In New Zealand, many vehicles already run on upgraded landfill gas (Nyns, 1992). Table 4.7 demonstrates a summary of advantages and disadvantages of vehicle fuel.

Table 4.7 Advantages and Disadvantages – vehicle fuel (USEPA, 2001)

Type of Technology	Advantages	Disadvantages
Vehicle fuel	- price lower than diesel fuel cost - reduction in use of fossil fuels - reduce local ozone pollution	- very small alternative-fuel vehicles - high vehicle conversion costs

Option #5 Fuel Cell

Landfill gas can also be used in fuel cells. This application has been tested in the United States for many years but it has unfavourable economics, requiring a big initial investment. The concept of a fuel cell is comparable to large electric batteries, which convert the chemical bonding energy of a chemical substance directly into electricity. The difference between a battery and fuel is that all reactants are present within the battery and are slowly being depleted during battery utilization. In a fuel cell, the reactants (fuel) are continuously supplied to the cell (Willumsen, 1999). The advantages of fuel cells over other options include higher energy efficiency, availability to smaller landfills, minimal by-product emissions, minimal labour and maintenance, and minimal noise impact. Table 4.8 demonstrates a summary of advantages and disadvantages in fuel cells technology.

Table 4.8 Advantages and disadvantages – fuel cells (SCS, 1997).

Type of Technology	Advantages	Disadvantages
Fuel cells	- high efficiency - low emissions - low noise - suitable in urban areas - modular construction - low water requirement - high grade waste heat for cogeneration - remote operation - few moving parts	- high capital cost - new technology - requires complex landfill gas pre-treatment system

Option #6 Leachate Evaporation

The innovative leachate evaporation (E-VAP) system is an innovative technology that uses landfill gas as a fuel source to evaporate landfill leachate. E-VAP is a practical and cost-effective alternative for treatment and disposal but creates no revenue. This option is initially introduced to many municipalities, due to the environmental and liability concerns of off-site leachate disposal and treatment which requires transportation. The E-VAP system, in comparison to conventional leachate treatment in Winnipeg (which required leachate transportation to wastewater facility), is less complex and costly to build, operate, and maintain.

E-VAP system consists basically of the same equipment for boiler use, such as gas pump and pipeline, with a thermal oxidizer by landfill gas for exhaust vapour treatment and a means to collect, store, and dispose of single waste stream sludge (Reinhart, 1994). Reinhart et al. (1994) noted that E-VAP could reduce by one-half to two-thirds capital costs of a conventional leachate treatment plant. Operating and maintenance costs would be potentially much lower due to reduced labour requirements. Up to 25 SCFM of landfill gas is needed to treat 0.004 cubic meters or one gallon of leachate. To date, more than 13 leachate evaporation systems are operating around the world, with several more in the planning stages. Table 4.9 demonstrates a summary of advantages and disadvantages in leachate evaporation technology.

Table 4.9 Advantages and disadvantages – leachate evaporation (USEPA, 2001)

Type of Technology	Advantages	Disadvantages
Leachate evaporation	- applicable to landfills that have limited leachate treatment options and high leachate disposal costs - proven technology - meets local air quality requirements	- generally applicable to larger landfill sites - does not provide revenue

Option #7 Other Technologies

There has been an interest in the new technologies, such as aerobic and anaerobic bioreactors and by-product carbon dioxide utilization. The laboratory- and field-scales have been observed in several places, especially in the United States, such as University of Central Florida. Yet, result information has not been adequately confirmed these technologies in terms of environmental performance and cost saving for larger landfill utilization applications, like Brady Road landfill. Therefore, these options are currently limited to only small landfills that seek to increase their landfill gas productions. According to USEPA (2000), these technologies could be adequately implemented and available for large projects in 2030.

4.7 Summary

The twelve-month field investigation indicated a consistent methane production of 56% at Brady Road landfill. This result reflected the stable fermentation stage of two-year-old waste deposits in the testing cell. A minute concentration of oxygen and hydrogen also confirmed the validity of sampling and testing process. On the other hand, overall physical characteristics of Brady Road landfill were influenced by the ambient environments. For example, increases in ambient pressure caused decreases in landfill gas generation pressure. Spring snow-melt also caused a gas temperature drop of 6°C for a short period. Overall trace contaminants, including hydrogen sulfide, vinyl chloride and siloxane, resulted in the low concentrations in comparison to typical ranges. For example, average concentration of vinyl chloride was approximately 0.28 ± 0.21 ppm, while the typical range was between 0.03 to 2.20 ppm.

The results of landfill gas generation estimates indicate that Brady Road landfill generated methane as high as 3,300 standard cubic feet per minute (SCFM) in 2050, based on site specific values. The 75% of waste diversion rate resulted in a significant reduction of the methane generation of 825 SCFM. However, even if composting resulted in diversion rates as high as 50% or 75%, methane generation would be enough to warrant landfill gas recovery from Brady Road Landfill. Moreover, the result of greenhouse gas reductions at Brady Road landfill is evident in a creditable revenue stream from greenhouse gas credits, of over than six million dollars, in the next few decades.

Several landfill gas utilization alternatives were discussed in this chapter. Direct uses (option #2) apparently are the most favourable option for Brady Road landfill due to the lower initial capital cost and minimal trace contaminant removals. Although the electrical power generation (option #1) has as much potential as direct uses option, the competitive price of electricity and adequate electric power in Manitoba makes this option less interesting. In addition, leachate evaporation (option #6) can be utilized in a combination with boilers as it reduces the enormous costs of leachate transportation to the North End wastewater treatment plant.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

Overview:

The main intent of this research was to evaluate the feasibility of landfill gas recovery at Brady Road landfill, considering landfill gas quality and landfill gas generation potential. The objectives outlined in Chapter One were adequately achieved by conducting a literature survey, field testing with laboratory analysis and mathematical models. From this research, several conclusions have been drawn to develop the current landfill gas model and the useful recommendations for the future gas utilizations at Brady Road landfill.

The results of site-specific investigation revealed that landfill gas generation at the Brady Road landfill produced consistent methane production (56.04% ± 2.63% by volume). The testing and sampling process was uncontaminated by outside air as minute, rather than atmospheric, concentrations of oxygen and nitrogen demonstrated the validity of the testing and sampling process. Changes in seasons did not have significant effects on landfill gas temperature, gas production rates, and landfill gas quality. For example, in the extreme winter weather (below -20°C), gas temperatures were relatively constant (average of 15.2°C ± 2.2°C). However, the spring snow-melt caused the gas temperature to drop to as low as 6°C. This resulted in a decrease of methane production for a short period of three to five days.

Low landfill gas generation pressure at headspace required a powerful vacuum pump system to draw the gas through the collection system at Brady Road landfill. The presence of relatively high % relative humidity (75.7% ± 10.0% by volume) of landfill gas indicated a considerable amount of moisture content contained in the landfill gas. High moisture content could create a detrimental effect on plant performance, as accumulation of water reduces the space available for gas flow and could lead to deposit formation on the pipe wall which reduces the smoothness in the pipe. However, a need of zero liquid water treatment is necessary only when upgrading landfill to meet natural gas pipeline specifications.

Overall concentrations of trace contaminants were found at fairly low concentrations, except concentrations of hydrogen sulfide were found at levels that are toxic and corrosive to landfill gas-to-energy equipment and have detrimental health effects such as cancer and birth defects. For example, average hydrogen sulfide concentrations in landfill gas were 11,800 ± 1,800 part per million by volume (typical value range for other landfill between 100 and 1,500 ppm). Therefore, careful attention must be given to this contaminant when assessing future gas utilization process. Vinyl chloride and siloxane appeared to have only a minor effect on the landfill gas utilization. For example, vinyl chloride concentration (<0.33 ± 0.21 ppm) was well below the industrial standard of Canada (10 ppm), while the corresponding average siloxane concentration was very minimal (0.48 ± 0.26 ppbv as representative hexamethyl disiloxane). Therefore, future pre-treatment systems are not required at this site-specific location.

Brady Road landfill clearly emits substantial amounts of methane under any waste management scenarios (i.e. no waste diversion to 75% waste diversion). Application of the Scholl Canyon model, with both site-specific data and accepted constants, confirmed that the Brady Road landfill generates sufficient amounts of landfill gas emissions to warrant a landfill gas recovery project. Brady Road landfill is similar to Keele Street Valley landfill in Toronto, which is currently profitable at recovering methane that contains 47% CH_4 with a landfill capacity of 25 million tonnes. However, Brady Road landfill is even more promising as it generates landfill gas with higher methane potential at 56% with a landfill site capacity of 50 million tonnes.

The landfill gas methane volume (56.10% ± 2.56% by volume) at Brady Road landfill produces a medium quality gas with an energy value of approximately 560 BTU/SCFM. The corresponding amount of electricity potential based on the 80% gas collection efficiency would create 7.7 MW (2000 to 2050). Moreover, the methane emission at Brady Road landfill (average eCO_2 of 167,489 tonnes, 2004 to 2050) indicated a significant contribution to the atmosphere. If recovered, it would create a creditable revenue stream ($6 million) through the greenhouse gas credits, which can also be used to offset the cost of operating landfill's gas control system.

The combined direct uses (i.e. direct combustion) (option #2) and leachate evaporation (option #6) options seem to be the most suitable technologies for gas utilization of the medium gas quality at Brady Road landfill. Direct use options are profitable for a large size capacity landfill and cost-effective as they require minimal trace contaminant removal. Due to the high cost of leachate transportation in Winnipeg, on-site leachate evaporation should also be included to minimize these excessive expenses. Although electrical power generation (option #1) is likely to be the superior option for future gas utilization, surplus power supply and cheap electricity in Manitoba are factors that make this option less appealing here.

In the pipeline natural gas (option #3) and vehicle fuel (option #4) applications, gas cleanup is very expensive and complex treatment processes that make other alternatives, such as boilers, more interesting. Advanced technologies, such as phosphoric acid fuel cell (option #5) and anaerobic bioreactor (option #7), are relatively new and it may be wise to allow these innovative technologies to develop further prior to investing in them. The new developing technology of carbon dioxide utilization as a carbon source for methanol synthesis, that involves trace contaminant removal, also holds promise but is still exploratory.

Recommendations:

The purpose of this section is to provide constructive recommendations to Manitoba Hydro and City of Winnipeg for implementation of the landfill gas utilization options. The following field related activities and landfill designs should be considered to optimize the landfill gas generation performance.

Manitoba Hydro:

This investigation provided year round analysis of landfill gas at five similar sites to determine its quality for methane recovery. An additional full-scale sampling program in more diverse site locations may be required to assess the influence of different landfill characteristics such as waste compositions, moisture content, pH, nutrient, and refuse density. These findings will have a practical dimension as they will assist in designing a full-scale gas utilization project and providing site-specific data to calculate emissions.

Landfill gas quantity should be monitored as the actual gas flow rates, multiplied by percent volume adjusted for atmospheric and other meteorological variables, represent true production rates.

The presence of trace contaminants would require an expensive removal process before it could be used for natural gas. This field study should be extended for another year to fully investigate trace contaminant production. Other trace components of landfill gas should also be monitored due to their health and environment implications, and impacts on the gas engine performance. For example, halogenated compounds (e.g. carbon tetrachloride, chlorobenzene, chloroform, and trifluoromethane) are broken down during the combustion process and will form acid gases like, hydrogen chloride. These gases are responsible for the corrosion of metal piping and engine components. Under different waste compositions (commercial versus household wastes) at Brady Road landfill, different contaminants are expected. A full-scale trace contaminant investigation in different locations of the landfill should be observed in order to assess what pre-treatment process is required for electrical generation or natural gas production. Alternatively, the methane could be burned as a heating fuel. Samples taken from different locations would create the data inputs for waste management options at Brady Road landfill.

City of Winnipeg:

Refuse thickness at Brady Road landfill should be considered to extend its depth from 10 metres to 40 metres (or more) to enhance the landfill gas generation. Moreover, innovative leachate collection and lining at Brady Road landfill are required to improve landfill management efficiency. For example, perforated plastic storm drainage pipe and storm liners could be used to collect rainwater, a principal source of leachate, and move it to the drainage ditches surrounding the landfill site rather than draining into the leachate collection pond. This performance could reduce a significant quantity of leachate generation and prevent leachate contaminants creating in the landfill.

In general, there are numerous factors enhancing landfill gas production. For example, recycled leachate would accelerate methane generation. Actions that should be considered to obtain the maximum gas production efficiency include: 1) adding sewage sludge to increase the moisture content, this would be favourable to bacterial growth to increase decay rate of waste; 2) adding a buffer (i.e. calcium carbonate) to create an optimal pH environment from acidic pH; 3) covering the completed cell with an insulating layer increases the temperature in the landfill cell; and 4) increasing the depth of the landfill.

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Appendix A: Results of Landfill Gas Analysis

Table A.1 Percent Gas Concentration Results (3^{rd} July, 2003)

Location	Sample1	Sample2	Sample3	% Average	S.D.
P101L					
N_2	1.2	1.2	1.1	1.17	0.06
O_2	0.6	0.6	0.6	0.60	0.00
CH_4	53.7	54.6	55.1	54.47	0.71
CO_2	42.9	41.9	41.6	42.13	0.68
P102L					
N_2	2.2	1.5	1.8	1.83	0.35
O_2	1.1	0.7	0.9	0.90	0.20
CH_4	56	57	56.7	56.57	0.51
CO_2	38.5	39.3	39.1	38.97	0.42
P103L					
N_2	4.5	3.3	3.7	3.83	0.61
O_2	2	1.5	1.7	1.73	0.25
CH_4	53	54.5	54	53.83	0.76
CO_2	36.2	37.4	37	36.87	0.61
P104L					
N_2	2.2	1.3	2	1.83	0.47
O_2	1	0.7	0.9	0.87	0.15
CH_4	57.6	52.7	52.1	54.13	3.02
CO_2	37.1	44	43.1	41.40	3.75
P105L					
N_2	1.7	2	1.5	1.73	0.25
O_2	0.8	1	0.8	0.87	0.12
CH_4	51.8	57.7	58.5	56.00	3.66
CO_2	44	37.3	37.7	39.67	3.76

Table A.2 Percent Gas Concentration Results (10th July, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.5	0.7	0.5	0.57	0.12
O_2	0.3	0.4	0.3	0.33	0.06
CH_4	55.9	55.9	56.3	56.03	0.23
CO_2	42.4	42.5	42.7	42.53	0.15
P102L					
N_2	0.6	0.6	0.7	0.63	0.06
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	58.4	58.7	58.5	58.53	0.15
CO_2	40.8	40.6	40.6	40.67	0.12
P103L					
N_2	0.7	0.8	0.8	0.77	0.06
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	58.8	58.6	58.6	58.67	0.12
CO_2	40.2	40.1	40.2	40.17	0.06
P104L					
N_2	1.5	0.7	0.8	1.00	0.44
O_2	0.7	0.4	0.4	0.50	0.17
CH_4	59.1	60.2	60.1	59.80	0.61
CO_2	38	38.5	38.5	38.33	0.29
P105L					
N_2	1.7	2	1.5	1.73	0.25
O_2	0.8	1	0.8	0.87	0.12
CH_4	51.8	57.7	58.5	56.00	3.66
CO_2	44	37.3	37.7	39.67	3.76

Table A.3 Percent Gas Concentration Results (17th July, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.8	1.2	1.2	1.07	0.23
O_2	0.5	0.6	0.6	0.57	0.06
CH_4	55.5	55.2	55.2	55.30	0.17
CO_2	41.9	41.6	41.4	41.63	0.25
P102L					
N_2	1.1	0.9	1.3	1.10	0.20
O_2	0.6	0.5	0.6	0.57	0.06
CH_4	56.9	57.4	56.9	57.07	0.29
CO_2	40.1	40	39.6	39.90	0.26
P103L					
N_2	2.3	1.9	1.6	1.93	0.35
O_2	1.1	0.9	0.8	0.93	0.15
CH_4	55.6	56	56.3	55.97	0.35
CO_2	38.1	38.5	38.8	38.47	0.35
P104L					
N_2	1.2	0.6	1.2	1.00	0.35
O_2	0.6	0.3	0.6	0.50	0.17
CH_4	58.8	59.8	58.9	59.17	0.55
CO_2	37.5	38	37.5	37.67	0.29
P105L					
N_2	10	6.9	8	8.30	1.57
O_2	0.9	0.6	0.8	0.77	0.15
CH_4	49.4	50	49.9	49.77	0.32
CO_2	46.3	46.9	46.7	46.63	0.31

Table A.3 Percent Gas Concentration Results (17th July, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.6	0.6	0.7	0.63	0.06
O_2	0.4	0.4	0.5	0.43	0.06
CH_4	56	56	55.9	55.97	0.06
CO_2	41.9	42.1	42.1	42.03	0.12
P102L					
N_2	0.7	0.7	0.9	0.77	0.12
O_2	0.4	0.4	0.5	0.43	0.06
CH_4	58.2	58.1	58	58.10	0.10
CO_2	40.3	40.4	40.2	40.30	0.10
P103L					
N_2	1	1	1.3	1.10	0.17
O_2	0.5	0.5	0.7	0.57	0.12
CH_4	58.8	58.8	58.5	58.70	0.17
CO_2	38.8	38.6	38.2	38.53	0.31
P104L					
N_2	1.1	1.1	1.4	1.20	0.17
O_2	0.6	0.6	0.7	0.63	0.06
CH_4	57.8	59.5	59.2	58.83	0.91
CO_2	38.1	38.1	37.9	38.03	0.12
P105L					
N_2	1.5	1.5	1.9	1.63	0.23
O_2	0.7	0.7	0.6	0.67	0.06
CH_4	49.8	49.9	49.8	49.83	0.06
CO_2	48.1	47.9	48	48.00	0.10

Table A.4 Percent Gas Concentration Results (24th July, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.6	0.6	0.7	0.63	0.06
O_2	0.4	0.4	0.5	0.43	0.06
CH_4	56	56	55.9	55.97	0.06
CO_2	41.9	42.1	42.1	42.03	0.12
P102L					
N_2	0.7	0.7	0.9	0.77	0.12
O_2	0.4	0.4	0.5	0.43	0.06
CH_4	58.2	58.1	58	58.10	0.10
CO_2	40.3	40.4	40.2	40.30	0.10
P103L					
N_2	1	1	1.3	1.10	0.17
O_2	0.5	0.5	0.7	0.57	0.12
CH_4	58.8	58.8	58.5	58.70	0.17
CO_2	38.8	38.6	38.2	38.53	0.31
P104L					
N_2	1.1	1.1	1.4	1.20	0.17
O_2	0.6	0.6	0.7	0.63	0.06
CH_4	57.8	59.5	59.2	58.83	0.91
CO_2	38.1	38.1	37.9	38.03	0.12
P105L					
N_2	1.5	1.5	1.9	1.63	0.23
O_2	0.7	0.7	0.6	0.67	0.06
CH_4	49.8	49.9	49.8	49.83	0.06
CO_2	48.1	47.9	48	48.00	0.10

Table A.5 Percent Gas Concentration Results (31st July, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.3	0.5	0.4	0.40	0.10
O_2	0.3	0.5	0.4	0.40	0.10
CH_4	55.3	55.3	55.3	55.30	0.00
CO_2	40.2	38.1	39.3	39.20	1.05
P102L					
N_2	0.4	0.5	0.3	0.40	0.10
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	56.2	56.2	57.5	56.63	0.75
CO_2	38	37.1	37.8	37.63	0.47
P103L					
N_2	0.4	0.5	0.4	0.43	0.06
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	58.2	58	58.1	58.10	0.10
CO_2	35.8	35	35	35.27	0.46
P104L					
N_2	0.4	0.4	0.4	0.40	0.00
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	58.6	58.7	58.7	58.67	0.06
CO_2	35.6	35.5	35.6	35.57	0.06
P105L					
N_2	0.5	0.4	0.4	0.43	0.06
O_2	0.4	0.4	0.4	0.40	0.00
CH_4	49.4	49.8	49.7	49.63	0.21
CO_2	44.2	44.7	44.5	44.47	0.25

Table A.6 Percent Gas Concentration Results (6th August, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	1	0.6	0.7	0.77	0.21
O_2	0.6	0.4	0.5	0.50	0.10
CH_4	55.5	56.3	56.2	56.00	0.44
CO_2	43	38.1	42.7	41.27	2.75
P102L					
N_2	0.9	1	1	0.97	0.06
O_2	0.5	0.6	0.5	0.53	0.06
CH_4	57.5	57.8	58.2	57.83	0.35
CO_2	40.9	40.4	40.1	40.47	0.40
P103L					
N_2	2.6	2.8	2.5	2.63	0.15
O_2	1.2	1.3	1.2	1.23	0.06
CH_4	56.8	56.9	57.5	57.07	0.38
CO_2	37.3	36.5	36.4	36.73	0.49
P104L					
N_2	1.1	0.5	0.9	0.83	0.31
O_2	0.6	0.3	0.5	0.47	0.15
CH_4	59.7	60.5	59.9	60.03	0.42
CO_2	38.1	38.3	38	38.13	0.15
P105L					
N_2	1.3	0.9	0.7	0.97	0.31
O_2	0.4	0.3	0.4	0.37	0.06
CH_4	50.2	50.5	50.4	50.37	0.15
CO_2	47.5	47.7	47.4	47.53	0.15

Table A.7 Percent Gas Concentration Results (14th August, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.9	0.9	0.8	0.87	0.06
O_2	0.5	0.5	0.5	0.50	0.00
CH_4	54.3	55.3	55.5	55.03	0.64
CO_2	42.8	42.2	42.2	42.40	0.35
P102L					
N_2	0.5	1.1	1.1	0.90	0.35
O_2	0.3	0.6	0.6	0.50	0.17
CH_4	58	57.5	57.7	57.73	0.25
CO_2	40.9	40	39.9	40.27	0.55
P103L					
N_2	1.1	1.3	1.3	1.23	0.12
O_2	0.6	0.7	0.7	0.67	0.06
CH_4	59.2	59	59	59.07	0.12
CO_2	37.8	37.6	37.7	37.70	0.10
P104L					
N_2	2.1	2.2	1.9	2.07	0.15
O_2	1	1	0.9	0.97	0.06
CH_4	58.4	58.2	58.6	58.40	0.20
CO_2	37.3	37	37.3	37.20	0.17
P105L					
N_2	1.9	1.4	2.1	1.80	0.36
O_2	0.9	0.7	1.4	1.00	0.36
CH_4	49.6	49.5	48.9	49.33	0.38
CO_2	46.6	47.5	46.7	46.93	0.49

Table A.8 Percent Gas Concentration Results (21st August, 2003)

Location	Sample1	Sample2	Sample3	% Average	S.D.
P101L					
N_2	3.8	3.7	4.3	3.93	0.32
O_2	1.5	1.4	1.6	1.50	0.10
CH_4	53	53.8	53.6	53.47	0.42
CO_2	39.8	39.4	38.73	39.31	0.54
P102L					
N_2	2.6	2.4	3.4	2.80	0.53
O_2	1.1	1.1	1.3	1.17	0.12
CH_4	56.7	57.2	56.5	56.80	0.36
CO_2	38.3	38.1	37.4	37.93	0.47
P103L					
N_2	3.3	3.2	3.1	3.20	0.10
O_2	1.3	1.3	1.3	1.30	0.00
CH_4	58.2	58.4	58.5	58.37	0.15
CO_2	35.6	35.7	35.8	35.70	0.10
P104L					
N_2	3.8	3.7	4.6	4.03	0.49
O_2	1.5	1.4	4.7	2.53	1.88
CH_4	58.1	58.1	46.2	54.13	6.87
CO_2	35.5	35.6	29.8	33.63	3.32
P105L					
N_2	3.9	3.3	3.7	3.63	0.31
O_2	1.5	1.3	1.4	1.40	0.10
CH_4	52.3	52.7	52.3	52.43	0.23
CO_2	41.3	41.8	41.8	41.63	0.29

Table A.9 Percent Gas Concentration Results (28th August, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.6	0.7	0.7	0.67	0.06
O_2	0.3	0.3	0.3	0.30	0.00
CH_4	54.8	55	55.2	55.00	0.20
CO_2	43.5	43.6	43.5	43.53	0.06
P102L					
N_2	1.2	1.2	1.2	1.20	0.00
O_2	0.4	0.5	0.4	0.43	0.06
CH_4	56.9	57.4	57.7	57.33	0.40
CO_2	41.2	40.7	40.8	40.90	0.26
P103L					
N_2	0.9	0.9	0.9	0.90	0.00
O_2	0.4	0.4	0.3	0.37	0.06
CH_4	59.3	57.3	59.7	58.77	1.29
CO_2	39.3	39	38.6	38.97	0.35
P104L					
N_2	N/A	3.6	1.1	2.35	1.77
O_2	N/A	1.1	0.4	0.75	0.49
CH_4	N/A	57	59.3	58.15	1.63
CO_2	N/A	37.7	39.1	38.40	0.99
P105L					
N_2	1.5	1.4	1.4	1.43	0.06
O_2	0.5	0.5	0.5	0.50	0.00
CH_4	54.5	54.7	54.7	54.63	0.12
CO_2	43.2	43	43.2	43.13	0.12

Table A.10 Percent Gas Concentration Results (11th September, 2003)

Location	Sample1	Sample2	Sample3	% Average	S.D.
P101L					
N_2	0.8	0.7	0.7	0.73	0.06
O_2	0.3	0.3	0.3	0.30	0.00
CH_4	55.1	55.9	56.4	55.80	0.66
CO_2	43.4	42.9	42.5	42.93	0.45
P102L					
N_2	0.5	0.7	0.9	0.70	0.20
O_2	0.2	0.3	0.4	0.30	0.10
CH_4	57.8	57.7	57.8	57.77	0.06
CO_2	41.7	41.6	41.1	41.47	0.32
P103L					
N_2	3.2	3.8	3.5	3.50	0.30
O_2	1	1.2	1.1	1.10	0.10
CH_4	57.1	57	57.5	57.20	0.26
CO_2	38.2	37.5	37.1	37.60	0.56
P104L					
N_2	7.4	7.1	7.2	7.15	0.07
O_2	2.3	2.2	2.3	2.25	0.07
CH_4	54	53.8	53.7	53.75	0.07
CO_2	34.8	35.1	35	35.05	0.07
P105L					
N_2	2.8	2.2	2	2.33	0.42
O_2	0.9	0.7	0.7	0.77	0.12
CH_4	54	54.6	54.7	54.43	0.38
CO_2	41.9	42.4	42.4	42.23	0.29

Table A.11 Percent Gas Concentration Results (25th September, 2003)

Location	Sample1	Sample2	Sample3	% Average	S.D.
P101L					
N_2	1.7	9.3	1.2	4.07	4.54
O_2	0.6	2.7	0.4	1.23	1.27
CH_4	54.1	47.1	55.3	52.17	4.43
CO_2	43.2	39.1	42.6	41.63	2.21
P102L					
N_2	0.6	1.3	0.8	0.90	0.36
O_2	0.3	0.4	0.3	0.33	0.06
CH_4	57.2	56.6	57.1	56.97	0.32
CO_2	41.7	41.3	41.5	41.50	0.20
P103L					
N_2	1.8	1.2	1.9	1.63	0.38
O_2	0.6	0.6	0.6	0.60	0.00
CH_4	57.8	58.9	58.3	58.33	0.55
CO_2	39	36.5	37.9	37.80	1.25
P104L					
N_2	1.4	5.1	0.9	3.00	2.97
O_2	0.5	1.6	0.3	0.95	0.92
CH_4	58.5	55	59	57.00	2.83
CO_2	38.8	37.1	39.1	38.10	1.41
P105L					
N_2	0.7	0.8	0.7	0.73	0.06
O_2	0.3	0.3	0.3	0.30	0.00
CH_4	56.1	56	56	56.03	0.06
CO_2	41.9	42	42	41.97	0.06

Table A.12 Percent Gas Concentration Results (9th October, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	1.2	2	1.9	1.70	0.44
O_2	0.4	0.7	0.6	0.57	0.15
CH_4	55.1	54.8	55.1	55.00	0.17
CO_2	43	41.9	41.9	42.27	0.64
P102L					
N_2	1.8	1.7	1.7	1.73	0.06
O_2	0.6	0.6	0.6	0.60	0.00
CH_4	56.9	56.4	56.4	56.57	0.29
CO_2	41.2	40.7	40.7	40.87	0.29
P103L					
N_2	N/A	0.9	1.2	1.05	0.21
O_2	N/A	0.4	0.4	0.40	0.00
CH_4	N/A	59	59.1	59.05	0.07
CO_2	N/A	38.6	38.1	38.35	0.35
P104L					
N_2	2.1	1.8	1.9	1.85	0.07
O_2	0.7	0.6	0.6	0.60	0.00
CH_4	58.3	58.6	58.6	58.60	0.00
CO_2	38	38.2	38.3	38.25	0.07
P105L					
N_2	1.9	3.3	1.8	2.33	0.84
O_2	0.6	1	0.6	0.73	0.23
CH_4	56.4	55.3	56.5	56.07	0.67
CO_2	40.4	39.3	40	39.90	0.56

Table A.13 Percent Gas Concentration Results (23rd October, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.9	0.8	N/A	0.85	0.07
O_2	0.4	0.3	N/A	0.35	0.07
CH_4	55.2	55.8	N/A	55.50	0.42
CO_2	42.4	42.4	N/A	42.40	0.00
P102L					
N_2	2.3	1.7	1.6	1.87	0.38
O_2	0.8	0.6	0.6	0.67	0.12
CH_4	56.2	56.7	56.8	56.57	0.32
CO_2	40	40.4	40.5	40.30	0.26
P103L					
N_2	9.5	8.1	7.6	8.40	0.98
O_2	3.1	2.7	2.5	2.77	0.31
CH_4	50.5	52	52.7	51.73	1.12
CO_2	32.7	33.7	33.8	33.40	0.61
P104L					
N_2	2.5	7.8	2.4	4.23	3.09
O_2	0.9	2.6	0.9	1.47	0.98
CH_4	58.4	52.7	58.3	56.47	3.26
CO_2	37.4	33.4	37.3	36.03	2.28
P105L					
N_2	10.7	2.6	7.2	6.83	4.06
O_2	3.6	0.9	2.4	2.30	1.35
CH_4	48	56.5	52	52.17	4.25
CO_2	32.9	38.9	35.4	35.73	3.01

Table A.14 Percent Gas Concentration Results (13th November, 2003)

Location	Sample1	Sample2	Sample3	% Average	S.D.
P101L					
N_2	0.5	4.9	0.9	2.10	2.43
O_2	0.2	1.1	0.3	0.53	0.49
CH_4	57	53	57.1	55.70	2.34
CO_2	43	41.8	42.9	42.57	0.67
P102L					
N_2	9.9	1.6	1.8	4.43	4.74
O_2	2.4	0.4	0.5	1.10	1.13
CH_4	51.4	58	58.3	55.90	3.90
CO_2	36.6	41.3	40.8	39.57	2.58
P103L					
N_2	14.4	7	12.1	11.17	3.79
O_2	3.5	1.6	3	2.70	0.98
CH_4	49.2	54.4	51.5	51.70	2.61
CO_2	32.2	37.7	33	34.30	2.97
P104L					
N_2	16.7	17.5	8	14.07	5.27
O_2	4.1	4.3	2	3.47	1.27
CH_4	47.6	45.9	53.6	49.03	4.05
CO_2	30.6	30.9	36.9	32.80	3.55
P105L					
N_2	13.3	8.3	3.2	8.27	5.05
O_2	3.2	2	0.8	2.00	1.20
CH_4	49	54.9	58.9	54.27	4.98
CO_2	33.9	35.5	38.3	35.90	2.23

Table A.15 Percent Gas Concentration Results (9th December, 2003)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	1.5	1.1	1.3	1.30	0.20
O_2	0.5	0.4	0.5	0.47	0.06
CH_4	56.5	57.2	57.2	56.97	0.40
CO_2	41.8	42	41.5	41.77	0.25
P102L					
N_2	0.6	0.9	0.7	0.73	0.15
O_2	0.2	0.3	0.3	0.27	0.06
CH_4	58.5	58.4	58.9	58.60	0.26
CO_2	41.8	41.4	41.1	41.43	0.35
P103L					
N_2	1	2.2	2.5	1.90	0.79
O_2	0.4	0.7	0.8	0.63	0.21
CH_4	59.6	58.3	58.2	58.70	0.78
CO_2	39.5	38.4	37.8	38.57	0.86
P104L					
N_2	2.5	1.2	0.8	1.50	0.89
O_2	0.8	0.4	0.3	0.50	0.26
CH_4	58.8	60.4	N/A	59.60	1.13
CO_2	37.6	38.6	38.9	38.37	0.68
P105L					
N_2	1.1	0.9	1.4	1.13	0.25
O_2	0.4	0.3	0.5	0.40	0.10
CH_4	58.3	58.8	58.3	58.47	0.29
CO_2	40.6	40.7	40.2	40.50	0.26

Table A.16 Percent Gas Concentration Results (8th January, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	0.5	1	1.2	0.90	0.36
O_2	0.2	0.3	0.3	0.27	0.06
CH_4	57.7	57.7	57.9	57.77	0.12
CO_2	42.4	42.3	42.1	42.27	0.15
P102L					
N_2	1.2	1.7	2.8	1.90	0.82
O_2	0.4	0.5	0.7	0.53	0.15
CH_4	58.5	58.2	57.6	58.10	0.46
CO_2	41.6	41.3	40.5	41.13	0.57
P103L					
N_2	2.2	5.3	1.5	3.00	2.02
O_2	0.6	1.3	0.4	0.77	0.47
CH_4	59.5	56.1	60.2	58.60	2.19
CO_2	39.2	38.6	39.4	39.07	0.42
P104L					
N_2	1.3	1.2	1.6	1.37	0.21
O_2	0.4	0.4	0.5	0.43	0.06
CH_4	60.9	61.1	60.8	60.93	0.15
CO_2	39	39	38.9	38.97	0.06
P105L					
N_2	4.6	2.4	2.3	3.10	1.30
O_2	1.2	0.6	0.6	0.80	0.35
CH_4	55.5	57.4	57.6	56.83	1.16
CO_2	40	41.2	41.1	40.77	0.67

Table A.17 Percent Gas Concentration Results (12th February, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	4.4	1	1.8	2.40	1.78
O_2	1.3	0.5	0.7	0.83	0.42
CH_4	55.4	58.7	58.2	57.43	1.78
CO_2	38.6	40	39.5	39.37	0.71
P102L					
N_2	5.5	1.7	3.9	3.70	1.91
O_2	1.6	0.7	1.2	1.17	0.45
CH_4	55.3	59	57.4	57.23	1.86
CO_2	37.6	39.2	37.8	38.20	0.87
P103L					
N_2	1.3	3.1	1.8	2.07	0.93
O_2	0.6	1	0.7	0.77	0.21
CH_4	60.4	59.5	60.7	60.20	0.62
CO_2	38.3	36.7	37	37.33	0.85
P104L					
N_2	3.4	2.8	3.9	3.37	0.55
O_2	1.1	0.9	1.2	1.07	0.15
CH_4	59.6	60.1	59.2	59.63	0.45
CO_2	36.3	36.7	36	36.33	0.35
P105L					
N_2	4.6	2.4	2.3	3.10	1.30
O_2	1.2	0.6	0.6	0.80	0.35
CH_4	55.5	57.4	57.6	56.83	1.16
CO_2	40	41.2	41.1	40.77	0.67

Table A.18 Percent Gas Concentration Results (18th March, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	6.1	11.6	5.1	7.60	3.50
O_2	1.7	3.1	1.5	2.10	0.87
CH_4	54.8	49.4	55.4	53.20	3.30
CO_2	35.6	34.2	37.3	35.70	1.55
P102L					
N_2	9.5	3.1	6.7	6.43	3.21
O_2	2.6	1	1.9	1.83	0.80
CH_4	51.8	57.3	54.6	54.57	2.75
CO_2	34.7	38.1	36.1	36.30	1.71
P103L					
N_2	3.6	7.1	3.3	4.67	2.11
O_2	1.1	2	1.1	1.40	0.52
CH_4	58.2	55.5	58.5	57.40	1.65
CO_2	36.7	34.6	36.8	36.03	1.24
P104L					
N_2	5.9	3.7	7.8	5.80	2.05
O_2	1.7	1.2	2.2	1.70	0.50
CH_4	57.6	59.4	55.9	57.63	1.75
CO_2	34.1	35.4	33	34.17	1.20
P105L					
N_2	14.3	5.9	12.1	10.77	4.36
O_2	3.8	1.7	3.2	2.90	1.08
CH_4	56.8	53.7	48.7	53.07	4.09
CO_2	32.8	37.8	34	34.87	2.61

Table A.19 Percent Gas Concentration Results (22nd April, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	5.5	5.5	5	5.33	0.29
O_2	1.7	1.7	1.5	1.63	0.12
CH_4	55	55.1	55.6	55.23	0.32
CO_2	37.3	37.4	37.7	37.47	0.21
P102L					
N_2	8.1	11.6	7.2	8.97	2.32
O_2	2.3	3.2	2.1	2.53	0.59
CH_4	53.7	51.1	54.6	53.13	1.82
CO_2	35.6	33.3	35.9	34.93	1.42
P103L					
N_2	6.2	8.4	6.1	6.90	1.30
O_2	1.8	2.4	1.8	2.00	0.35
CH_4	56.6	54.8	57.1	56.17	1.21
CO_2	35.3	33.9	34.8	34.67	0.71
P104L					
N_2	4	6.3	4.4	4.90	1.23
O_2	1.3	1.9	1.4	1.53	0.32
CH_4	59.7	57.8	59.4	58.97	1.02
CO_2	35.1	33.9	34.9	34.63	0.64
P105L					
N_2	6.5	1.2	13	6.90	5.91
O_2	1.9	0.6	3.5	2.00	1.45
CH_4	53.6	57.8	48.3	53.23	4.76
CO_2	38.1	41.1	34.1	37.77	3.51

Table A.20 Percent Gas Concentration Results (20th May, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	4.4	N/A	N/A	4.40	0.00
O_2	1.1	N/A	N/A	1.10	0.00
CH_4	53.5	N/A	N/A	53.50	0.00
CO_2	41.3	N/A	N/A	41.30	0.00
P102L					
N_2	7.8	9.7	7.7	8.40	1.13
O_2	1.9	2.3	1.8	2.00	0.26
CH_4	53.3	54	53.6	53.63	0.35
CO_2	37.5	36.4	37.4	37.10	0.61
P103L					
N_2	N/A	9.5	N/A	9.50	0.00
O_2	N/A	2.2	N/A	2.20	0.00
CH_4	N/A	52	N/A	52.00	0.00
CO_2	N/A	36.5	N/A	36.50	0.00
P104L					
N_2	9.5	N/A	N/A	9.50	0.00
O_2	2.2	N/A	N/A	2.20	0.00
CH_4	52	N/A	N/A	52.00	0.00
CO_2	36.5	N/A	N/A	36.50	0.00
P105L					
N_2	2.1	2.6	N/A	2.35	0.35
O_2	0.6	0.7	N/A	0.65	0.07
CH_4	55.2	54.9	N/A	55.05	0.21
CO_2	42.8	42.6	N/A	42.70	0.14

Table A.21 Percent Gas Concentration Results (17th June, 2004)

Location	**Sample1**	**Sample2**	**Sample3**	**% Average**	**S.D.**
P101L					
N_2	4.4	5.1	N/A	4.75	0.49
O_2	1.1	2.6	N/A	1.85	1.06
CH_4	53.5	58.2	N/A	55.85	3.32
CO_2	41.3	38.2	N/A	39.75	2.19
P102L					
N_2	2.2	1.6	1.5	1.77	0.38
O_2	1.8	0.5	0.4	0.90	0.78
CH_4	53.9	58	58.1	56.67	2.40
CO_2	40	40.1	40	40.03	0.06
P103L					
N_2	1.9	2.3	1.8	2.00	0.26
O_2	0.5	0.6	0.4	0.50	0.10
CH_4	58.5	59.1	57	58.20	1.08
CO_2	38.5	37.5	39	38.33	0.76
P104L					
N_2	2.3	3.3	2.7	2.77	0.50
O_2	0.8	0.7	1.5	1.00	0.44
CH_4	56.2	58.3	40.4	51.63	9.78
CO_2	37.6	32.6	33.9	34.70	2.59
P105L					
N_2	2.5	3.2	3.9	3.20	0.70
O_2	1.8	1.5	1.7	1.67	0.15
CH_4	57.1	54.8	57.7	56.53	1.53
CO_2	35.2	33.5	35.5	34.73	1.08

APPENDIX B: RESULTS OF TRACE CONTAMINANTS

Table B.1 Results of hydrogen sulfide monitoring in five locations at Brady Road landfill.

Location	Hydrogen Sulfide Concentration (% by volume)		
	24/07/03	11/09/03	12/02/04
L101P	0.05	0.05	0.05
L102P	<0.05	<0.05	<0.05
L103P	0.43	0.20	0.55
L104P	<0.05	<0.05	0.25
L105P	<0.05	<0.05	<0.05

Table B.2 Results of Vinyl Chloride monitoring in five locations at Brady Road landfill.

Location	Vinyl Chloride Concentration (ppm)	
	11/09/03	12/02/04
L101P	<0.1	<0.05
L102P	0.4	0.1
L103P	<0.1	<0.05
L104P	0.2	<0.05
L105P	0.2	0.1

APPENDIX C: RESULTS OF ESTIMATED LANDFILL GAS GENERATION

Table C.1 Estimated Landfill Gas Generation Based of Environment Canada Default Values (Lo = 1.87 ft^3/lb; K = 0.006)

Year	Amount of Waste (tones)	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	Waste Diversion Options		
					25%	50%	75%
2006	450000	0.009	34.000	781.2129	195.3032	390.6065	585.9097
2007	450000	0.009	35.000	824.2348	206.0587	412.1174	618.1761
2008	450000	0.009	36.000	866.9992	216.7498	433.4996	650.2494
2009	450000	0.009	37.000	909.5079	227.3770	454.7539	682.1309
2010	450000	0.009	38.000	951.7623	237.9406	475.8811	713.8217
2010	450000	0.009	39.000	993.7638	248.4410	496.8819	745.3229
2011	450000	0.009	40.000	1035.5142	258.8785	517.7571	776.6356
2012	450000	0.009	41.000	1077.0148	269.2537	538.5074	807.7611
2013	450000	0.009	42.000	1118.2671	279.5668	559.1336	838.7003
2014	450000	0.009	43.000	1159.2727	289.8182	579.6363	869.4545
2015	450000	0.009	44.000	1200.0329	300.0082	600.0165	900.0247
2016	450000	0.009	45.000	1240.5494	310.1373	620.2747	930.4120
2017	450000	0.009	46.000	1280.8234	320.2059	640.4117	960.6176
2018	450000	0.009	47.000	1320.8566	330.2141	660.4283	990.6424
2019	450000	0.009	48.000	1360.6502	340.1626	680.3251	1020.4877
2020	450000	0.009	49.000	1400.2059	350.0515	700.1029	1050.1544
2021	450000	0.009	50.000	1439.5248	359.8812	719.7624	1079.6436
2022	450000	0.009	51.000	1478.6086	369.6522	739.3043	1108.9565
2023	450000	0.009	52.000	1517.4586	379.3647	758.7293	1138.0940
2024	450000	0.009	53.000	1556.0762	389.0190	778.0381	1167.0571
2025	450000	0.009	54.000	1594.4628	398.6157	797.2314	1195.8471
2026	450000	0.009	55.000	1632.6197	408.1549	816.3099	1224.4648
2027	450000	0.009	56.000	1670.5484	417.6371	835.2742	1252.9113
2028	450000	0.009	57.000	1708.2502	427.0625	854.1251	1281.1876
2029	450000	0.009	58.000	1745.7264	436.4316	872.8632	1309.2948
2030	450000	0.009	59.000	1782.9785	445.7446	891.4893	1337.2339
2031	450000	0.009	60.000	1820.0078	455.0019	910.0039	1365.0058
2032	450000	0.009	61.000	1856.8155	464.2039	928.4077	1392.6116
2033	450000	0.009	62.000	1893.4030	473.3508	946.7015	1420.0523
2034	450000	0.009	63.000	1929.7717	482.4429	964.8858	1447.3288
2035	450000	0.009	64.000	1965.9228	491.4807	982.9614	1474.4421
2036	450000	0.009	65.000	2001.8576	500.4644	1000.9288	1501.3932
2037	450000	0.009	66.000	2037.5775	509.3944	1018.7888	1528.1832
2038	450000	0.009	67.000	2073.0837	518.2709	1036.5419	1554.8128
2039	450000	0.009	68.000	2108.3776	527.0944	1054.1888	1581.2832
2040	450000	0.009	69.000	2143.4602	535.8651	1071.7301	1607.5952
2041	450000	0.009	70.000	2178.3331	544.5833	1089.1665	1633.7498
2042	450000	0.009	71.000	2212.9973	553.2493	1106.4986	1659.7480
2043	450000	0.009	72.000	2247.4541	561.8635	1123.7271	1685.5906
2044	450000	0.009	73.000	2281.7048	570.4262	1140.8524	1711.2786

Table C.1 Continued

2045	450000	0.009	74.000	2315.7507	578.9377	1157.8753	1736.8130
2046	450000	0.009	75.000	2349.5928	587.3982	1174.7964	1762.1946
2047	450000	0.009	76.000	2383.2326	595.8081	1191.6163	1787.4244
2048	450000	0.009	77.000	2416.6711	604.1678	1208.3355	1812.5033
2049	450000	0.009	78.000	2449.9095	612.4774	1224.9548	1837.4321
2050	450000	0.009	79.000	2482.9491	620.7373	1241.4746	1862.2119

Table C.2 Estimated Landfill Gas Generation Based of Clean Air Act (CAA) Default Values (Lo = 2.72 ft^3/lb; K = 0.05)

Year	Amount of Waste (tones)	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	Waste Diversion Options		
					25%	50%	75%
2006	450000	0.009	34.000	3723.772	930.9429	1861.886	2792.829
2007	450000	0.009	35.000	3835.566	958.8916	1917.783	2876.675
2008	450000	0.009	36.000	3941.909	985.4772	1970.954	2956.432
2009	450000	0.009	37.000	4043.065	1010.766	2021.532	3032.299
2010	450000	0.009	38.000	4139.287	1034.822	2069.644	3104.466
2010	450000	0.009	39.000	4230.817	1057.704	2115.409	3173.113
2011	450000	0.009	40.000	4317.883	1079.471	2158.942	3238.412
2012	450000	0.009	41.000	4400.703	1100.176	2200.351	3300.527
2013	450000	0.009	42.000	4479.483	1119.871	2239.742	3359.612
2014	450000	0.009	43.000	4554.421	1138.605	2277.211	3415.816
2015	450000	0.009	44.000	4625.705	1156.426	2312.852	3469.279
2016	450000	0.009	45.000	4693.512	1173.378	2346.756	3520.134
2017	450000	0.009	46.000	4758.012	1189.503	2379.006	3568.509
2018	450000	0.009	47.000	4819.366	1204.842	2409.683	3614.525
2019	450000	0.009	48.000	4877.728	1219.432	2438.864	3658.296
2020	450000	0.009	49.000	4933.244	1233.311	2466.622	3699.933
2021	450000	0.009	50.000	4986.052	1246.513	2493.026	3739.539
2022	450000	0.009	51.000	5036.284	1259.071	2518.142	3777.213
2023	450000	0.009	52.000	5084.067	1271.017	2542.034	3813.05
2024	450000	0.009	53.000	5129.519	1282.38	2564.76	3847.14
2025	450000	0.009	54.000	5172.755	1293.189	2586.378	3879.566
2026	450000	0.009	55.000	5213.882	1303.471	2606.941	3910.412
2027	450000	0.009	56.000	5253.003	1313.251	2626.502	3939.752
2028	450000	0.009	57.000	5290.217	1322.554	2645.108	3967.662
2029	450000	0.009	58.000	5325.615	1331.404	2662.807	3994.211
2030	450000	0.009	59.000	5359.287	1339.822	2679.643	4019.465
2031	450000	0.009	60.000	5391.317	1347.829	2695.658	4043.487
2032	450000	0.009	61.000	5421.784	1355.446	2710.892	4066.338
2033	450000	0.009	62.000	5450.766	1362.691	2725.383	4088.074
2034	450000	0.009	63.000	5478.334	1369.584	2739.167	4108.751
2035	450000	0.009	64.000	5504.558	1376.139	2752.279	4128.418
2036	450000	0.009	65.000	5529.503	1382.376	2764.751	4147.127
2037	450000	0.009	66.000	5553.231	1388.308	2776.615	4164.923
2038	450000	0.009	67.000	5575.802	1393.95	2787.901	4181.851
2039	450000	0.009	68.000	5597.272	1399.318	2798.636	4197.954
2040	450000	0.009	69.000	5617.695	1404.424	2808.848	4213.271
2041	450000	0.009	70.000	5637.122	1409.281	2818.561	4227.842
2042	450000	0.009	71.000	5655.602	1413.9	2827.801	4241.701
2043	450000	0.009	72.000	5673.18	1418.295	2836.59	4254.885
2044	450000	0.009	73.000	5689.901	1422.475	2844.95	4267.426
2045	450000	0.009	74.000	5705.806	1426.452	2852.903	4279.355
2046	450000	0.009	75.000	5720.936	1430.234	2860.468	4290.702

Table C.2 Continued

2047	450000	0.009	76.000	5735.328	1433.832	2867.664	4301.496
2048	450000	0.009	77.000	5749.018	1437.255	2874.509	4311.764
2049	450000	0.009	78.000	5762.04	1440.51	2881.02	4321.53
2050	450000	0.009	79.000	5774.428	1443.607	2887.214	4330.821

Table C.3 Estimated Landfill Gas Generation Based of AP-42 (Wet) Default Values (Lo = 1.60 ft^3/lb; K = 0.04)

Year	Amount of Waste (tones)	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	Waste Diversion Options		
					25%	50%	75%
2006	450000	0.009	34.000	2136.811	534.2028	1068.406	1602.609
2007	450000	0.009	35.000	2211.467	552.8669	1105.734	1658.601
2008	450000	0.009	36.000	2283.196	570.7991	1141.598	1712.397
2009	450000	0.009	37.000	2352.113	588.0282	1176.056	1764.084
2010	450000	0.009	38.000	2418.327	604.5817	1209.163	1813.745
2010	450000	0.009	39.000	2481.944	620.4861	1240.972	1861.458
2011	450000	0.009	40.000	2543.068	635.7669	1271.534	1907.301
2012	450000	0.009	41.000	2601.794	650.4486	1300.897	1951.346
2013	450000	0.009	42.000	2658.218	664.5546	1329.109	1993.664
2014	450000	0.009	43.000	2712.43	678.1074	1356.215	2034.322
2015	450000	0.009	44.000	2764.516	691.1289	1382.258	2073.387
2016	450000	0.009	45.000	2814.559	703.6398	1407.28	2110.919
2017	450000	0.009	46.000	2862.64	715.6601	1431.32	2146.98
2018	450000	0.009	47.000	2908.836	727.2091	1454.418	2181.627
2019	450000	0.009	48.000	2953.221	738.3052	1476.61	2214.916
2020	450000	0.009	49.000	2995.865	748.9663	1497.933	2246.899
2021	450000	0.009	50.000	3036.837	759.2093	1518.419	2277.628
2022	450000	0.009	51.000	3076.203	769.0507	1538.101	2307.152
2023	450000	0.009	52.000	3114.025	778.5063	1557.013	2335.519
2024	450000	0.009	53.000	3150.364	787.591	1575.182	2362.773
2025	450000	0.009	54.000	3185.278	796.3196	1592.639	2388.959
2026	450000	0.009	55.000	3218.823	804.7059	1609.412	2414.118
2027	450000	0.009	56.000	3251.053	812.7633	1625.527	2438.29
2028	450000	0.009	57.000	3282.019	820.5048	1641.01	2461.515
2029	450000	0.009	58.000	3311.771	827.9428	1655.886	2483.828
2030	450000	0.009	59.000	3340.357	835.0891	1670.178	2505.267
2031	450000	0.009	60.000	3367.821	841.9553	1683.911	2525.866
2032	450000	0.009	61.000	3394.209	848.5522	1697.104	2545.656
2033	450000	0.009	62.000	3419.562	854.8904	1709.781	2564.671
2034	450000	0.009	63.000	3443.92	860.9801	1721.96	2582.94
2035	450000	0.009	64.000	3467.324	866.831	1733.662	2600.493
2036	450000	0.009	65.000	3489.81	872.4525	1744.905	2617.357
2037	450000	0.009	66.000	3511.414	877.8536	1755.707	2633.561
2038	450000	0.009	67.000	3532.171	883.0429	1766.086	2649.129
2039	450000	0.009	68.000	3552.115	888.0287	1776.057	2664.086
2040	450000	0.009	69.000	3571.276	892.819	1785.638	2678.457
2041	450000	0.009	70.000	3589.686	897.4215	1794.843	2692.265
2042	450000	0.009	71.000	3607.374	901.8435	1803.687	2705.531
2043	450000	0.009	72.000	3624.369	906.0922	1812.184	2718.277
2044	450000	0.009	73.000	3640.697	910.1742	1820.348	2730.523
2045	450000	0.009	74.000	3656.385	914.0962	1828.192	2742.289
2046	450000	0.009	75.000	3671.458	917.8644	1835.729	2753.593

Table C.3 Continued							
2047	450000	0.009	76.000	3685.939	921.4849	1842.97	2764.455
2048	450000	0.009	77.000	3699.853	924.9634	1849.927	2774.89
2049	450000	0.009	78.000	3713.222	928.3055	1856.611	2784.916
2050	450000	0.009	79.000	3726.066	931.5165	1863.033	2794.55

Table C.4 Estimated Landfill Gas Generation Based of AP-42 (Dry) Default Values (Lo = 1.60 ft^3/lb; K = 0.02)

Year	Amount of Waste (tones)	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	Waste Diversion Options		
					25%	50%	75%
2006	450000	0.009	34.000	1628.362	407.0906	814.1812	1221.272
2007	450000	0.009	35.000	1703.532	425.883	851.766	1277.649
2008	450000	0.009	36.000	1777.213	444.3033	888.6065	1332.91
2009	450000	0.009	37.000	1849.435	462.3588	924.7176	1387.076
2010	450000	0.009	38.000	1920.227	480.0568	960.1136	1440.17
2010	450000	0.009	39.000	1989.617	497.4043	994.8087	1492.213
2011	450000	0.009	40.000	2057.633	514.4084	1028.817	1543.225
2012	450000	0.009	41.000	2124.303	531.0757	1062.151	1593.227
2013	450000	0.009	42.000	2189.652	547.413	1094.826	1642.239
2014	450000	0.009	43.000	2253.707	563.4268	1126.854	1690.28
2015	450000	0.009	44.000	2316.494	579.1235	1158.247	1737.371
2016	450000	0.009	45.000	2378.038	594.5094	1189.019	1783.528
2017	450000	0.009	46.000	2438.363	609.5907	1219.181	1828.772
2018	450000	0.009	47.000	2497.493	624.3733	1248.747	1873.12
2019	450000	0.009	48.000	2555.453	638.8632	1277.726	1916.59
2020	450000	0.009	49.000	2612.265	653.0661	1306.132	1959.198
2021	450000	0.009	50.000	2667.952	666.9879	1333.976	2000.964
2022	450000	0.009	51.000	2722.536	680.6339	1361.268	2041.902
2023	450000	0.009	52.000	2776.039	694.0098	1388.02	2082.029
2024	450000	0.009	53.000	2828.483	707.1208	1414.242	2121.362
2025	450000	0.009	54.000	2879.889	719.9722	1439.944	2159.917
2026	450000	0.009	55.000	2930.276	732.5691	1465.138	2197.707
2027	450000	0.009	56.000	2979.666	744.9166	1489.833	2234.75
2028	450000	0.009	57.000	3028.078	757.0195	1514.039	2271.059
2029	450000	0.009	58.000	3075.531	768.8829	1537.766	2306.649
2030	450000	0.009	59.000	3122.045	780.5113	1561.023	2341.534
2031	450000	0.009	60.000	3167.638	791.9094	1583.819	2375.728
2032	450000	0.009	61.000	3212.328	803.0819	1606.164	2409.246
2033	450000	0.009	62.000	3256.132	814.0331	1628.066	2442.099
2034	450000	0.009	63.000	3299.07	824.7675	1649.535	2474.302
2035	450000	0.009	64.000	3341.157	835.2893	1670.579	2505.868
2036	450000	0.009	65.000	3382.411	845.6028	1691.206	2536.808
2037	450000	0.009	66.000	3422.848	855.712	1711.424	2567.136
2038	450000	0.009	67.000	3462.484	865.6211	1731.242	2596.863
2039	450000	0.009	68.000	3501.336	875.334	1750.668	2626.002
2040	450000	0.009	69.000	3539.418	884.8545	1769.709	2654.564
2041	450000	0.009	70.000	3576.746	894.1865	1788.373	2682.56
2042	450000	0.009	71.000	3613.335	903.3338	1806.668	2710.001
2043	450000	0.009	72.000	3649.199	912.2999	1824.6	2736.9
2044	450000	0.009	73.000	3684.354	921.0884	1842.177	2763.265
2045	450000	0.009	74.000	3718.812	929.703	1859.406	2789.109
2046	450000	0.009	75.000	3752.588	938.1469	1876.294	2814.441

Table C.4 Continued							
2047	450000	0.009	76.000	3785.695	946.4237	1892.847	2839.271
2048	450000	0.009	77.000	3818.146	954.5365	1909.073	2863.61
2049	450000	0.009	78.000	3849.955	962.4888	1924.978	2887.466
2050	450000	0.009	79.000	3881.134	970.2835	1940.567	2910.851

Table C.5 Estimated Landfill Gas Generation Based of Brady Road Values (Lo = 1.78 ft^3/lb; K = 0.01)

Year	Amount of Waste (tones)	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	Waste Diversion Options		
					25%	50%	75%
2006	450000	0.009	34.000	1131.467	282.8667	565.7333	848.6
2007	450000	0.009	35.000	1190.802	297.7005	595.4011	893.1016
2008	450000	0.009	36.000	1249.547	312.3868	624.7736	937.1604
2009	450000	0.009	37.000	1307.708	326.927	653.8539	980.7809
2010	450000	0.009	38.000	1365.29	341.3224	682.6449	1023.967
2010	450000	0.009	39.000	1422.299	355.5747	711.1494	1066.724
2011	450000	0.009	40.000	1478.74	369.6851	739.3702	1109.055
2012	450000	0.009	41.000	1534.62	383.6551	767.3102	1150.965
2013	450000	0.009	42.000	1589.945	397.4861	794.9723	1192.458
2014	450000	0.009	43.000	1644.718	411.1795	822.3591	1233.539
2015	450000	0.009	44.000	1698.947	424.7367	849.4734	1274.21
2016	450000	0.009	45.000	1752.636	438.1589	876.3179	1314.477
2017	450000	0.009	46.000	1805.791	451.4476	902.8953	1354.343
2018	450000	0.009	47.000	1858.416	464.6041	929.2082	1393.812
2019	450000	0.009	48.000	1910.519	477.6297	955.2593	1432.889
2020	450000	0.009	49.000	1962.103	490.5256	981.0513	1471.577
2021	450000	0.009	50.000	2013.173	503.2933	1006.587	1509.88
2022	450000	0.009	51.000	2063.735	515.9339	1031.868	1547.802
2023	450000	0.009	52.000	2113.795	528.4487	1056.897	1585.346
2024	450000	0.009	53.000	2163.356	540.839	1081.678	1622.517
2025	450000	0.009	54.000	2212.424	553.106	1106.212	1659.318
2026	450000	0.009	55.000	2261.004	565.251	1130.502	1695.753
2027	450000	0.009	56.000	2309.1	577.2751	1154.55	1731.825
2028	450000	0.009	57.000	2356.718	589.1795	1178.359	1767.539
2029	450000	0.009	58.000	2403.862	600.9656	1201.931	1802.897
2030	450000	0.009	59.000	2450.537	612.6343	1225.269	1837.903
2031	450000	0.009	60.000	2496.748	624.1869	1248.374	1872.561
2032	450000	0.009	61.000	2542.499	635.6246	1271.249	1906.874
2033	450000	0.009	62.000	2587.794	646.9485	1293.897	1940.846
2034	450000	0.009	63.000	2632.639	658.1597	1316.319	1974.479
2035	450000	0.009	64.000	2677.037	669.2594	1338.519	2007.778
2036	450000	0.009	65.000	2720.994	680.2486	1360.497	2040.746
2037	450000	0.009	66.000	2764.514	691.1284	1382.257	2073.385
2038	450000	0.009	67.000	2807.6	701.9001	1403.8	2105.7
2039	450000	0.009	68.000	2850.258	712.5645	1425.129	2137.693
2040	450000	0.009	69.000	2892.491	723.1228	1446.246	2169.368
2041	450000	0.009	70.000	2934.304	733.5761	1467.152	2200.728
2042	450000	0.009	71.000	2975.701	743.9253	1487.851	2231.776
2043	450000	0.009	72.000	3016.686	754.1716	1508.343	2262.515
2044	450000	0.009	73.000	3057.264	764.3159	1528.632	2292.948
2045	450000	0.009	74.000	3097.437	774.3593	1548.719	2323.078
2046	450000	0.009	75.000	3137.211	784.3027	1568.605	2352.908

Table C.5 Continued

2047	450000	0.009	76.000	3176.589	794.1472	1588.294	2382.442
2048	450000	0.009	77.000	3215.575	803.8938	1607.788	2411.681
2049	450000	0.009	78.000	3254.173	813.5434	1627.087	2440.63
2050	450000	0.009	79.000	3292.388	823.0969	1646.194	2469.291

APPENDIX D: RESULTS OF ESTIMATED GREENHOUSE GAS REDUCTION

Table D.1 Estimated Greenhouse Gas Emissions Reduction for 0% diversion option.

Year	Amount of Waste (tones	Fraction of Total Mass		Gas Gen. Rate (No Diversion)	GHG Reduction* (tonnes-eCO$_2$/year)
2004	450000	0.009	32.000	1011.001	75634.048
2005	450000	0.009	33.000	1071.535	80162.676
2006	450000	0.009	34.000	1131.467	84646.243
2007	450000	0.009	35.000	1190.802	89085.198
2008	450000	0.009	36.000	1249.547	93479.985
2009	450000	0.009	37.000	1307.708	97831.043
2010	450000	0.009	38.000	1365.29	102138.81
2010	450000	0.009	39.000	1422.299	106403.71
2011	450000	0.009	40.000	1478.74	110626.17
2012	450000	0.009	41.000	1534.62	114806.62
2013	450000	0.009	42.000	1589.945	118945.48
2014	450000	0.009	43.000	1644.718	123043.15
2015	450000	0.009	44.000	1698.947	127100.05
2016	450000	0.009	45.000	1752.636	131116.58
2017	450000	0.009	46.000	1805.791	135093.15
2018	450000	0.009	47.000	1858.416	139030.15
2019	450000	0.009	48.000	1910.519	142927.97
2020	450000	0.009	49.000	1962.103	146787.02
2021	450000	0.009	50.000	2013.173	150607.66
2022	450000	0.009	51.000	2063.735	154390.29
2023	450000	0.009	52.000	2113.795	158135.28
2024	450000	0.009	53.000	2163.356	161843.01
2025	450000	0.009	54.000	2212.424	165513.84
2026	450000	0.009	55.000	2261.004	169148.15
2027	450000	0.009	56.000	2309.1	172746.3
2028	450000	0.009	57.000	2356.718	176308.64
2029	450000	0.009	58.000	2403.862	179835.54
2030	450000	0.009	59.000	2450.537	183327.35
2031	450000	0.009	60.000	2496.748	186784.41
2032	450000	0.009	61.000	2542.499	190207.07
2033	450000	0.009	62.000	2587.794	193595.68
2034	450000	0.009	63.000	2632.639	196950.57
2035	450000	0.009	64.000	2677.037	200272.08
2036	450000	0.009	65.000	2720.994	203560.54
2037	450000	0.009	66.000	2764.514	206816.27
2038	450000	0.009	67.000	2807.6	210039.62
2039	450000	0.009	68.000	2850.258	213230.89
2040	450000	0.009	69.000	2892.491	216390.4
2041	450000	0.009	70.000	2934.304	219518.48
2042	450000	0.009	71.000	2975.701	222615.44

Table D.1 Continued

2043	450000	0.009	72.000	3016.686	225681.57
2044	450000	0.009	73.000	3057.264	228717.2
2045	450000	0.009	74.000	3097.437	231722.63
2046	450000	0.009	75.000	3137.211	234698.15
2047	450000	0.009	76.000	3176.589	237644.06
2048	450000	0.009	77.000	3215.575	240560.67
2049	450000	0.009	78.000	3254.173	243448.25
2050	450000	0.009	79.000	3292.388	246307.09
Average = 167489 tonnes-eCO_2/year Sum$_{(2004\text{-}2050)}$ = 8039475 tonnes-eCO_2/year					

* 75% collection system efficiency

APPENDIX E: RESULTS OF ESTIMATED ELECTRICAL GENERATION

Table E.1 Estimated heating potential and electrical potential of Brady Road landfill for 0% diversion option.

Year	**Amount of Waste (tones)**	**Fraction of Total Mass**		**Gas Gen. Rate (No Diversion)**	Heating Potential (Btu/hr)	Electrical Potential (kWe)
2000	450000	0.009	28.000	762.7186	20501876	1793.442
2001	450000	0.009	29.000	825.7232	22195440	1941.59
2002	450000	0.009	30.000	888.1009	23872153	2088.264
2003	450000	0.009	31.000	949.858	25532183	2233.478
2004	450000	0.009	32.000	1011.001	27175695	2377.248
2005	450000	0.009	33.000	1071.535	28802854	2519.587
2006	450000	0.009	34.000	1131.467	30413822	2660.509
2007	450000	0.009	35.000	1190.802	32008761	2800.03
2008	450000	0.009	36.000	1249.547	33587830	2938.162
2009	450000	0.009	37.000	1307.708	35151187	3074.92
2010	450000	0.009	38.000	1365.29	36698989	3210.317
2010	450000	0.009	39.000	1422.299	38231389	3344.366
2011	450000	0.009	40.000	1478.74	39748542	3477.082
2012	450000	0.009	41.000	1534.62	41250599	3608.478
2013	450000	0.009	42.000	1589.945	42737710	3738.566
2014	450000	0.009	43.000	1644.718	44210024	3867.359
2015	450000	0.009	44.000	1698.947	45667689	3994.871
2016	450000	0.009	45.000	1752.636	47110849	4121.115
2017	450000	0.009	46.000	1805.791	48539650	4246.102
2018	450000	0.009	47.000	1858.416	49954234	4369.846
2019	450000	0.009	48.000	1910.519	51354743	4492.358
2020	450000	0.009	49.000	1962.103	52741316	4613.651
2021	450000	0.009	50.000	2013.173	54114093	4733.737
2022	450000	0.009	51.000	2063.735	55473210	4852.629
2023	450000	0.009	52.000	2113.795	56818804	4970.337
2024	450000	0.009	53.000	2163.356	58151009	5086.875
2025	450000	0.009	54.000	2212.424	59469958	5202.252
2026	450000	0.009	55.000	2261.004	60775784	5316.482
2027	450000	0.009	56.000	2309.1	62068616	5429.575
2028	450000	0.009	57.000	2356.718	63348585	5541.543
2029	450000	0.009	58.000	2403.862	64615817	5652.397
2030	450000	0.009	59.000	2450.537	65870441	5762.147
2031	450000	0.009	60.000	2496.748	67112580	5870.806
2032	450000	0.009	61.000	2542.499	68342360	5978.383
2033	450000	0.009	62.000	2587.794	69559904	6084.89
2034	450000	0.009	63.000	2632.639	70765333	6190.338
2035	450000	0.009	64.000	2677.037	71958768	6294.736
2036	450000	0.009	65.000	2720.994	73140328	6398.095

Table E.1 Continued

2037	450000	0.009	66.000	2764.514	74310131	6500.426
2038	450000	0.009	67.000	2807.6	75468294	6601.738
2039	450000	0.009	68.000	2850.258	76614934	6702.043
2040	450000	0.009	69.000	2892.491	77750164	6801.35
2041	450000	0.009	70.000	2934.304	78874098	6899.668
2042	450000	0.009	71.000	2975.701	79986849	6997.008
2043	450000	0.009	72.000	3016.686	81088528	7093.38
2044	450000	0.009	73.000	3057.264	82179246	7188.792
2045	450000	0.009	74.000	3097.437	83259110	7283.255
2046	450000	0.009	75.000	3137.211	84328230	7376.779
2047	450000	0.009	76.000	3176.589	85386711	7469.372
2048	450000	0.009	77.000	3215.575	86434661	7561.043
2049	450000	0.009	78.000	3254.173	87472183	7651.802
2050	450000	0.009	79.000	3292.388	88499382	7741.659

Key Assumptions

1. Collection System – based on estimated landfill gas results

Collection efficiency	0.80
LFG BTU/CF	448 (560 BTU/CF x 0.80)

2. Electrical Potential – based on Caterpillar 3516 gas turbine*

Generation efficiency	0.95
Fuel consumption (btu/kWe-hr)	10,860

* Caterpillar 3516 is an industrial heavy duty gas turbine designed and developed by GE Oil & Gas for power generation.