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Landfill gas extraction and purification technologies

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LANDFILL GAS EXTRACTION AND PURIFICATION TECHNOLOGIES

by

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Landfill Gas Extraction and Purification Technologies

M. Eng., Civil Engineering, 2008

Valeriy Bekmuradov

Civil Engineering Program

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Abstract

The extraction and purification technologies of landfill gas (LFG) from municipal waste continue to generate strong environmental concerns. Historically, the focus of these concerns was an odour in the immediate region of the landfill and the risk of explosions in structures caused by the movement of LFG through soil. While these are still important environmental issues, health risks associated with volatile organic compounds in LFG and damage to the atmosphere through the emission of greenhouse and ozone depleting gases, have also become prominent issues.

The primary objective of this project is to study and examine LFG generation, extraction and purification technologies. Composition of LFG and gas extraction processes is analyzed. Comprehensive literature review of different models for LFG generation rate is provided. The study of LFG extraction and collection systems including design considerations and gas capture schemes are examined. Complete analysis of current purification processes of LFG along with upgrading techniques of methane to bio-methane are carried out.

Discussion and recommendation on gas purification methods are conducted relevantly with certain type of LFG composition, level treatment required, quality of LFG anticipated, and its final application.

Accurate portrayals of prior and current LFG extraction and purification technologies will advance the knowledge used to select appropriate waste management and reduction strategies in future.

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List of Abbreviations

GAC	Granular Activated Carbon
GHG	Greenhouse Gas
LFG	Landfill Gas
MSW	Municipal Solid Waste
NMOC	Non-Methane Organic Compounds
U.S. EPA/EPA	United States Environmental Protection Agency
U.S. ACE	United States Army Corps of Engineers
VOC	Volatile Organic Compounds
WC	Water Column (unit measure of pressure head in imperial method)

List of Unit Conversion Factors

a. Length

From/To	M	mm	Km
Inch (in.)	0.0254	25.4	2.54E-05
Foot (ft)	0.3048	304.8	3.048E-04
Yard (yd)	0.9144	914.4	9.144E-04
Mile (mi)	1,609	1,609,000	1.609

b. Volume

From/To	m^3	l
Cubic foot (ft^3)	0.02832	28.32
Gallon US	0.003785	3.785
Gallon Imp. (Imp gal)	0.004546	4.546
Acre-foot (ac-ft)	1,233	1,233,000

c. Flow

From/To	M^3/s	l/s	m^3/hr
Cubic foot/second (cfs)	0.02831	28.31	40.77
Million gallon/day (MGD)	0.04381	43.81	63.09
Gallon (US)/minute (gpm)	0.00006309	0.06309	0.09086
Acre-foot per day (ac-ft/day)	0.01427	14.27	20.55

d. Pressure

From/To	Pa	kPa	atm	mm H_2O	Kg/cm^2
bar	1.00E+05	100	0.9869	10,200	1.0204
Pounds per square foot (psf)	47.88	0.04788	4.725E-04	4.884	4.886E-04
Pounds per square inch (psi)	6894	6.594	0.06805	703.3	0.07035
Feet water (ft H_2O)	2,986	2.986	0.02948	304.6	0.03047
Millimeters mercury (mm Hg)	133.3	0.1333	0.001316	13.60	0.001360

e. Power

From/To	Watt (W)	Kilowatt (kW)	Horsepower (hp)
Foot pound f/sec (ft-lbf/s)	1.355	0.001355	0.001816
BTU/hour (BTU/hr)	0.2929	0.0002929	0.0003926

f. Viscosity

From/To	Pascal-Second (Pa-s)	Centipoise (cP)
Square feet/second (ft^2/s)	47.88	47,880

g. Kinematic Viscosity

From/To	Square meter/second (m^2/s)	Centistroke (cS)
Square feet/second (ft^2/s)	0.09290	9.290E+04

h. Velocity

From/To	Meter/second (m/s)	Kilometer/hour (km/hr)
Feet/second (fps)	0.3048	1.097
Miles/hour (mph)	0.4470	1.609

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1. INTRODUCTION

1.1 General Review

Landfill gas (LFG) basically comprises from methane, carbon dioxide and some other compounds like hydrogen, oxygen, nitrogen and trace amounts of non-organic compounds and volatile organics (Gardner et al, 1993). They are mainly generated as end products of the physical, chemical and biochemical processes of solid wastes containing organic and non-organic matters. A process usually takes place within organic wastes placed inside landfills where anaerobic decomposition befalls in the absence of oxygen. The principal and essential substances in generation of LFG are microorganism and bacteria. They release methane and carbon dioxide from waste during biodegradation process of organics. Studies on full size landfills and extraction tests have shown a LFG production to range between 0.05 m^3 to 0.4 m^3 per kilogram of waste put into landfill (Ham, 1989).

Methane gas poses a potential threat when it is disappearing uncontrollably from landfill or from its storage tank. It provides significant problems to the environment transforming some volatile organic, nitrogen oxides compounds. It yet can be extremely explosive when concentration of LFG between 5-15% in an air. Numerous incidents of LFG explosions have been reported (Stone, 1978). However governed extraction and utilization of LFG using up-to-date technology of landfill's slogan gas-to-energy could show benefit to environment protection, air quality improvements and economic returns. On the whole, LFG to energy technologies include gas generation, extraction facility, collection systems, purification, and gas utilization systems. However, the generation of LFG is up to specific level of landfill's design properties and operating mode (anaerobic or aerobic). In ordinary anaerobic process, the organic waste in landfill decomposes to generate a LFG, which is a blend of methane and carbon dioxide matters. It occurs once the oxygen depletes and the anaerobic microorganisms become dominant and produce CH_4 and CO_2 in landfill (Schumacher, 1983). Methane emissions from landfills vary considerably depending on waste properties (composition, density, particle size, moisture, pH and others) and the site-specific environment (depth of waste, oxygen content and temperature) (El Fadel, 1998). Therefore, a LFG control system is an imperative component of landfill design to collect and prevent unregulated migration of LFG. Such objective can be accomplished by distinctive LFG extraction technologies which will be described further in Chapter 4.

A LFG control system and a recovery system are the basic components of a properly designed and constructed landfill. Furthermore, bored wells and horizontal trenches help with the extraction and recovery of LFG. Then the collection of LFG is accumulated at a central point by the gas collection header, which is an underground network of pipes. It should be mentioned that moisture is one of the principal barriers that disrupts the collection of the LFG through the piping system by blocking gas flow to extraction wells. Therefore, properly designed and constructed landfill may have purification and scrubbing systems to reduce or remove those impurities.

1.2 Objectives

The primary objective of this project is to study and examine LFG generation, extraction and purification technologies. Composition of LFG and gas extraction processes will be analyzed. Comprehensive literature review of different models for LFG generation rate will be provided. The study of LFG extraction and collection systems including design considerations, gas capture schemes will be examined. Complete analysis of current purification processes of LFG along with upgrading techniques of methane to bio-methane will be carried out. Discussion and recommendation on gas purification methods will be conducted relevantly with certain type of LFG composition, level treatment required, quality of LFG anticipated, and its final application.

2. LANDFILL GAS GENERATION

2.1 Solid waste management

Production of wastes is an unavoidable part of human activity. Waste is generated either during production processes of various materials or it is discarded after use. Waste landfillling is a contemporary version of a long-used practice of depositing waste in remote areas. This practice served the purpose of isolating the community from the health problems associated with decomposing waste. Landfills are necessary components of municipal solid waste (MSW) management. Waste reduction efforts, recycling, composting or incineration can diminish the quantity of materials sent to landfill. However, there will be residual material which yet requires treatment.

MSW mainly consists of paper and yard wastes, but to a lesser extent of glass, wood, metals, plastics, food wastes, rubber, and textiles. Based on EPA classifications, typical MSW classified as product and non-product wastes in 2006 in the United States of America are given in Figure 1.

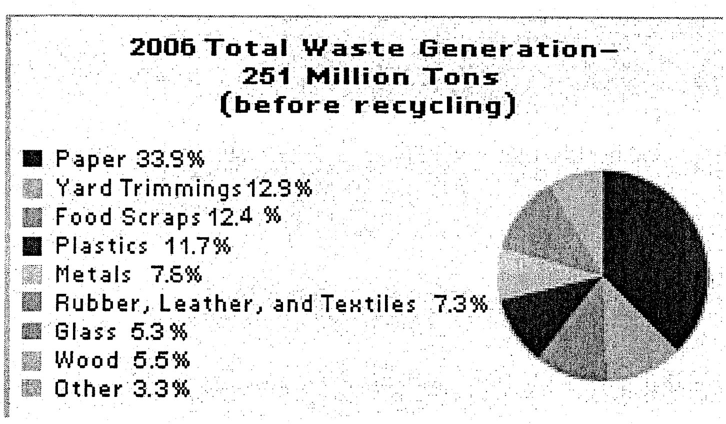


Figure 1. Composition of US municipal solid waste by-product and non-product categories, (2006)

Source: US EPA, 2006

Despite the fact that an immense attempt and investment are directed in waste reduction, recycling, and reuse, a substantial amount of solid wastes still find their way into landfills and incinerators. For instance, in 2002, (Statistics Canada, 2005) the residential component of Canada's waste was estimated at just over 12 million tones, a 6.8% increase from 2000. An estimated 2.5 million tones, or about one-fifth of the residential total, were recycled or otherwise diverted, a 17% increase from 2000. The remainder, about 9.5 million tones, was disposed of in landfills or in incinerated. Hence, still considerable quantities of solid wastes are dumped in landfills, with some burned in incinerators.

2.2 Landfills and anaerobic processes

Landfills are large methane producers, contributing 10-20% (20-70 Tg/yr) of total yearly global anthropogenic emissions (Czepiel et al., 2003). However, a majority of landfills are ignored or unappreciated as they are an essential part of our lives. Much like any other structure, landfills are designed taking into account: location, public safety, economics and environment disturbance. Tchobanoglous and colleagues (1993) defined landfills as "physical facilities used for disposal of residue solid waste in the surface soils of the Earth". This definition is valid for the conventional style of landfill but in recent days a new wording is imperative in order to integrate the more practical and up-to-date design. Nowadays, accordingly to Tchobanoglous et al. (1993), landfills are considered as an engineered facility for disposal of MSW designed and operated to minimize the public health and environmental impacts.

According to the US EPA 2003 solid waste takes about 40 years or more of process time to decompose in landfills. Schumacher (1983) noted that after the waste has been placed in the landfill, aerobic decomposition of the organic waste begins and a small amount of greenhouse gas is produced. Once the oxygen has been depleted the anaerobic microorganisms become dominant and produce greenhouse gases in landfill sites. Specifically, anaerobic decomposition is a two-stage process shown in Figure 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.

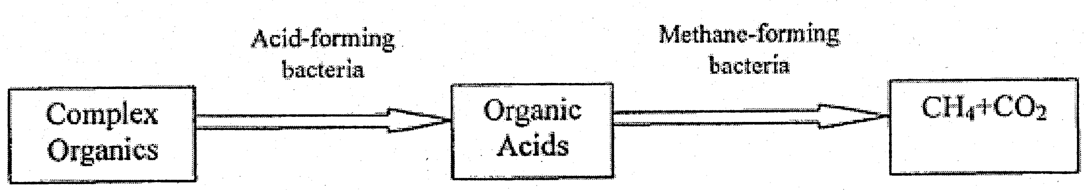


Figure 2. Two stages of anaerobic decomposition of complex organic waste

Source: Emcon Associates, 1980

During the second stage of methane fermentation, the organic acids are consumed by a special group of bacteria and transformed into methane and carbon dioxide (Emcon, 1980). It's believed that an anaerobic process in typical landfill occurs between 180 and 500 days after landfilling, depending on waste composition, moisture content, pH value, temperature, nutrients and refuse density (Boyle, 1977).

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

a) Hydrolysis- complex insoluble organic material is solubilized by enzymes excreted by hydrolytic microorganisms.
b) Acidogenesis- soluble organic components including the products of hydrolysis are converted into organic acids, alcohols, hydrogen and carbon dioxide.
c) Acetogenesis- the products of the acetogenesis are converted into acetic acid, hydrogen and carbon dioxide.
d) 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 most significant.

Table 1 shows the typical LFG composition and characteristics.

In final stage, LFG production and composition approach steady state condition with methane (CH_4) ranging 40~60%, carbon dioxide (CO_2)- 40~50% , small amount of oxygen- 0,2~1%, 2~5% nitrogen, 0~1% hydrogen and other trace components such as hydrogen sulfide (0,0017~0,91%) and vinyl chloride less than 0,0001% (Senior,1990).

Table 1. Typical landfill gas composition and characteristics

Source: 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

2.3 Landfill gas generation

When solid waste decomposes, a significant portion of organic waste is ultimately converted to gaseous end products. The rate of gas production is the function of numbers of factors, namely: refuse composition, climate, moisture content, particle size and compaction, nutrient availability and buffer capacity (El-Fadel et al., 1996). Reported generation rate vary from 0,12~0,41m^3/kg dry waste (Pohland & Harper, 1986).

The most widely used method to evaluate gas flow rate at full scale landfills is pump testing. This process involves pumping gas from the site, then measuring the volume and composition of the gas and then using pressure sensing probes to determine the volume of the landfill affected by pumping. This is possibly the volume of refuse producing measured gas. Finally, to get the total gas flow rate, several wells or trenches are used to withdraw the gas from the entire site. The major drawbacks are defining the area of influence and accuracy of the pressure device.

To predict methane production from sanitary landfills, Lu and Kunz (1981) developed the model based on field measurements of changes in landfill gas pressure caused by pumping gas from landfill. To use this model accurately, measurements of landfill gas pressure at three points radially outward from a withdrawal well are needed.

Farquhar and Rovers (1973) predicted LFG generation as a rate with graphical demonstration in Figure 3 that showed four distinct phases. The generation of methane begins at the end of second phase when available oxygen is just about to deplete. Methane production rate shows exponential growth during the third phase with peak value and then slowly approach to steady horizontal line with constant production.

The current trend in assessing LFG production rate is utilizing Landfill Bioreactor Technology. The potential of LFG generation rate is defined, in a basic analysis, by the size and age of the waste volume, type of waste and moisture content (Reinhart, et al., 1996).

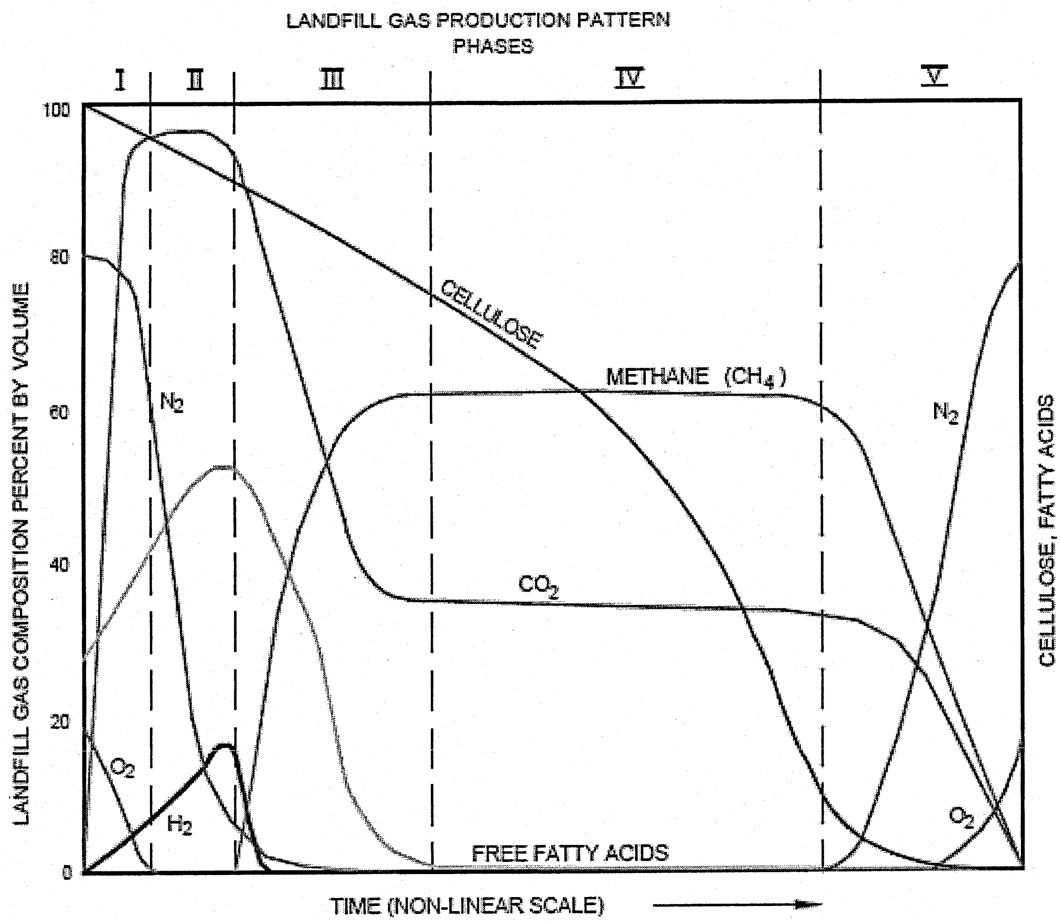


Figure 3. Landfill gas production phases

2.4 Major components influencing landfill gas generation

There are a number of factors influencing on LFG generation rate: refuse deposits, moisture content, pH and temperature, nutrients.

2.4.1 Refuse deposits

Inorganic materials such as demolition and construction rubble decompose more rapidly than refuse in high organic matter such as food waste, garden waste, and paper. It is reported that 60% or more of methane gas production is derived from the biodegradation of paper waste components (Pacey, 1986).

2.4.2 Moisture content

The rate of methane production is increasing with higher moisture content. The optimum moisture content should be approximately 40% - 45% (wet weight) for the maximum gas production (Pacey, 1986). Studies have shown that gas production may increase after a heavy rainfall while recorded high moisture content (Emcon Association, 1980).

2.4.3 pH and temperature

Boyle (1977) reported that optimum pH values for anaerobic digestion ranges from 6.4 to 7.4. In addition, he demonstrated that the pH value in landfills can be affected by many factors including industrial waste discharges, alkalinity, and clear water infiltration. Bacterial functioning is determined by the temperature of the landfill. The optimal growing temperature of mesophile bacteria ranges from $20^{O}C$ to $40^{O}C$, and the optimal growing temperature for thermophile bacteria is above $45^{O}C$ (Schumacher, 1983). It was found that most landfills operate in the mesophilic range, which produces less methane than thermophilic digestion (Emcon Association, 1980).

2.4.4 Nutrients

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

3. LFG GENERATION AND MODELING

Studies on the gas generation and modeling in landfills are important in order to fulfill LFG control measures, which are an essential to minimize possible explosive risks (Nyns, et al., 1993). Several models exist that are used to describe LFG production, movement and extraction through gas wells. The majority of these are one- or two-dimensional models.

Single-well models were proposed by Esmaili (1975), which does not include gas generation rate in the landfill. Another single-well model was developed by Lu and Kunz (1981) and this model utilizes measurements of landfill gas pressures and pressure changes resulting from the withdrawal of gas to calculate the landfill's methane production rate. Their assumption was that landfills consist of a number of small cylindrical volume elements whose axes coincide with the axes of withdrawal wells.

A more realistic model of LFG generation and transport in landfill cells of rectangular shapes was developed by Young (1989, 1992) for the flow of single gas species inside non-isotropic porous media within which gas is continuously generated. To illustrate the internal pressure variations in terms of the gas production rate, the permeability and the boundary condition of the site, a linear parabolic equation was developed. This model is used to calculate the gas fluxes within the site of rectangular cross section, into which a random number of horizontal extraction pipes have been put in.

Because there is no change in the pressure profiles along the depth of the wells, this model is two-dimensional.

A three-dimensional municipal solid waste landfill model has been developed by Arigala et al. (1995), and this represents a continuation of Young's model. This is based on a more realistic description of MSW biodegradation. This model describes the effects of several parameters on the overall pressure distribution the gas fluxes through landfill margins. This model assumes that the LFG is treated as a single component, ignoring the differential diffusional and transport properties of the constituent gases.

3.1 Major characteristics of LFG

LFG consists of a number of gaseous components, which are products of decomposition of the organic fractions of MSW. Some of these gases, though present in small trace quantities, may be toxic and pose threats to the public health. The typical percent compositions of gases found in LFG are presented in Table 2.

Table 2. Typical components found in MSW landfill gas

Source: McWhorrter, 1990

Component	Percent(dry volume basis)
Methane	45-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0.1-1.0
Sulfides, disulfides, mercaptans, etc.	0-1.0
Ammonia	0.1-1.0
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

Methane and carbon dioxide are the principal gases, produced from anaerobic process of the biodegradable organic portion of MSW. The information in Table 3 is illustrative of the trace compounds found in the LFG from most MSW landfills. Most of these compounds would be labeled as volatile organic compounds (VOCs).

Table 3. Typical concentration of trace compounds found in LFG

Adapted from Moshen, et al., 1980

Compound	Median Concentration, ppbv	Mean Concentration, ppbv	Maximum Concentration, ppbv
Acetone	0	6,838	240,000
Benzene	932	2,057	39,000
Chlorobenzene	0	82	1,640
Chloroform	0	245	12,000
1,1-Dichloroethane	0	2,801	36,000
Dichloromethane	1,150	25,694	620,000
1,1-Dichloroethene	0	130	4,000
Diethylene chloride	0	2,835	20,000
trans-1,2-Dichloroethane	0	36	850
Ethlene dichloride	0	59	2,100
Ethyl benzene	0	7,334	87,500
Methyl ethyl kethone	0	3,092	130.000
1,1,1-Trichloroethane	0	615	14,500
Trichloroethlene	0	2,079	32,000
Toluene	8,125	34,907	280,00
1,1,2,2-Tetrachloroethane	0	246	16,000
Tetracchloroethylene	260	5,244	180,000
Vinyl chloride	1,150	3,508	32,000
Styrenes	0	1,517	87,000
Vinyl acetate	0	5,663	240,000
Xylenes	0	2,651	38,000

3.1.1 Density

Even though air is denser than methane, carbon dioxide is even denser. A gas that has 54% of methane and 46% of carbon dioxide is almost as dense as air. As a result, depending on its composition, LFG can be about as buoyant as air. Therefore, it is risky to just presume that LFG will raise all the time. When it is denser than air, it can collect at low levels and persist unless forced to move through air movements or pressure build-up.

Increasing the waste density decreases the gas generation rate. This attributed to the reduction in exposed surface area to enzymatic hydrolysis and the decrease in the mobility of liquids (Dewalle et al., 1978; Levelton & Associates, 1991). Most of the time, the density of methane in LFG is 0,72kg/m^3.

3.1.2 Viscosity

Viscosity of the fluid is defined as the resistance of a fluid to the flow due to its internal friction. The resistance to flow is illustrated as a coefficient of dynamic or (absolute) viscosity and it is the force necessary to move a unit area a unit distance. The estimated dynamic viscosity of CH_4 and composite gas of 1 atmosphere of pressure is as follows:

$$\mu \text{ of } CH_4 = 1.04 \cdot 10^{-5} \text{ N} \cdot \text{sec} \cdot \text{m}^{-2}$$

$$\mu \text{ of composite gas} = 1.15 \cdot 10^{-5} \text{ N} \cdot \text{sec} \cdot \text{m}^{-2}$$

3.1.3. Solubility

Most components of LFG can dissolve in aqueous matter, which include landfill leachate and condensate. The degree to which compound enters into solution under equilibrium condition is influenced by several factors such as temperature, prevailing pressures and chemical interactions between the compound and the aqueous media. When the liquid with dissolved gases is faced with temperature changes, pressure changes or mechanical agitation, degassing could result.

Methane is slightly soluble in water 35 ml methane/L water at $17^{O}C$ (Budvaris, 1989). However, carbon dioxide is more soluble in water than methane (1,45 kg/m^3 of water), and this forms bicarbonate and carbonate ions. This discrepancy in solubility is partially responsible for observed variations in bulk gas composition. The aqueous media found in the landfill, such as leachate and condensate, act as vehicles for transportation of dissolved methane. It is important to take into consideration the risk assessment of methane migration and emission with the help of leachate and condensate. Accumulation in confined areas should be monitored in situations where there is a possibility of methane migration by leachate and condensate.

3.1.4 Moisture content

The most important factor that influences methane generation in landfills is moisture content (Farquhar & Rovers, 1973). This is because moisture acts as the medium for mass transfer and it transports the metabolites away from microorganisms, diluting and buffering the system. The moisture content in the refuse at the time of placement generally varies between 15%-45% and about 20% on a wet weight basis (Palmisano & Barlaz, 1996). There is a lack of coincide between optimum moisture content for waste biodegradation in literature. On the other hand, the usual moisture content, 20%, is seen as fairly low for biodegradation at the time of placement (Palmisano & Barlaz, 1996).

The moisture content is basically a function of several factors such as: precipitation, an infiltration through the cover and a period for which a landfill was open (US EPA, 1996).

3.1.5 Heat

Two main processes are in charge for the heat flow in landfills: temperature gradients existing in the landfill will force heat transport by conduction in the system as a whole and heat transport mechanisms by means of mass migration of the fluid components in the gas and liquid phase.

The concentrated mixture of the composite gas or LFG has a fuel value of 18-22 MJ/m^3 (~500 BTU/cft) (Spokas et al., 2005), whereas the caloric value of methane is 35,9 MJ/m^3 (1000BTU/scf). Half the calorific value of LFG is equal to the calorific value of natural gas. Between concentration limits of 5% to 15% at $20^{O}C$ a 1 atmosphere pressure, methane becomes highly flammable and acts as an explosive mixture with air. The minimum oxygen content required, for methane to ignite, is about 14% by volume.

3.2 LFG condensate

3.2.1 Gas condensate configuration

LFG condensate is a liquid produced in LFG collection systems.

Production of condensate occurs from movement of LFG through physical process such as volume expansion. Condensate is mainly comprised of water and organic compounds. Often organic compounds are not soluble in water and condensate separates into watery phase and floating hydrocarbon phase. This organic portion may consist of up to five percent of liquid.

3.2.2 Condensate properties

There is little published information on the characteristics and quantities of condensate generated in LFG collection systems. However, the major organic components of LFG condensate could be identified by using standard EPA analytical methods for priority pollutants in water samplings.

The type and quality of gas condensate are subjects of the following parameters:

- age and quality of the landfill's refuse
- value of moisture content
- temperature distinction
- shape and size of landfill
- type of cover and liner materials
- weather condition

Research has shown that the aqueous phase of LFG condensate normally passes Toxicity Characteristics Leaching Procedure regulatory limits (USACE, 1995). If the condensate contains non-aqueous phase liquid, ignitability testing would fail. Landfills operating as a municipal landfill are hardly ever found to have non-aqueous phase fraction. It is possible that the hydrocarbon or organic phase of the condensate is ignitable and should, therefore, be recognized as hazardous (US EPA, 2003). Wastes with a flash point below $60^{O}C$ are considered ignitable.

3.3 Transport mechanism in LFG movement

Gas transport in landfill occurs mainly by three mechanisms: advection or pressure driven transport, diffusion/dispersion or concentration driven flow, and convection. Gas migration is also influenced by refuse density, moisture content, presence of high and low permeability layers, depth of groundwater, cover soils and liners (Nastev et al, 2001). The major portion of gas migration usually takes place in a vertical direction with minor fraction migrating in a lateral direction. Latham and Young (1993) studied gas movement in landfills and found that fluctuation in gas compositions and flux are most prominent within 2~3m of the surface. However, due to complexity of the nature of landfills and many other parameters, gas movement in landfills is still difficult to predict precisely.

3.3.1 Permeability of LFG

The permeability of porous medium has significant influence on gas flow rate and gas recovery rate (Poulsen et al., 2001). Typically the coarse-grained refuse particles have large gas permeability and more uniform gas flow patterns and fine-grained particles are characterized by smaller values of gas permeability and gas flow patterns (USACE, 1995).

The coefficient permeability denoted "k" is frequently used to depict the rate of discharge of fluid under laminar flow conditions and at temperature $20^{O}C$ through unit cross-sectional area of a porous medium under a unit hydraulic gradient. LFG permeability is a function of the intrinsic and relative permeability. The intrinsic permeability is a measure of the ability of material (typically rock or unconsolidated material) to transmit LFG, water or other fluids. The intrinsic permeability is specific for each landfill and its value affected by porous medium. It's expressed in unit darcies, where 1 darcy is equal to $9{,}87 \cdot 10^{-9} cm^2$.

3.3.2 Atmospheric pressure

Barometric pressure changes at the surface can impact the adjective gas flow. As fluxes of landfill gas at the surface increases, atmospheric pressure decreases, where as an increase in atmospheric pressure would result in decreased flux rates (Latham & Young, 1993; Poulsen et al., 2003).

3.3.3 Heterogeneities

Landfills are heterogeneous environment in their type of waste. Some of these heterogeneities are contributing for spatial variations in gas generation and gas recovery rates (USACE, 1995). An important aspect to consider is that waste represents a highly compressible porous medium. A porosity of solid waste within the landfill can be defined as a ratio of the void volume to the total volume of the porous medium. Waste porosity can be determined by following expression:

$$n = \frac{V_V}{V_T}$$

where: n - waste porosity, dimensionless,

V_V - volume of void space, m^3,

V_T - bulk volume of particles, m^3

It's generally accepted that waste porosity of landfills ranges from 0,04~0,10.

3.3.4 Landfill cover and liner systems

There are three types of covers that are in use for landfill: daily cover, intermediate and final. Daily cover is placed on the top of the landfill at the end of each day. Sand is usually used as a daily cover but other types of soil are also used. Intermediate cover is used on the top areas of landfill mostly for periods not more than 2 years. Intermediate cover is made from any type of soil available in landfill. The final cover is used to seal landfill and reduce the amount of water that will enter landfill after closing.

Landfill covers improve LFG collection system by allowing maximum recovery from all portions of the landfill. Landfill liners just as landfill covers are designed and constructed to create barrier between the waste and the environment to prevent drainage of leachate into LFG collection systems. Landfill liners made up from materials with low permeability, including compacted clay liners, geo-synthetic clay liners and geo-membranes.

3.4 Landfill gas flow

LFG flow through the waste and adjacent soil is a complicated process. Pressure and concentration gradients are identified as the principal driving forces. LFG tends to pass through the waste and surrounding soils which has a low resistance. A permeability of the soils surrounding landfill attributes to this movement. A dehydrated soil is a desirable medium for gas flow, while saturated soil may reduce or prevent gas flow completely. Various models for gas flow have been developed in the past three decades (El-Fadel et al., 1997). However, none of these models consider the effect of temperature changes on gas generation rate as well as the oxidation rate of methane in final cover.

Darcy's Law is often in use to characterize the gas flow through the refuse (Findikakis & Leckie, 1979). Darcy's Law applies for laminar flow only. Mathematically it can be expressed by following equation:

$$V_r = -k \cdot \frac{dh}{dl}$$

where: V_r – gas velocity at distance l, m/sec

k – permeability coefficient, m/sec

l – radial distance from recovery well, m

h – hydraulic head, m

$\frac{dh}{dl}$ – hydraulic or pressure gradient at distance l.

3.5 Landfill gas generation

3.5.1 Introduction

There are several methods that have been in used to measure landfill generation and emission into atmosphere. Table 4 presents summary of emissions found in literature. In a nut-shell, prediction tools for estimating LFG emission are categorized as modeling and measurements. The common prediction tool, widely available is modeling. It's required validation though using actual measurement of gas emissions. Modeling employs a comprehensive study of various parameters to provide future trend and accurate predictions of gas emissions.

Table 4. Measurements of methane emissions from landfills

Location	Method	Conditions	Flux (g CH_4/m^2 per day) Min.	Max	Mean (n)	Reference(s)
New Hampshire, USA						Czepiel
Site 1	Static	No gas rec.	-0.03	1500	58 (139)	(1996a:Czepiel
Site 2	chamber		0	215	12(92)	unpubl.)
Site3	w/o collar		-0.06	433	14(111)	
Site 4			-0.02	4560	274(106)	
Site 5			-0.01	2050	48(124)	
Site 1	SF6 tracer	No gas rec.			0.68	
Illinois, USA						
Proximal, (6/95-2/95)	Static chamber	Silty clay cover soil	-4.10^{-4}	-0.43	-0.006 (22)[a]	Bogner *et al.* (1997)[#]a
Distal		optimised gas rec.	-6.70^{-4}	-0.092	-0.011 (25)[a]	
Proximal(Spring 94)	Static	Same	-2.50^{-4}	-0.002	-0.001 (5)[a]	Bogner *et al.*
Distal	chamber –c		-0.001	-0.004	-0.002 (6)[a]	(1995)[#]
Proximal(93,transect)	Static	w/gas rec. start-	0	0.007	0.003 (12)[a]	Bogner *et al.*,
Distal	chamber	up phase	3.2	29.8	19.7[b] (29)[a]	(1993)[#]
Proximal(93,transect)	Vert. Conc.	Same- dry			0.012[b]	Bogner *et al.*,
Distal, Dry	Gradient				32.9[b]	(1993)[#]
Distal , Wet					108[b]	
California, USA						
Proximal (1994)	Static chamber –c	Sandy silt cover soil w/gas rec.	0.4	11.7	4.03 (18)[a]	Bogner *et al.*, (1995)[#]
		Clayey silt cover soil w/gas rec.	2.00^{-4}	1	0.004 (9)[a]	
Same area, no wells (1988)	Static chamber	Sandy silt cover soil	320	1910	1120 (8)[a]	Bogner *et al.*, (1995)[#]
	Vert. Conc. Gradient	(dry) w/o gas rec.	1670	1880	1730 (8)[a]	Bogner *et al.*, (1992)[#]
UK (26 sites)	Static	Winter	6.10^{-4}	4.3	0.48 (16)	Gregory &
	chamber	Summer	0.003	29.3	3.6 (10)	Skennerton, (1997
		Clay cover	0.003	4.3	0.7 (11)	unpubl.)[#]
		Sand/LPDE	0.005	0.025	0.01(3)	
		Other soil cover	6.10^{-4}	29.3	2.9 (12)	
		Age < 10 y	6.10^{-4}	4.3	0.39 (17)	
		Age > 10 y	0.002	29.3	4.1 (9)	
		No gas rec.	6.00^{-4}	5.2	1.3 (9)	
		Partial gas rec.	0.002	29.3	2.9 (11)	
		Full gas rec.	0.003	0.03	0.01 (6)	
Tennessee, USA	Eddy correlation	No gas rec.			6.5	Myers *et al.* (1992)[#]
Moscow, Russia	Static chamber	No gas rec.			34	Nozhevnikova *et al.* (1993)[#]
Sweden						
Hökhuvud	Static				0.33	Börjesson &
Hogbytorp	chamber				-0.003	Svensson (1993)[#]
Netherlands						
VAM site	Dynamic		2.6	746		Verschut *et al.*
AURI site	chamber		6.9	3000		(1991)[#]
ARN site			0.1	214		
VAM site	Micromet.		51.4	398		
AURI site	(gradient)		17.1	386		

Location	Method	Conditions	Flux (g $CH_4/m^2/d$)			Reference(s)
			Min.	Max	Mean (*n*)	
Japan						
H-1	Static chamber	Dense veg			0	Tanaka *et al.* (1997)
		Sparse veg.			0	
		No veg.			9.3	
H-2		Dense veg			0	
		Sparse veg.			2.2	
		No veg.			235	
H-3		Cover soil			7.7	
		Slope cover soil			20.7	
		Waste no cover			0.6	
Luleå ,Sweden						Maurice & Lagerkvist. (1997)
Mar 7/96	Static chamber	No gas rec	0.088	3.156	0.745 (9)	
May –Dec /96					<0.044 (59)	
France						
	Static chamber				89	Savanne *et al.* (1997) *
					82	
	Tracer gas				63 ± 22	
					52 ± 17	
	Eddy correlation				1.5 ± 0.5	
	Mass balance				23 ± 7	
Italy						
Pecantia Landfill	Static	No gas rec.	1.89	443		Cossu *et al.* (1997)*
	Dynamic		962	1,132		
Netherlands						
Naurena	Plume transect	No gas rec.			9	Scharff & Henson (1999)
Hollandse Brug					7	
Ontario, Canada						
Ridge Road ,E. Hill	Dilution tube	No gas rec.	0	10,344	137	Williams & Williams (1995)*
Ridge Road ,W. Hill			0	9,023	219	
Brockville			17	86	39.3	
Florida, USA						
Central Florida		No gas rec.				
Site 1-green	Dynamic Flux chamber w/o collar				29	Walker (1991)
Site 1-brown					6144	
Site 2- A1					6.8	
Site 2- A2					162	
Site 2- A1-1	Dynamic Flux chamber w/ collar		BDL	158	33.9	Rash (1992)
Site 2- A1-2			BDL	1578	239.8	
Site 2- A1-3			6.03	1206	266.1	
Site 2- A1-4			BDL	305	84.9	
Site 2- A2			BDL	509	108.9	
Alachua County LF	Flux tube		9.8	159	74.5	Paladugu (1994)
Sweden						
Hagby	Static chamber	Gas rec.	-0.023	335		Börjesson & Svensson (1997a)

[a] *n* values are for daily means (2-6 flux measurements per day). [b] Based on geometric mean of conc in profile w/: with; w/o without; gas rec.: pumped gas recovery in operation; proximal: near gas rec. well; distal: between wells; -c: with collar; LPDE: low density polyethylene; veg.: vegetation; BDL: below detection limit; * data reported as normalized volume converted to mass by multiplying by density of methane at 25 °C and 1 atm. (# Original source, Bogner *et al.*, 1997b;+ with additions)

The emissions obtained by different methods range from an average -0,001 to 6.44g $CH_4/m^2/d$. The negative value obtained by the static chamber method was caused by the oxidation process in landfill cover. The status of landfill such as presence of gas recovery, waste age and cover material will contribute to the distinctions in LFG emissions. The following sections will briefly discuss the various methods of LFG emissions with emphasis of latest most used models.

3.5.2 Scholl Canyon model

A number of theoretical models to estimate gas generation, based on zero order and first order reaction kinetics, have been proposed. The majority of theoretical models to estimate are based on first order reaction kinetics, which means that limiting factor is amount of substrate remaining for biodegradation (Cossu et al., 1996).

Scholl Canyon model is first order decay model most often used in industry and regulatory agencies, including the US EPA. The principal feature of this model is that after an initial lag time during which anaerobic processes are established, the gas production rate peaks. Thereafter, LFG rate is supposed to decrease as the organic fraction of waste declines. Furthermore, in Scholl Canyon model, refuse mass is broken down into sub masses that are placed during each year of landfill activity. If L_o and k are the same for all sub masses in the landfill, the composite methane gas generation rate is expressed by following equation:

$$Q = \frac{dl}{dt} = -k \cdot L_O \cdot \left(\sum_{i=j}^{n} r_i \cdot e^{-k \cdot t_i} \right)$$

where; Q – methane generation rate at time t, m^3/yr

k – methane generation rate constant , $year^{-1}$

L_O – ultimate methane generation potential, m^3/yr

r_i – ratio of the weight of each sub mass to total

refuse waste

t – time, years

n – number of years (number of sub masses)

Typical values of k range from 0,02 for dry sites to 0,07 for wet. Suggested ranges and recommended parameter assigned for the rate constant k, are given in Table 5.

Table 5. Suggested k value ranges for corresponding annual precipitation

Annual Precipitation	**Range of k Values**		
	Relatively Inert	**Moderately Decomposable**	**Highly Decomposable**
<250 mm	0.01	0.02	0.03
>250 to <500 mm	0.01	0.03	0.05
>500 to <1000 mm	0.02	0.05	0.08
>1000 mm	0.02	0.06	0.09

(Source: Conestoga, 2004, *Handbook for the Preparation of Landfill Gas to Energy Projects, The World Bank)*

L_O parameter is function of waste composition, and fraction of organic matters specifically. It is numerical value assessed on carbon content of the refuse, the biodegradable carbon fraction and stoichiometric conversion coefficient. Common methane values for this parameter are in range between 125 and 300

m^3/ton of waste. Suggested L_O values by organic waste content are shown in Table 6.

Table 6. Suggested L_O values by organic waste content

Waste Categorization	Minimum "Lo" Value	Maximum "Lo" Value
Relatively Inert Waste	5	25
Moderately Decomposable Waste	140	200
Highly Decomposable Waste	225	300

(Source: Conestoga, 2004, *Handbook for the Preparation of Landfill Gas to Energy Projects, The World Bank)*

LFG generation curve with emphases on peak LFG generation rate and first order generation constant is shown on an illustrative example in Figure 4. The LFG generation and computation curve is generated with application of Scholl Canyon model. The graph shown on Figure 4 represents theoretical total amount of LFG produced and the LFG collected with system collection efficiency suggested by US EPA.

3.5.3 LandGEM (Landfill gas emission model)

The US EPA (2005) has developed the model called LandGEM, which is based on first order reaction kinetics. The version 3.02 was released in 2005 and assumed that methane and carbon dioxide were generated in equal volumes by default. However, the ratio can be changed and model is able to estimate the emissions for other pollutants in landfills. The inputs for a model such as this are the following: year landfill opens; landfill's closure year; annual waste acceptance rate until current time; methane generation rate constant - k; and the ultimate methane generation potential - L_O. The rate of methane generation can be calculated by following equation:

$$Q = \sum_{i=j}^{n} \sum_{j=0,1}^{1} k \cdot L_O \frac{M_i}{10} \cdot e^{k \cdot t_0}$$

where: Q – annual methane generation in the year of calculation,m^3/yr

i – time increment (usually one year)

n – (year of the calculation) – (initial year of waste acceptance)

$j = 0,1$ year time increment

Figure 5 shows the estimated gas generation rate for Clover Bar landfill in city of Edmonton, Alberta, Canada where the LandGEM model has been used (Chakraborty et al., 2005). Figure 5 also shows a stepped gas extraction for optimum gas recovery without varying the extraction rate frequently. Although LandGEM is simple and onward in its use, there are apparently some drawbacks. LandGEM does not consider direct measurement of moisture content and site-specific composition is not taken into account. Moreover, the model neglects lag time between first placement of refuse into the landfill and the initial generation.

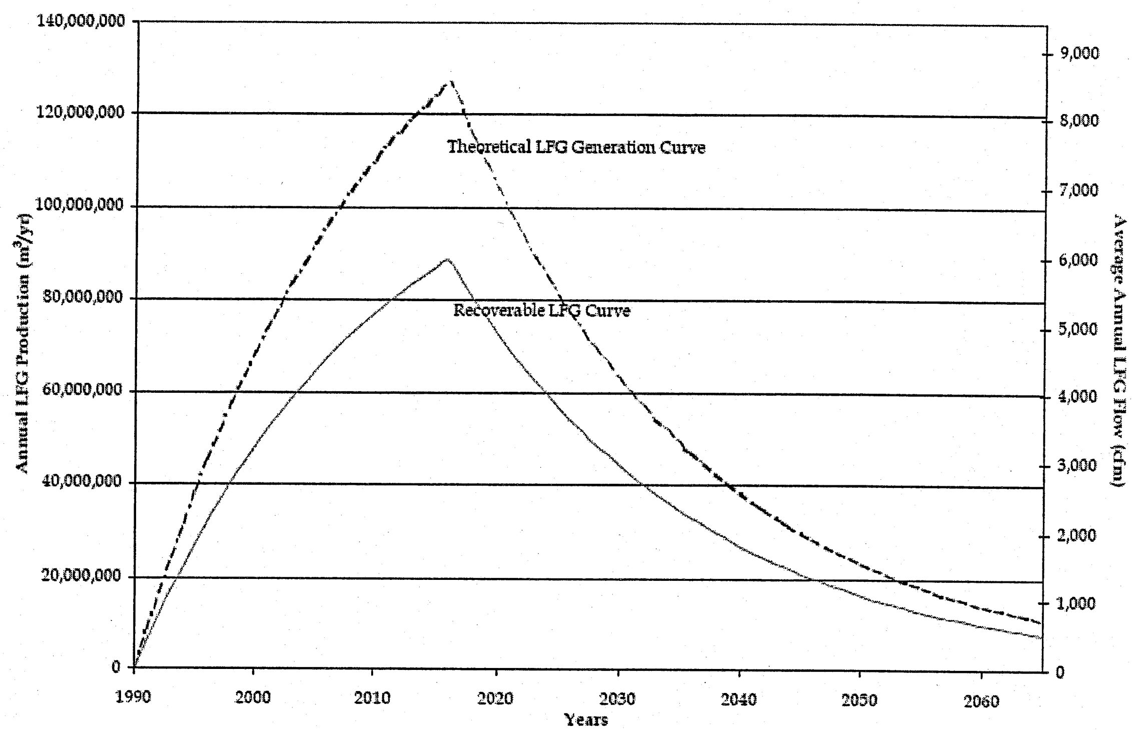


Figure 4. Typical LFG Generation Curve (Scholl Canyon model applied)

Source: Conestoga, 2004, Handbook for the Preparation of Landfill Gas to Energy Projects, The World Bank)

k – methane generation rate constant, year^{-1}

L_O – ultimate methane generation potential, m^3/Mg

M_i – mass of waste accepted in i^{th} year, Mg

t_{ij} – age of the j^{th} portion of waste mass M_i accepted in the i^{th} year.

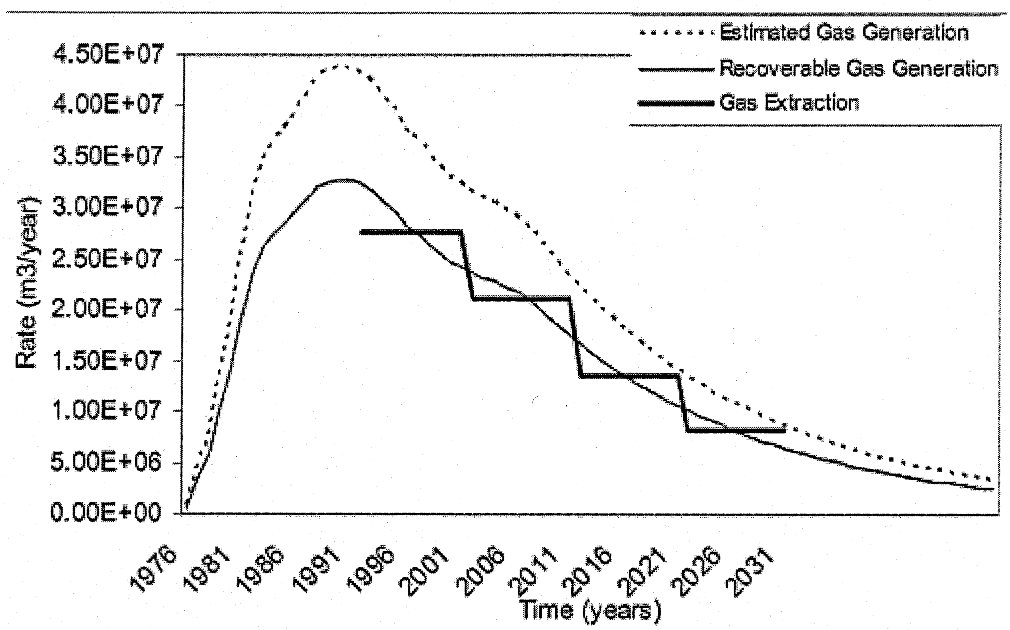


Figure 5. Gas generation estimated by LandGEM model and gas extraction at landfill.

Source: Chakraborty et al., 2005

3.5.4 Ladfill gas generation model (LFGGEN)

The LFG generation (LFGGEN) model was developed at the University of Central Florida (Keely, 1994). This model has been in use for full scale landfills in the United States to estimate gas generation rates successfully. The assumptions for this model combine those made by Findikakis et al., (1988) and Tchobanoglous et al., (1993), which are:

- methanogenesis is preceded by lag phase;
- the first stage of methanogenesis is represented by a linearly increasing generation rate;

- the second stage of methanogenesis is represented by first-order reaction kinetics, with exponentially decreasing generation rate.

The distinctive feature of LFGGEN is that the model can be used not only for estimations of gas generation rates but also for sizing equipment of LFG collection and combustion facilities as well. The model has some additional features, which are:

- methods of analysis provided are theoretical stoichiometric generation of methane and carbon dioxide;
- biodegradable refuse is divided by even categories;
- moisture is classified as wet, moderate and dry;
- biodegradability rates are classified as rapid, moderate and slow;
- biodegradability rates are also function of moisture.

The modeling approach pursued in LFGGEN proceeds to outline a unit curve that illustrate gas generation rate versus time. Figure 6 shows the unit curve with four stage process (CH2M HILL).

As one can see from the graph in Figure 6 there is a four-stage process depicted on the curve line. The first stage is the lag phase, followed by the rising phase, stable phase and declining phase. This model includes a time delay t_O to establish anaerobic conditions, followed by a linear increase to specific peak rate Q_{sp}, that occurs at the end of the year, t_p. After the peak, the generation rate decreases exponentially from the peak to a rate near at the end of the prescribed biodegradation time, t_{99}, which is the time for the gas generation rate to decline to one percent of the peak rate.

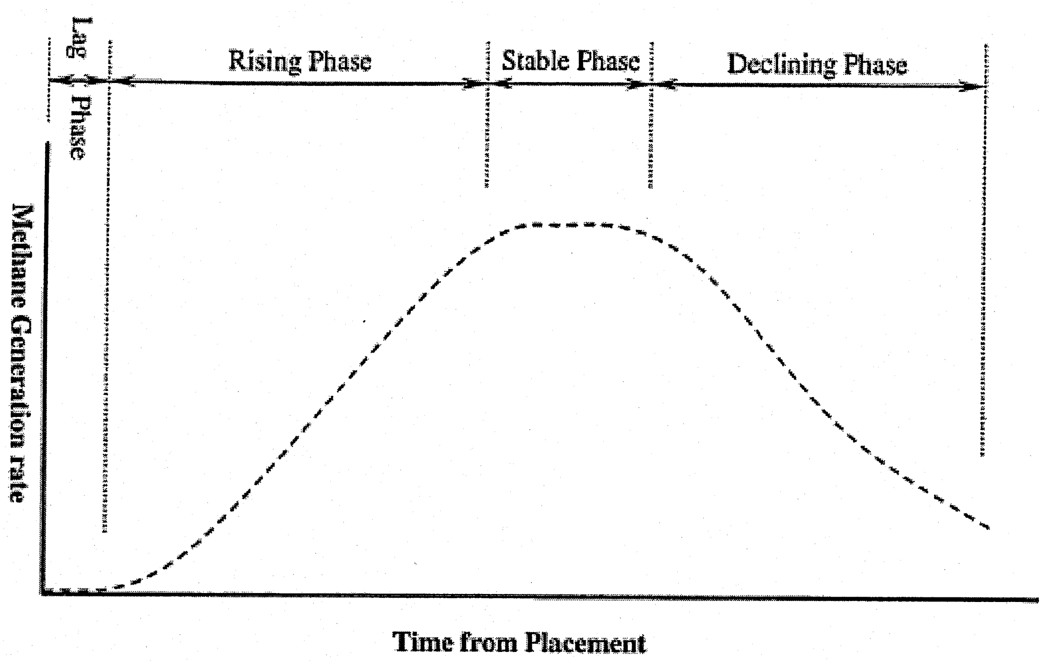


Figure 6. Typical four-stage process of landfill gas generation curve using LFGGEN model

Source: CH2M HILL, 2002

Drawbacks of this model include that the model parameters are highly dependent on moisture conditions and capture efficiency. Both of these values are site specific and difficult to quantify. Therefore, more data from full-scale landfills are required with complete data sets that replete descriptions of gas collection systems, gas quality and quantity, refuse placement rate and moisture condition. Full details for each phase of four-stage process during LFG generation can be found in the Inventory Report for Potential Landfill Bioreactors (CH2M HILL, 2002).

3.6 Landfill gas collection efficiency

3.6.1 Introduction

The Alberta Research Council (2007) defines collection efficiency as the amount of LFG in the recovery system compared to the amount generated. This value is influenced by several factors including: cover type (daily, intermediate, final), type of collection system (active, passive, air quality control, LFG migration control). The efficiency rates are usually derived from previous models by dividing actual gas extraction rates by modeled gas extraction rates. These calculated values tend to range from 50% to 75% prior to better efficiency rates (Spokas et al., 2006). However, these values are highly dependent on the accuracy of the LFG model used, and therefore the values may not reflect the actual efficiency. Huitric and Kong (2007) include flux chamber and tracer gas measurements in their calculation. However, there are may be uncertainty concerns for use of these values.

The US EPA (2004) recommends using a collection efficiency default value of 75% based on industry estimates. However, authors have argued that this value is unreliable and inaccurate (Huitric & Kong, 2007; Spokas et al., 2006). These authors suggest efficiency rates ranging from 85% to 98% based on their emission estimates.

3.6.2 Mass balance of landfill gas

Once methane is yielded in a landfill, direct emission to the atmosphere via diffusive and convective flux mechanism is one of the possible pathways. A typical diagram of methane pathways within landfill is shown in Figure 7.

Methane may also be oxidized to CO_2 in aerobic cover soils, recovered by the active gas extraction system, temporarily retained within the landfill volume or migrated laterally in subsurface. Lateral migration through layered strata should be insignificant at well governed sites. Nevertheless, one study confirms migration is possible to a distance of more than 300m (Kjelsden, 1995). This mass balance relationship is summarized in the following equation (Bognar & Spokas, 1993):

$$CH_4 production = CH_4 emmited + CH_4 oxidized + CH_4 re\mathrm{cov}erd + \\ + CH_4 lateral\ migration + \Delta CH_4 storage$$

Simply, the mass of CH_4 produced, oxidized and emitted in a particular year is subject to waste quantity, years in place, climate, landfill design, and management factors. Therefore, CH_4 recovery is probably the single most significant factor influencing emissions. Spokas, et al., (2006) conducted intensive field measurement at three landfills in France with the purpose of quantifying all the pathways for methane-generated sites. The collection efficiency was calculated as a ratio of recovered gas to empirically modeled gas generation. Efficiencies between 85% and 98% were calculated for sites with completed clay covers similar to those widely used in North America.

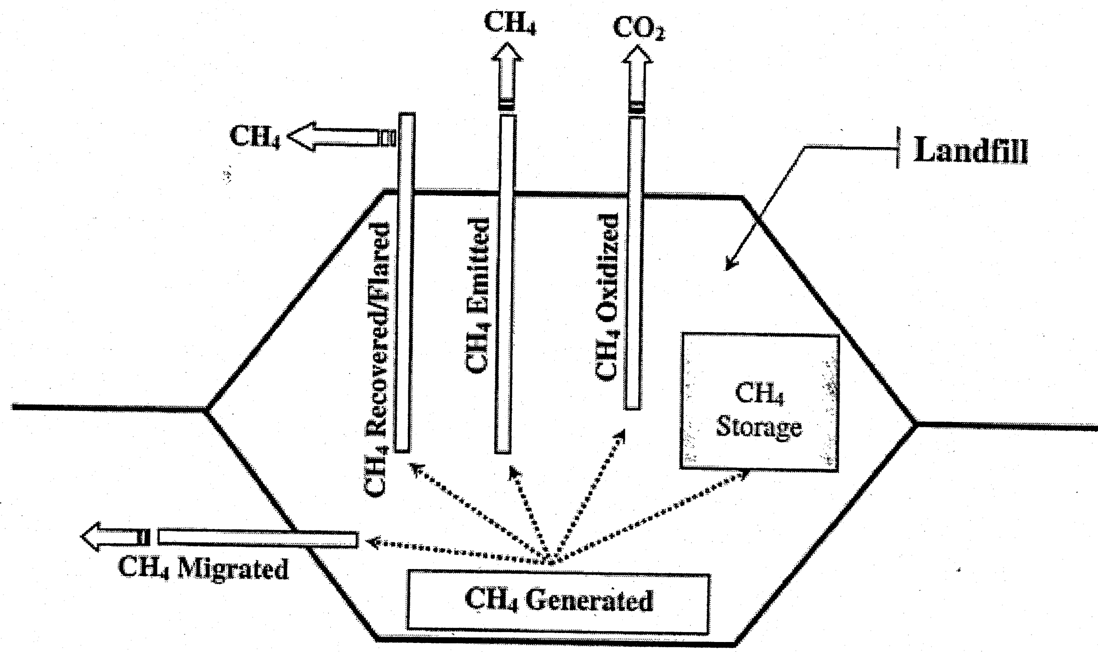


Figure 7. Schematics of methane pathways within landfill

Interestingly, the study reported direct measurements of collection and emissions, the sum of which, in the absence of any storage changes, is the generation. This supports the study's original findings of high efficiency and suggests that actual values may be higher. In practice, the equation above is rewritten in terms of CH_4 emissions and applied by the IPCC (Intergovernmental Panel on Climate Change) group (1996) as a Tier 1 default methodology for calculating methane emissions from solid waste disposal.

3.6.3 Other methane generation models

LFG generation models have traditionally followed zero, first and multi-phase models to quantify methane generation in all three stages. Currently, single-phase or multi-phase first order kinetics models are most popular (Jacobs & Scharff, 2001).

A description of some available gas generation models is delineated below: A zero order model, such as the German ERER model, generates the rate of methane production independent of the amount organic waste remaining. Zero order models predict an extreme decline in methane production towards the end of the landfill span. Zero order models maybe appropriate for approximating operational landfills. However, once the landfill is closed, gas production declines as a phenomenon that is not reflected in this type of model (Jacobs & Scharff, 2001). This model shows successful approximations of domestic and residential wastes that are currently undergoing waste deposition. Evaluation of appropriate gas generation models commenced in late 1970's, when a notion was established that landfill decomposition follows a decreasing first order model (Huitric & Soni, 1997). It's assumed that gas production is proportional to the degradation of organic matter along first order kinetics with gradual decrease in the LFG rate after closure (Borjesson, et al., 2000). First order models such as TNO (The Netherlands Organization of Applied Scientific Research), Belgium, Scholl Canyon, and LandGEM are the most used in the United States, Canada, Norway, Denmark and other countries. However, those models are criticized for not following the gas production trend in initial waste placement, as they lack some data (Findikakis, et al., 1988).

Multi-phase models such as Afvalzorg or GasSim models are best represents what actually happens in landfill because typical waste composition can be taken into account since all waste contains typical fractions of the three phase degradable materials (Coops, et al., 1995). Nevertheless, multi-phase models are also under heavily criticism due to the complexity of dividing waste into distinct categories and weights with appropriate modeling kinetics (Huitric & Soni, 1997).

4. LANDFILL GAS EXTRACTION

4. 1 General review

In order to assess the economic feasibility of LFG extraction potential, it is necessary to estimate both: the rate of methane production and the total volume of methane that can be extracted from the landfill. The few data available on methane production come from full-scale landfills (Ham, et al., 1979).

It shows that methane yields are between 1% and 50%, calculated by stoichiometry (Halvadakis, et al., 1983). Current practice is to evaluate the rate of methane by pump or drawdown tests. Combined methane production volume can be evaluated from mass balances on samples of buried waste with support of theoretical models.

4. 2 Landfill gas production assessment techniques

There are two ways of determining LFG production from landfills. The first method is to exploit mathematical models, while the second method requires site investigations based on pumping tests. While a gas production rate can be defined correctly from laboratory tests, full-scale measurements of gas emissions are more difficult to achieve (Reinhart & Al-Yousfi, 1996).

Pump testing is the most widely used method to assess the gas production rate at full-scale landfills. The basic idea is to pump gas from the site, while measuring the volume of the landfill affected by pumping, which is the volume of waste producing the measured gas. Multiple wells or trenches are used to withdraw the gas from the entire site to get total gas flow rates. Another technique to assess gas production rate and volume is flux box testing. This technique consists of placing a device over a portion of the landfill surface to capture gas flow. The device can range in capture area from a few to several square meters, and can range from simple inverted cans with plastic bag collectors to large plastic sheets. The devices are usually sealed by attachment to a metal ring pressed into the landfill cover or by placement in a small trench with water around the test area. The main problem with flux boxes is non-uniform gas flow through the cover. Therefore, it is recommended to use as many test areas as possible. Some additional minor problems with flux devices include wind effects, changes in moisture content, leaks and diffusion via capture device, gas dissolution and adsorption.

4. 2.1 Preliminary assessment of gas collection system

Many landfills install gas collection system because of regulatory requirements. An installment of a gas collection system is required to obtain comprehensive information about the landfill site and study all aspects thoroughly. To complete an entire picture of the gas collection system for a particular landfill, it is necessary to consider the following parameters:

- landfill size
- method and rate of landfilling
- mass of waste in place
- type of waste and composition pattern
- waste compaction, moisture content, and density
- pH and internal temperature of waste
- type of cover
- meteorological conditions and rainfall data
- state of groundwater and water table
- site topography and surface water conditions

4.2.2 Landfill gas and methane modeling difficulties

This section discusses some difficulties in accurate estimation of LFG and methane productions. Estimates in gas production can be significantly inaccurate since many variables and factors affect it.

A single method suitable for record all LFG production estimates would be desirable, preventing confusion and inconsistencies between different cases. However, this may not be realistic due to a lack of reliable LFG production, emission and modeling data (Borjesson, et al., 2000). A high volume of uncertainties encloses methane production estimates because of scarce landfill production data. When available, data is often uncertain due to inaccurate measurement originating from the large area that the landfill occupies as well as its heterogeneous environment (Mosher, et al., 1999). Uncertainties may also arise from the efficiency of the gas collection system due to site-specific conditions, degree of waste saturation, waste and soil cover permeability, landfill design and operational variances (Copty et al., 2004). Accurate LFG predictions require data for waste quantity, age and composition – factors that are often unknown (Scharff, et al., 2002). Moreover, there are some factors specific to each landfill design such as depth, liner, and gas recirculation that cannot be incorporated into a simple formula. Regardless of which LFG production model is used, general inputs are consistently required for computing methane production. Typically, inputs regarding landfill waste, decay rate and organic content are mandatory. The methodology involved in calculation of inputs may vary and different techniques are applied.

The Department of Environment (1991, 1992) calculated an average figure for gas yield of about $150m^3$ for every wet tonne of waste. This value would vary depending on the source, while 70% to 80% of the gas yield would be recoverable. It is estimated that 6 to 10m3 of LFG is produced per tonne per year as long as 10 to 15 years beyond placement. Computer programs can produce graphed curves from measured waste fractions, deposited amounts, and periods of depositions, which can then be used to model varying concentrations of methane produced within the gas stream. From this, the size of the gas collection system needed can be determined for the landfill's maximum efficiency.

4.2.3 Pumping test of landfill gas movement

While conducting a pumping test, gas maybe withdrawn either by trench or well. If a well is used, then a vertical pipe, perforated in the bottom, is placed in the landfill. Usually, a 0,15m pipe, perforated over one or two thirds of the depth of landfill, is the placed in a hole 0,7~1,0m diameter. Then the perforated end is backfilled with gravel while the upper portion is covered in sealant (such as bentonite). The gas flow rate pumped from the landfill is then monitored as a function of the suction applied to the trench or well using pressure-sensing probes (0,01m pipe) placed in holes (0,15m deep) located radially and proceeding outwards from the well. Multiple probes are placed at varying distances to compute an average force of pressure.

Trenches may be installed during the landfill construction phase and used in place of wells. A trench may comprise of a horizontal section of perforated pipe placed in gravel. Pressure sensing probes similar to those already described are placed on either end of the trench. Pipe within 35~70m from the sides of the trench would be non-perforated in order to prevent air intrusion if gas withdrawn by pumping.

While conducting a pump test it's rational to retain that there are always some obstacles. The first and main problem in pump testing is determining the area of influence. Correct measurement of the static pressure prior to pumping is crucial. However, static pressure changes hourly, as well as from day to day and from location to location within the landfill. Static pressure has effects on barometric changes, moisture changes and heterogeneities within the landfill as well. Some other challenges are the accuracy of the pressure sensing device and pumping time before pressure readings are stable cannot be neglected.

4.3 Landfill gas pressure

Landfills are capable of producing enough gas pressure that could summon the destruction of landfill cover. LFG needs higher pressure than that of the atmosphere to propel itself out of landfill. If the landfill does not produce a gas at sufficient rate, the air may be pumped into the landfill. This process is extensively applied for passive gas collection systems when collection of gas in landfill is low.

On the other hand, when active gas collection systems are used, continuous withdrawal may produce a vacuum in the landfill. It usually occurs in the air passing into the landfill and causing low nitrogen-air to mix with recovery gas to form low quality gas. In such situations, considerable volumes of methane capture could be lost to the air seeping into the landfill.

4.4 Landfill gas collection systems

4.4.1. Passive gas collection system

Generally a gas collection system can be divided into two categories: passive and active. In passive collection systems, shown in Figure 8, perforated pipes are installed within landfill or enclosed soil. These collection wells (also referred to as extraction wells) are drilled from 50% to 90% of the landfill depth (Chen et al., 2003). In passive collection systems, a pressure of generated gas supports the driving forces to move methane through the collection system. This system is easy to install and less expensive to operate and maintain. It works well for small landfills producing small quantities of gas.

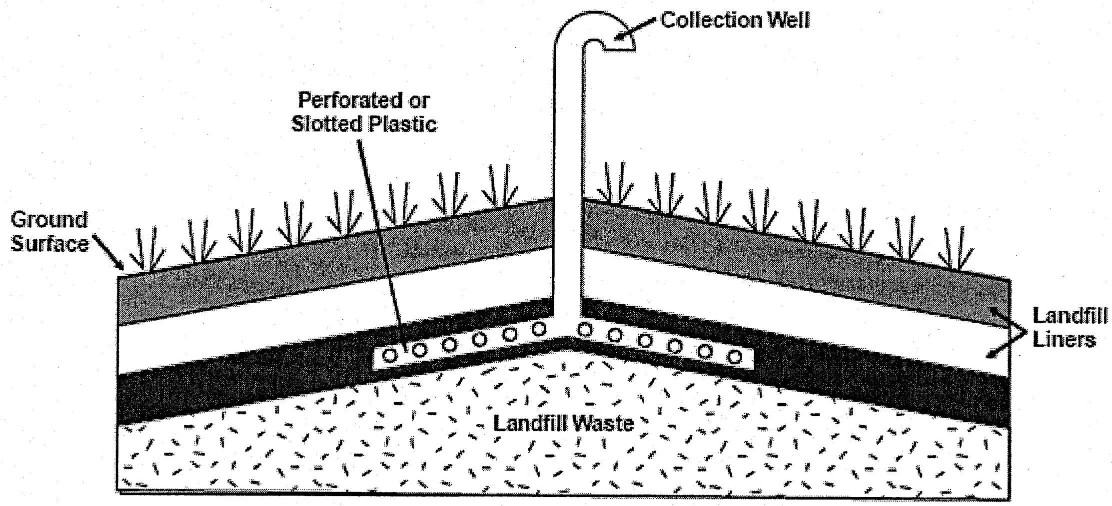


Figure 8. Passive gas collection system

Source: USEPA, 1996

4.4.2 Active gas collection system

In an active gas collection system the gas flow is vacuum controlled and managed according to individual landfill policy (Guo & Song, 1996). Basically, a gas is collected through perforated pipes and negative pressure is applied to force gas into the wells. Vertical gas collection wells are typically of 18~36-inch-diameter boring, with perforated PVC or HDPE pipes through the landfill (Frantz, et al., 1998). Schematic representation of a typical active gas collection system is shown in Figure 9. Vertical wells are drilled to approximately 75% of the landfill depth (Chen, et al., 2003). All wells are coupled by horizontal pipes to a main header. The size and number of blowers is a function of gas flow rate.

Sometimes a flare system is also incorporated into the active gas collection system to burn off excessive gas.

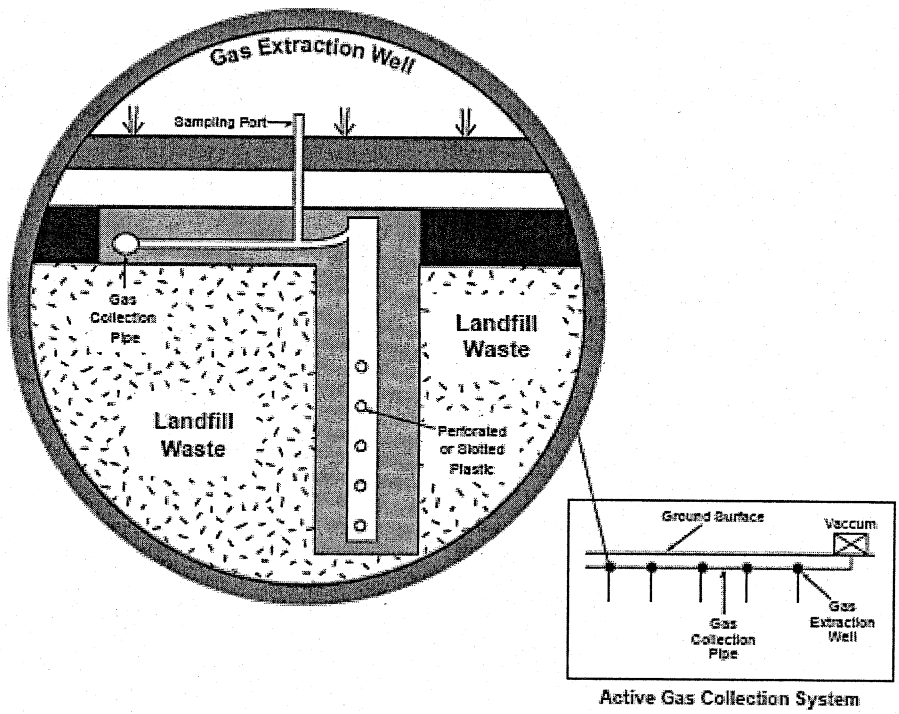


Figure 9. Typical active gas collection well

Source: USEPA, 1996

4.5 Lanfill gas collection system

A LFG collection system generally contains following elements:

- landfill collection site;

- a containment system that retains a gas within the site and prevent off-site migration;

- a system for gas venting with respective back up facilities;

- a distinct system to control gas migration on the site;
- gas monitoring system;
- utilization and flaring components.

4.5.1 Landfill collection site

LFG collection sites are usually installed as a system to capture gas and send it further to utilization systems. LFG collection sites include collection wells surrounded by gravel or shredded aggregate with low calcareous substances. Vertical collection wells may be constructed during refuse placement time or they may be drilled after closure of the landfill. Typical horizontal gas collection system and vertical gas collection well are shown in Figure 10 and Figure 11 respectively.

It should be mentioned that horizontal gas collection systems are less expensive than vertical gas collection wells and are specifically suitable for installation in active filling areas. The advantages of horizontal collection systems include low effects from the high leachate level problem in landfills, and less obstruction for the landfill performance. The disadvantages are high effects from refuse settlement and low recovery efficiency per well (The World Bank, 2004). "Handbook for the Preparation of LFG to Energy Projects in Latin America and the Caribbean,") Available online at: www.bancomundial.org.ar/lfg

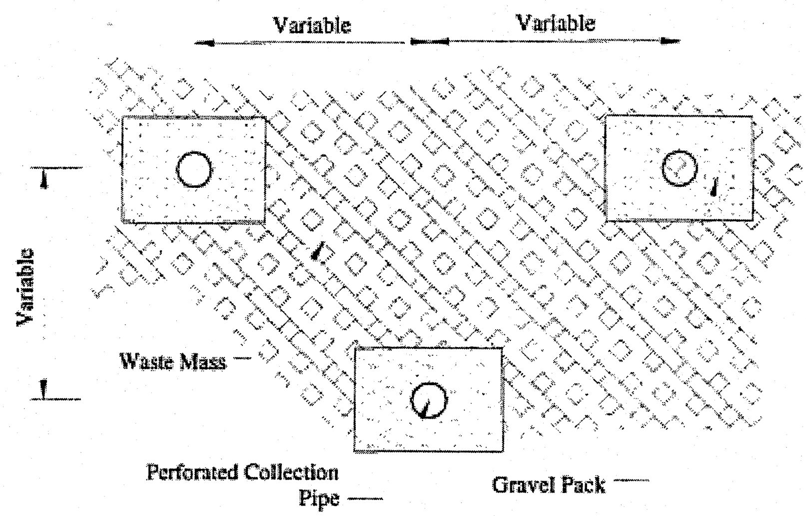


Figure 10. Typical horizontal gas collection system

Source: Conestoga, 2004, Handbook for preparation of landfill gas to energy projects, World Bank

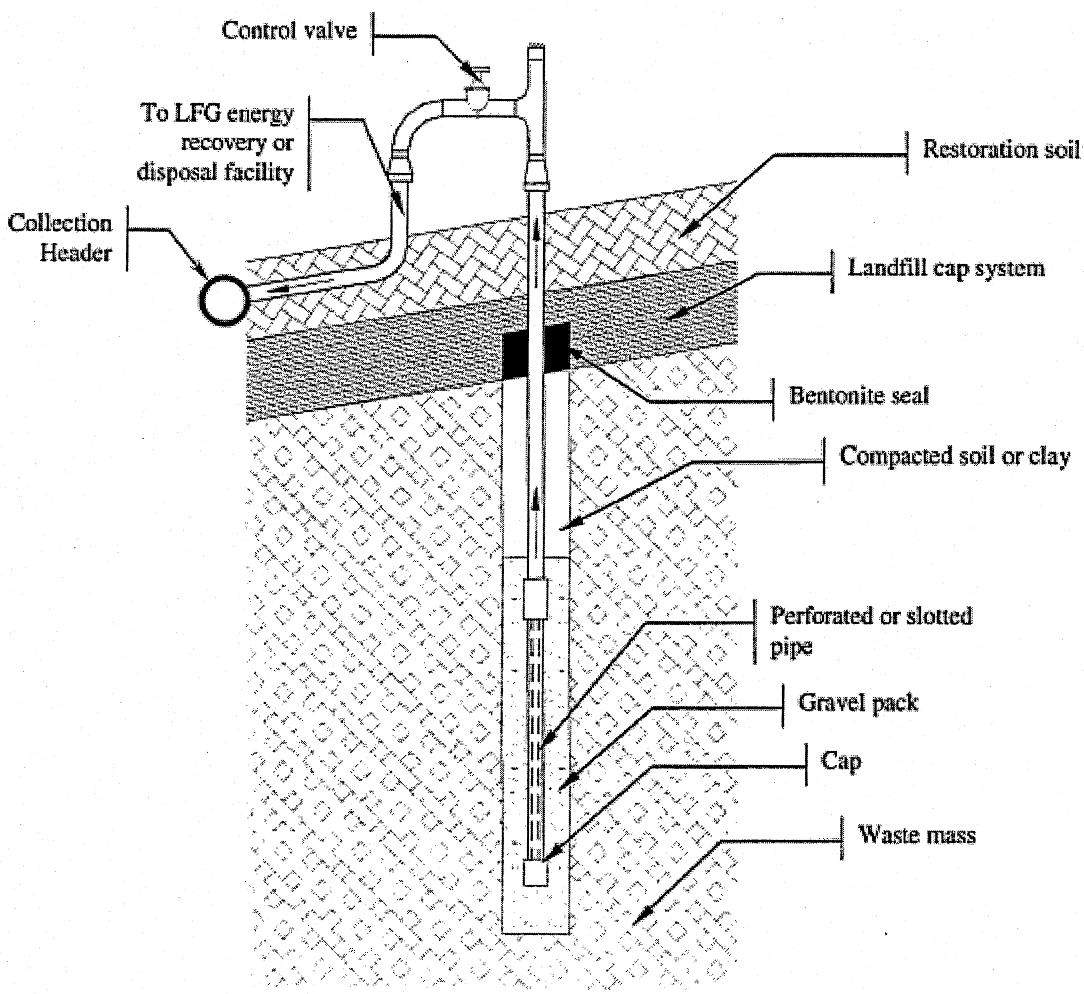


Figure 11. Typical vertical gas collection well

Source: USACE,1983

4.5.2 Landfill gas pipe system

There are two common layouts for LFG collection pipe systems: the herringbone and the ring header (Environmental Agency, UK, 2002). A herringbone arrangement, shown in Figure 12, has a single main header with sub- headers and headers branching from it. This arrangement is the most efficient use of the pipe system. This layout would allow minimizing the amount of condensate by means of shifting piping works to the LFG wells.

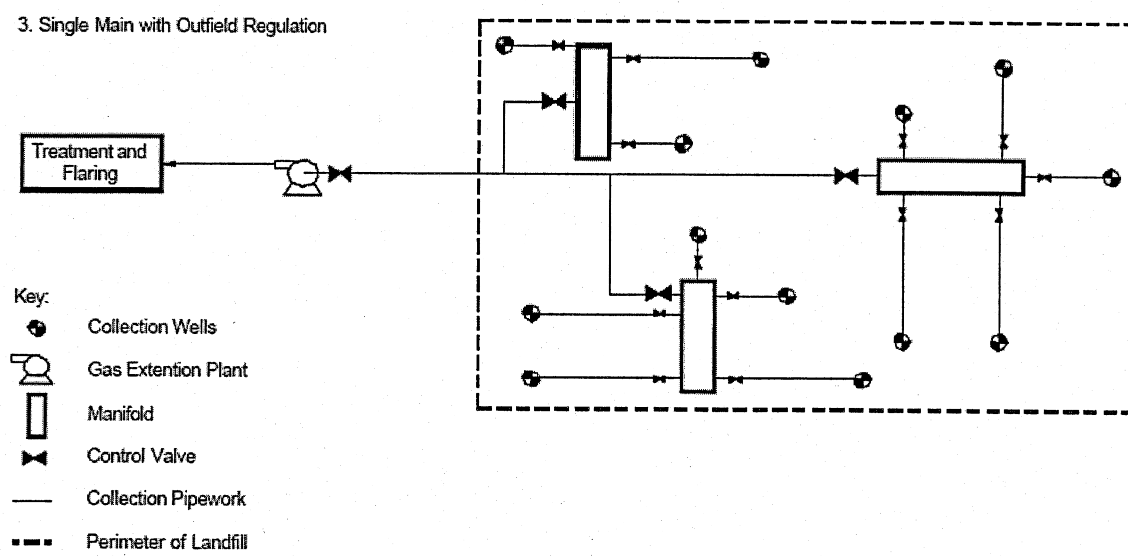


Figure 12. Typical landfill collection options with single conduit with outfield regulation system

Source: Environmental Agency, "Guidance on the management of landfill gas", UK, 2002

The ring header arrangement is shown in Figure 13. Its simple design is used when space outside the perimeter of headers is limited. Usually, ring headers have valves in particular sections to isolate portions of the system. Multiple header systems, shown in Figure 14, are used wherever landfills are large and deep and the site is active for long periods of time. This pipe system facilitates the segregation of methane rich gas found in deeper portions of the site from the gas near the surface, which is diluted from air intrusions.

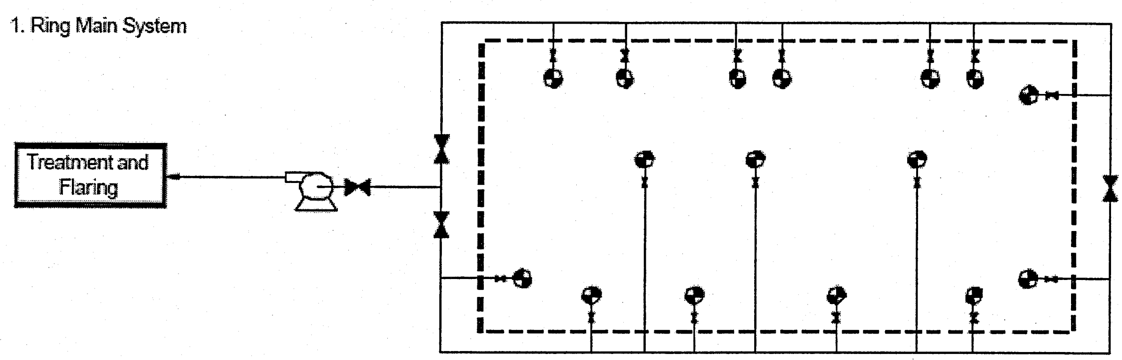


Figure 13. Typical landfill collection options with ring main system

Source: Environmental Agency, "Guidance on the management of landfill gas", UK, 2002

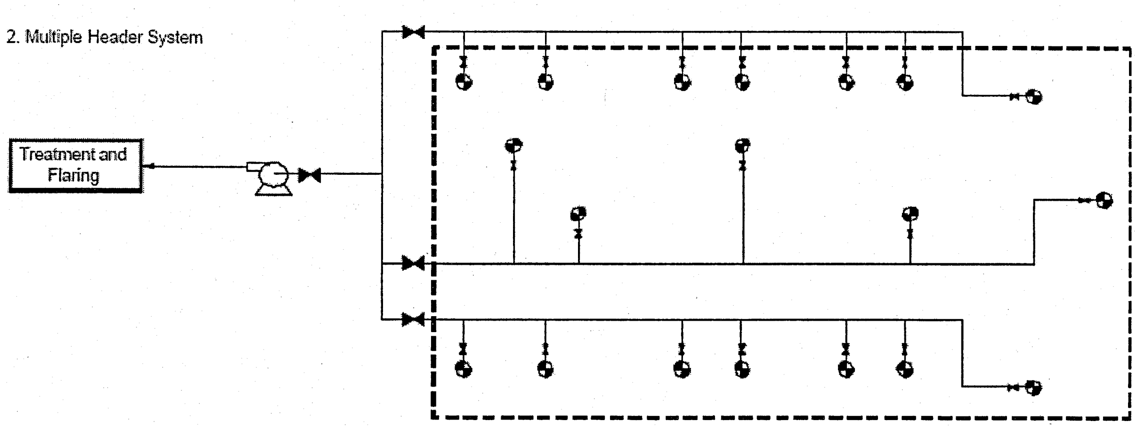


Figure 14. Typical landfill collection options with multiple header system

Source: Environmental Agency, "Guidance on the management of landfill gas", UK, 2002

Piping systems can be installed above or below the ground based on the site conditions and budget. When above the grade, pipe systems are the least expensive to build. High density polyethylene (HDPE) piping is recommended for most of the LFG piping. However, the cost of HDPE piping cost is linked to the price of petroleum and proximity to suitable pipe manufacturers (Conestoga Rovers, 2004, The World Bank, ESMAP).

4.5.3 Landfill gas condensate

LFG condensate is a liquid generated from the LFG collection system. Usually, condensate forms when LFG cools or forms by physical processes such as volume expansion. Condensate is comprised principally of water and organic compounds, which may consist of up to 5% of the liquid.

Condensate in LFG systems may cause a significant problem including reduction of flow or complete blockage of the gas collection network. The principal approach in battling condensate is to eliminate liquid from gas collection pipes using a combination of low point drainage through water sealed traps and disposal into drained points. A typical condensate drainage point sketch is shown in Figure 15.

An effective design positions the pipe runs to fall towards the drainage points using minimum gradients of 1% to 2%. If this cannot be achieved, pipework can be stepped in "saw-tooth" alignment, shown in Figure 16.

While designing the elements of a control and treatment system, it is logical to consider condensate properties, particularly corrosiveness. This provides a number of obstacles in terms of system performance and failure. For example, deterioration of valves and other parts, leakage oil into the gas, loss of lubricant, and the failure of seals can all impede the piping system. Typical properties of condensate are presented in Table 7.

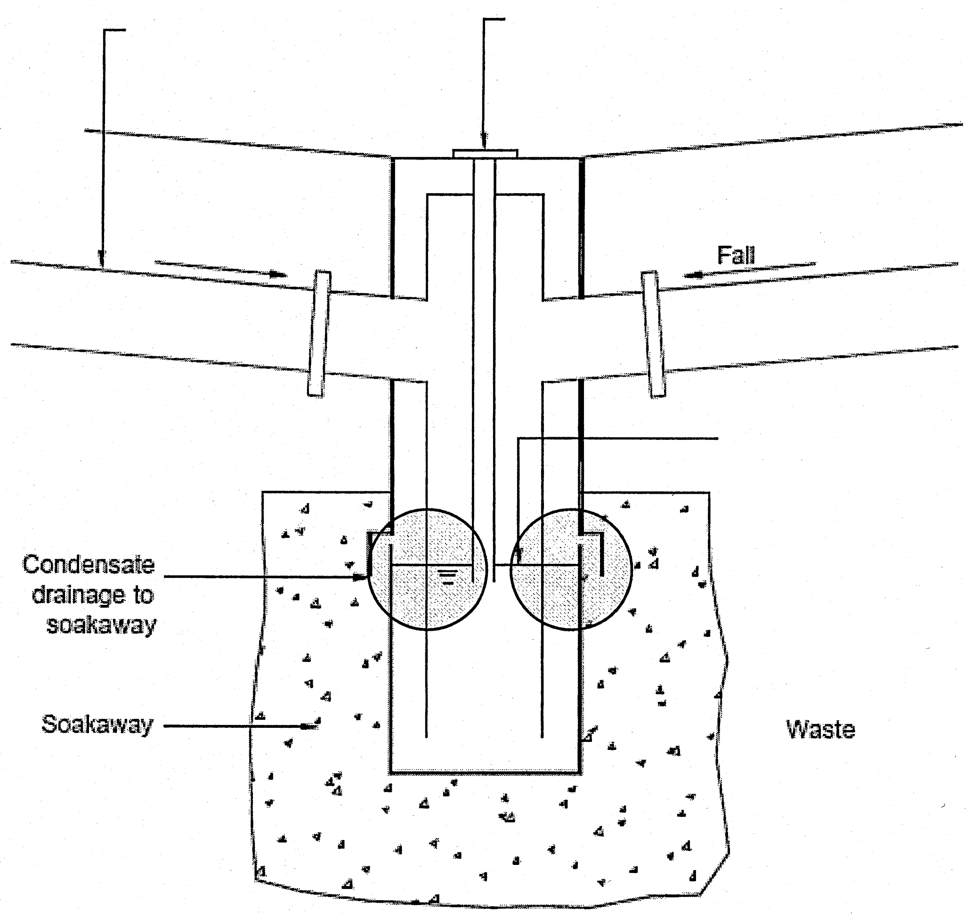


Figure 15. Typical condensate drainage point

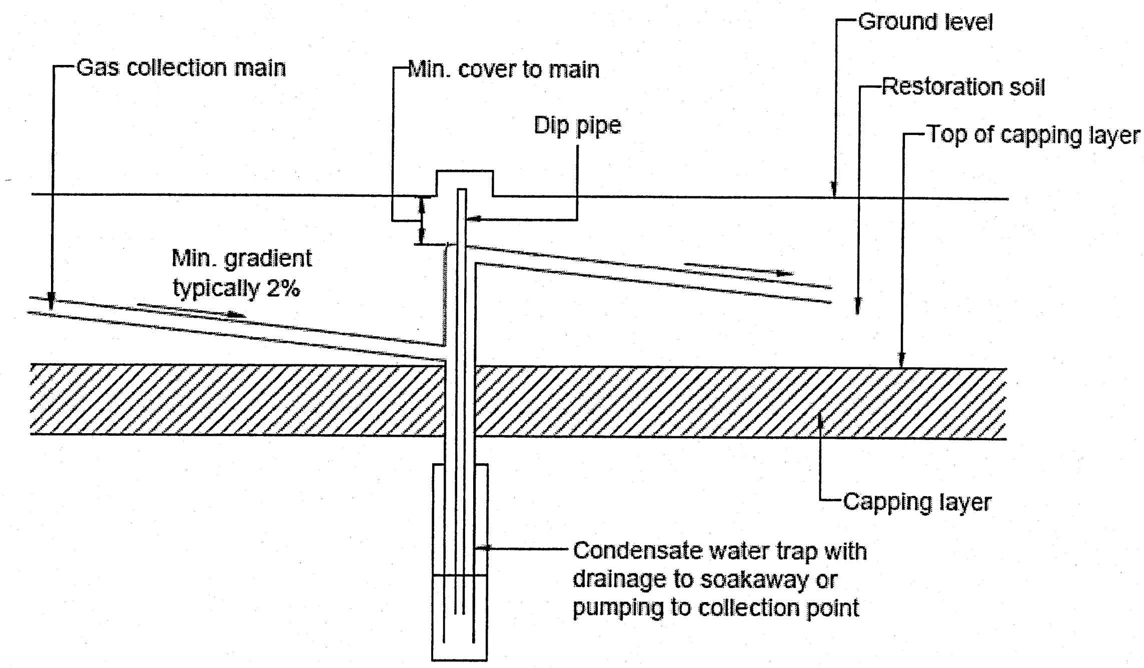


Figure 16. Typical condensate drainage collection pipework

Table 7. Typical characteristics of landfill gas condensates

(Adapted from Knox, 1990)

Component (Parameter)	Plant/Flare Typical Upper Values	Typical Lower Values	Gas field drains Typical Upper Values	Typical Lower Values
pH	7.6	4.0	3.9	3.1
Conductivity	5700	76	340	200
Chloride	73	1	4	<1
Ammoniacal N	850	<1	15	3
TOC	4400	222	9300	720
COD	14 000	804	4600	4600
BOD	8800	446	2900	2900
Phenols	33	3	17	4
Total volatile acids	4021	141	4360	730

Notes: All values in mg/litre except pH (dimensionless) and conductivity (μS/cm)

4.5.4 Blower system

The blower system is considered to be the core of the LFG system. A blower pumps the gas out of landfill and sends it to utilization system and flare station. A flare station is normally an integral component to the blower system. When the gas utilization equipment isn't operating, a backup blower or flare system must be in place to avoid gas pressure build-up.

A modern blower station typically is self-contained and has automated gas recovery and destroying devices. Blowers are used to recover or vacuum the gas and discharge it under pressure into an incineration or utilization unit. A typical incineration system consists of blowers, demister and particulate removal system, automatic safety shut-off valve, flame arrester, utility or enclosed flare, temperature and flame control instrumentation, ignition system, instrumentation, and monitoring control systems. A complete blower/flare system is typically the single most expensive and crucial component of the LFG gas collection system.

4.5.5 Landfill gas utilization and flaring system

A landfill utilization facility is an important part of gas control measurement. It consists of: direct gas use or sale, electricity generation and pipeline upgrade. In practice, all LFG utilization facilities require a gas collection system to optimize gas recovery and provide protection against odor and other emissions. However, LFG is comprised from number of trace gases with variable concentrations that cannot be neglected from designs. The high level of moisture content of LFG may cause problems with condensate removal and interference with ability to collect a gas through the pipe network. Moreover, interaction of some gases with moisture may cause corrosion of equipment or other operational appurtenances. Based on design requirement and level of application, LFG may sometimes need prior utilizing to reduce contaminated air emission. For this purpose, LFG is classified into three categories or level of pretreatment prior to utilization: low grade LFG fuel, medium grade LFG fuel and high grade fuel.

Utilization of LFG as a low grade fuel type requires minimum processing. It involves a condensate removal chamber and a moisture pot to reduce the moisture in the gas flow. Utilization of LFG as a medium grade fuel type requires an additional gas treatment device. It exploits compression and refrigeration of LFG as well as chemical treatment or scrubbing some compounds such as mercaptans, siloxanes and volatile organics. Lastly, utilization of LFG as a high grade fuel includes an extensive gas pretreatment to separate the carbon dioxide and other major constituent gases from methane and remove impurities. Heating value of LFG that has been utilized as high grade fuel might be substituted for natural gas in pipeline application. A schematic diagram shown in Figure 17 provides a visual representation to aid in understanding the various applications for the three grades of fuel treatment.

Flares are used when the odorous gas emissions from landfills must be controlled. The concept of a landfill flare system is very simple: ignition of LFG and air combined. Several configurations of conduits and chambers can be utilized for this purpose. However, any flare system has basic components in addition to piping, valves and body of flare. A basic flare arrangement is shown in Figure 18. It includes gas cleaning/conditioning, blower or booster, flame arrestors, burner, ignition system and flame detector. A state-of-the-art high temperature flare design is shown in Figure 19 (first image from left) which burns the gas at temperatures as high as 1200^{O}C. The combustion chamber of high-quality flares has an insulation of ceramic liners approximately 0,10m. Exhaust gas retention time can be accurately determined. The minimum retention time is recommended as 0,3sec at a minimum temperature of 1000^{O}C. This is an indicative level that is appropriate to achieve the emission standards. However, alternative criteria offering the same performance may also be considered.

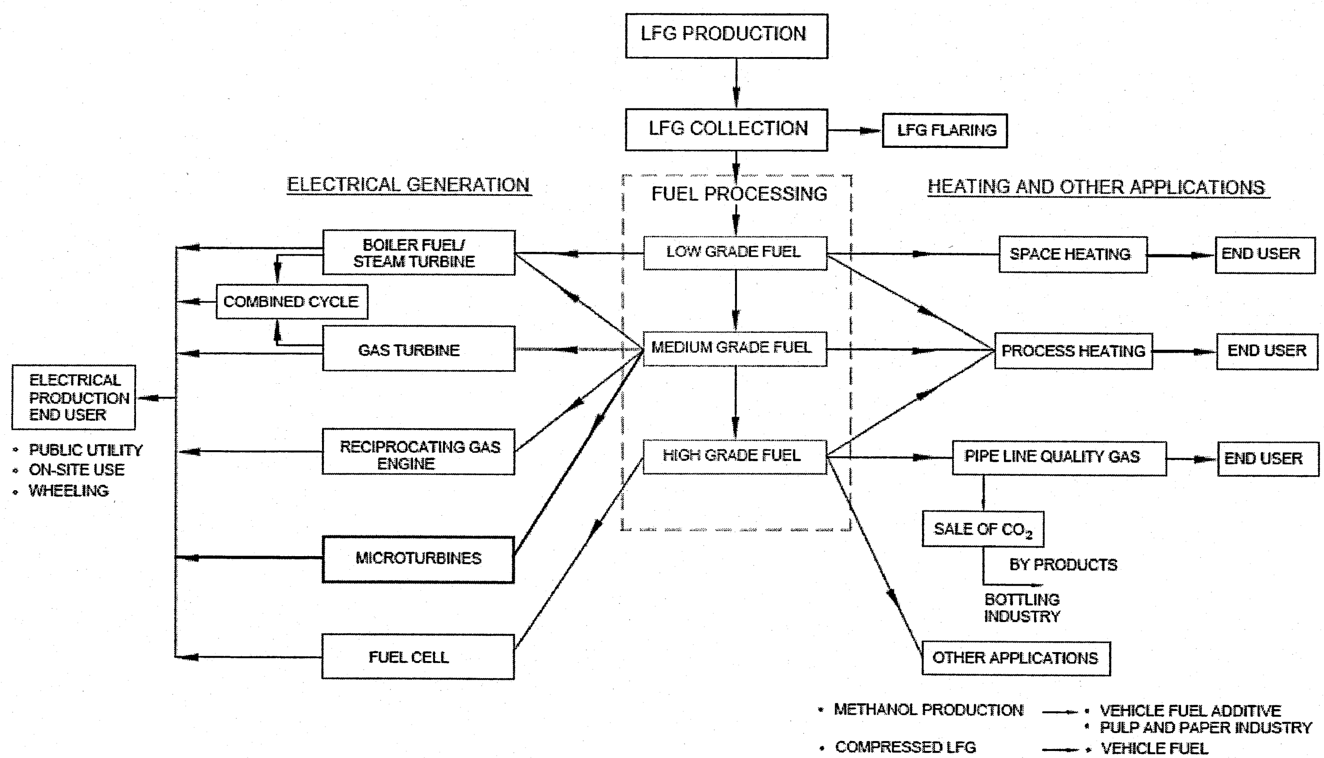


Figure 17. LFG utilization options
Source: The World Bank, 2002

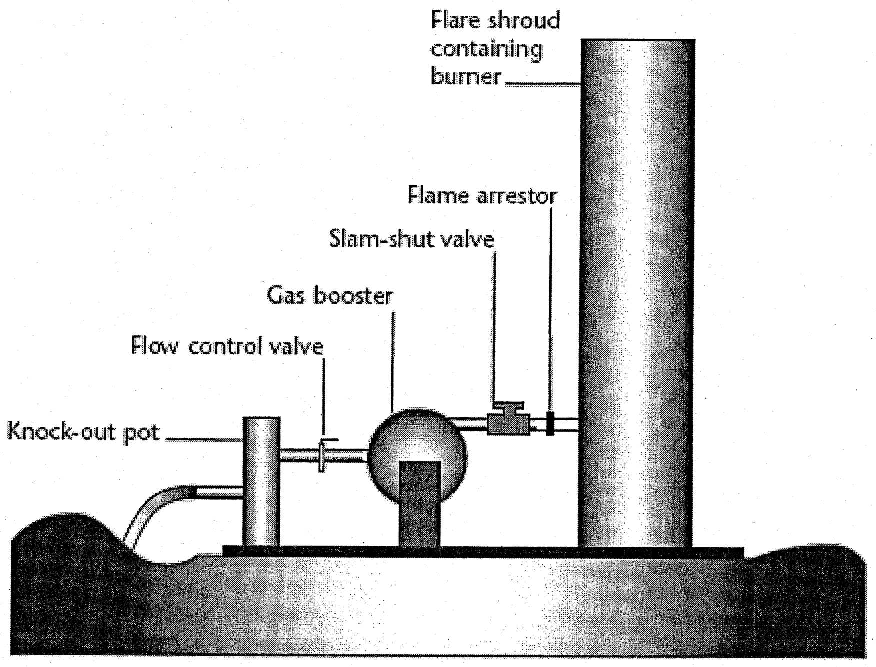
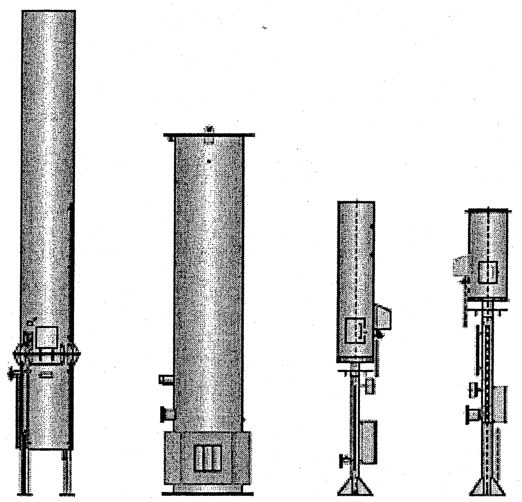


Figure 18. Basic flare arrangement

Ideally, a flare system should be placed at a higher elevation than a gas collection system to minimize the threats of liquid draining in to it. As a flare is exhibited to all weather conditions, it is essential that surface on the exterior of the flare is weatherproof and heat-resistant. Explosion hazards must be also considered as a priority issue.



HTV: High temperature flaring at 1,200°C; with ventilator and 0.3 seconds retention time
HTN/MTN: High/medium temperature flaring at 900°C – 1,200°C; with natural ventilation and 0.3 sec. retention time
MTU: Medium temperature flaring at 800°C to 1,000°C; uninsulated flare stack. 0.3 seconds retention time
LTO: Low temperature combustion; flare with open combustion ("candle" flare)

Figure 19. Flare design (from left to right)

Source: Stachowitz, 2000

4.6 Design analysis for LFG extraction system

While designing a LFG extraction system for energy recovery, one should know the composition of LFG, expected changes in gas flow with time, processing equipment, amount of gas generated and radius of influence from the extraction wells (Gardner, et al., 1990). There are two important phases in the design consideration for the LFG extraction process. While expected gas flow with time is useful for technical and economical analysis, the amount of gas generated is important when designing the capacity of the power generation plant.

4.6.1 Technical assessment (Phase1)

Technical assessment of designing LFG extraction system includes the following procedures: data collection, site inspection and interviews, survey and base data examination, screening process management, and conducting site tests. Data collection basically contains the following parameters: opening and closure data, waste type and weight, gas and leachate data, and the size of the site. Site inspection will assist in supporting the data collected and also help clarify design details if LFG extraction system.

4.6.2 Design procedure (Phase2)

The complete design of the main components of LFG extraction systems includes design gas collection system and treatment system. More specifically, a LFG extraction system consists of: wellheads, manifold station, dewatering system, condensate wells, booster and flare systems, gas utilization system and telecontrol system (Figure 20).

4.6.3 Landfill collection wells

Landfill collection wells are usually assembled as the pipework to assist removal of LFG from waste. The layout and spacing of collection wells can differ in some cases, relay upon a number factors, and should be designed by risk-based approach. Typically space between wells should not be greater than

40m if there are no other applied rules. Closer spacing of collection wells may be required to provide tightened control in specific sensitive areas depending on site-specific conditions and effective zone. General arrangement for LFG collection wells is shown in Figure 21. In order to provide sufficient gas

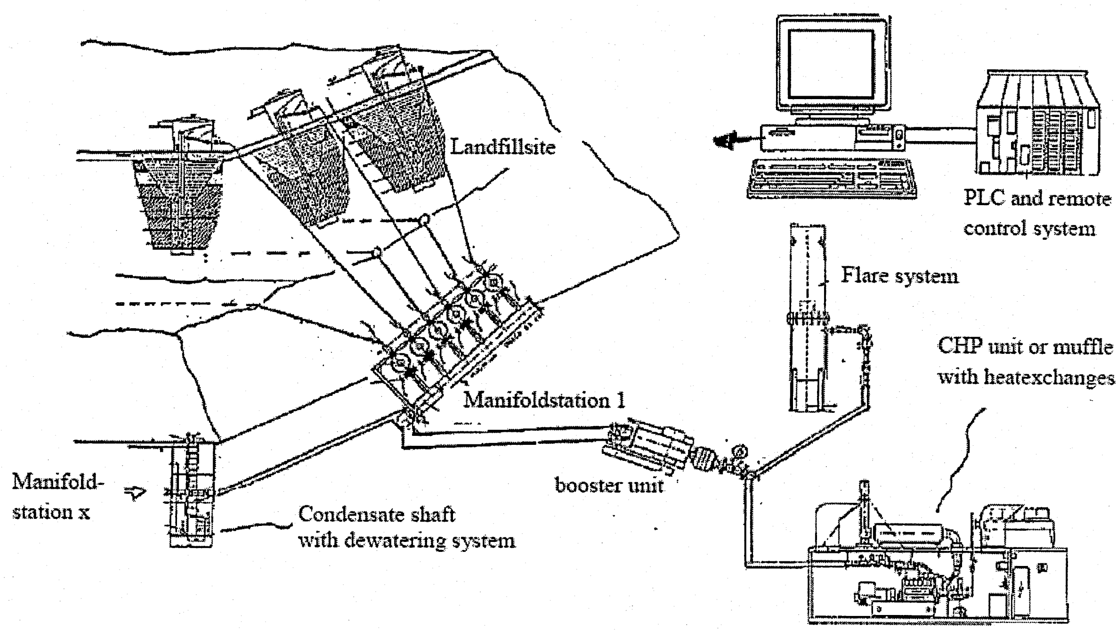


Figure 20. Typical gas extraction system

extraction and make control possible, the following aspects should be taken into account while installing gas collection wells:

- use a telescopic gas pipe to compensate settling occurrence;
- outgoing pipe preferred to be minimum 110mm in diameter with slope gradient 3% to 5% to prevent water seals;

- prevent air entering into gas collection system by placing a surrounding layer of clay and loam with sufficient thickness;
- provide gas supply pipes with proper mount sample points, couples and butterfly valves;
- supply sufficient length of pipe upstream and downstream of the flowrate measuring device;
- replete facility with remote controlled camera for video inspection.

Construction of LFG extraction wells implies an installation of the wells around the site to effectively trap a gas. Extraction wells are often constructed in the range of 30~100cm diameter boreholes. Primary materials for construction of extraction wells are PVC, HDPE, stainless steel and other composites. Pipe diameter is recommended to be larger than 50mm but smaller than 300mm. It's also recommended that the bottom ¾ of pipe has a perforation with 12mm diameter holes spaced at 90 degrees every 150mm.

4.6.4 Gas transport equipment

LFG transport equipment includes pipeline header and compressor/blower mechanisms. The typical pipe header range is 150~600mm in diameter. A pipe header is usually installed within a restoration layer because of after-use and visual requirements. In some landfills, especially those that have not ceased landfilling, pipe header may be installing above ground level. This is an

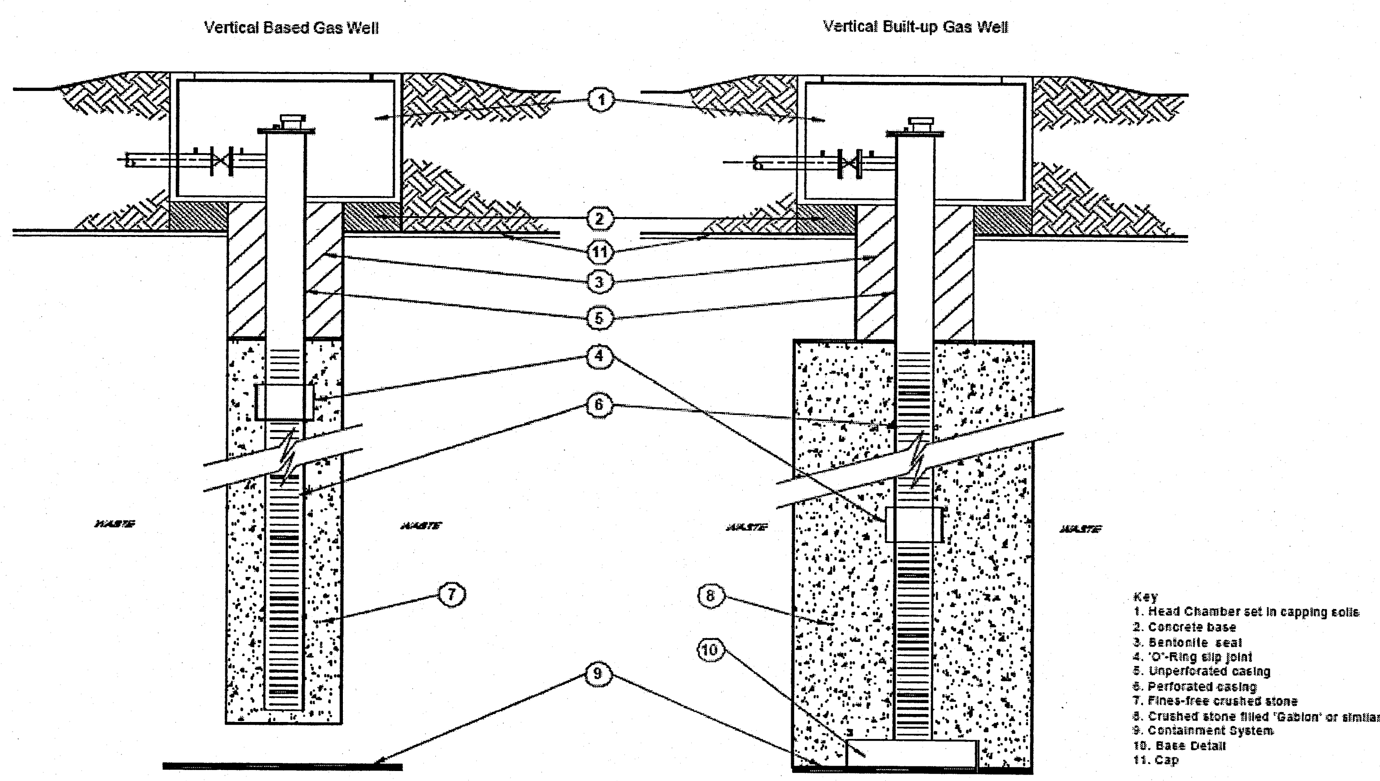


Figure 21. Typical well collection arrangement

advantage to provide a simple access for adjustment and monitoring. Typical wellhead arrangement is given in Figure 22.

The size and type of compressor/blower mechanism is based on total gas flow rate, total pressure drop and vacuum required to induce the pressure gradient. A variety of compressors with individual uses are available in a range of capacities, permitting selection to fulfill the needs of the site. Table 8 provides details of the most often used compressors, although this is not a complete list.

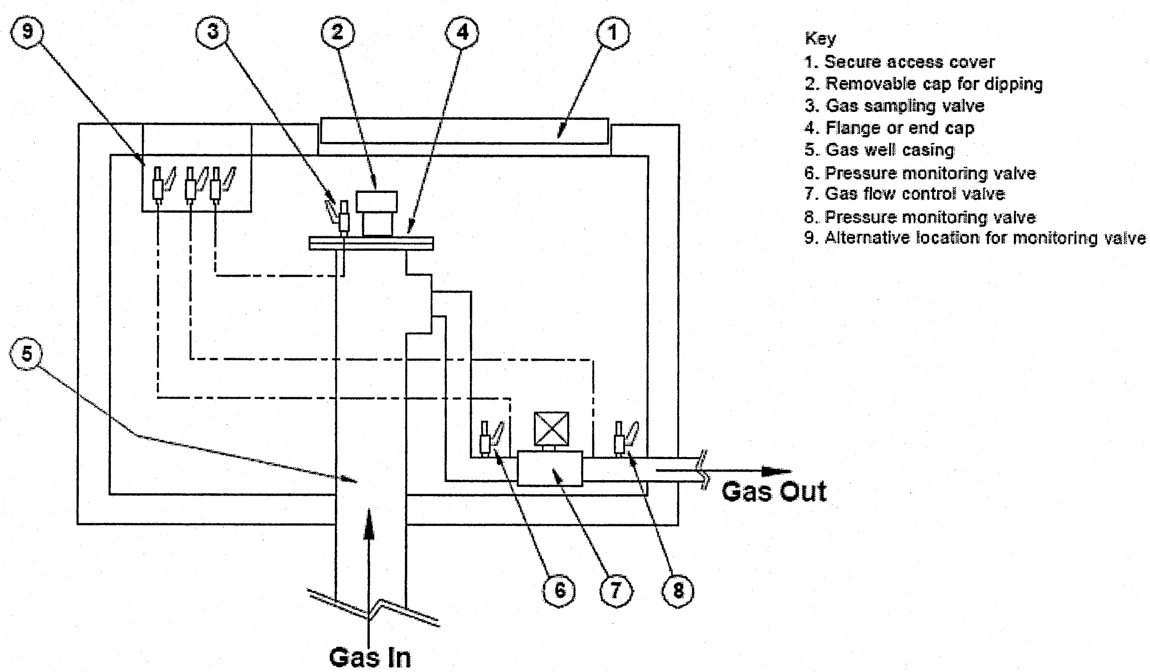


Figure 22. Typical well header arrangement

Table 8. Examples of types of compressors and boosters

Type	Typical flow rate (Nm^3 $hour^{-1}$)	Typical pressure rise (mbarg)	Comments
Single stage centrifugal booster	2 000	130	Well suited to landfill gas abstraction, by far the most common machine used. Low maintenance costs and tolerant of 'dirty' gases.
Two stage centrifugal booster	2 000	200	Well suited to landfill gas abstraction and supply to consumer. Frequently used to supply electricity generating sets.
Regenerative booster	1 000	200	Suitable for landfill gas although much less frequently used than centrifugal boosters.
Roots blower	1 000	1 500	Occasionally used for landfill gas to supply generators. Positive displacement machine which will not tolerate liquid water.
Sliding vane rotary compressor	1 000	1 000	Similar to Roots machines. Relatively high operating and maintenance costs.
Reciprocating compressor	1 000	>50 000	Capable of very high supply pressures, have been used to feed gas processing systems. High operating and maintenance costs.

4.6.5 Condensate control system

A principal technique of condensate control system is focused on withdrawing liquid from the gas collection network by the combined use of wellhead de-watering, low point drainage traps and a series of drained manifolds/points. The effective design of a condensate control system is based on the concept that pipes are set to fall toward drainage points with minimum gradients of 1% to 2%. If such falls cannot be maintained due to different kind of constraints, then the pipe network maybe exposed to 'saw-tooth' alignment. A basic empirical formula to calculate amount of condensate removed from collection system as a result of pressure drop is given below:

$$Q_{COND} = \frac{0{,}0203 \cdot Q_{TOTAL}}{760 - 1{,}87 \cdot \Delta P_{TOTAL}}$$

where: Q_{COND} – flow rate of condensate, m/min^3

Q_{TOTAL} – total gas flow rate, m/min^3

ΔP_{TOTAL} – total pressure drop, N/m^2

5. LANDFILL GAS PURIFICATION TECHNOLOGY

5.1 Background

Production of high concentrated gas (with methane content >90% by volume) involves the removal of carbon dioxide and other gases. When more than 90% methane content, LFG may be considered a high grade fuel (Conestoga Rovers, 2004, The World Bank). This high grade fuel can be used for different applications: as pipeline quality gas or fuel cells for the production of hydrogen, methanol, and/or fertilizer. Since one of the main objectives of this project is focused on producing high grade fuel LFG, the next discussion will emphasize the removal impurities from trace gases (sulfur, halogen, siloxanes) as well as removal of moisture and carbon dioxide stripping.

5.2 Hydrogen sulfide removal

Hydrogen sulfide (H_2S) is one of the most prevalent compounds accountable for landfill odors and can have an extremely low odor level (the lowest reported value is 0,5ppb in Ruth, 1986 cited in ATSDR, 2004). Hydrogen sulfide is a highly corrosive compound which may provoke damage to the gas pipe collection system and also emits a very unpleasant odor. Hydrogen sulfide emissions can be minimized by proper operation and maintenance. When odor problems occur, it requires corrective actions depending on whether odors have sufficient frequency, intensity, duration and offensiveness as well as other factors such as land uses, a presence of an exposed population and the location of the landfill. Today, several techniques are available for hydrogen sulfide removal. Some of them, more often used, are outlined below: air/oxygen infusion, iron chloride addition, activated carbon sieve, water scrubbing, lime scrubbing and biological treatment.

5.2.1 Air/Oxygen infusion

A main purpose of air/oxygen infusion is enhancing degradation of sulfides in the LFG. A typical infusion ratio of air to gas is 2% to 6% (where little excess of O_2 over the stoichiometric requirement. The results of the reaction are hydrogen and a cluster of simple sulfur. The process can be dangerous and explosive if the infusion of the air is disordered.

5.2.2 Iron chlorine addition

Iron chloride injection into a landfill collection system is the technique that can be used to overcome removal of hydrogen sulfide. Chemical reaction of iron chloride with hydrogen sulfide is the reaction that assists to form iron sulfide salt particles. Injection can be accomplished by directly injecting into the digester or into the mixing tank. This approach results in reducing high levels of hydrogen sulfide, but is less effective in retaining the low and stable hydrogen sulfide level. The entire removal of hydrogen sulfide is achievable but it is requires additional action.

5.2.3 Activated carbon sieve

Addition of activated carbon into a pressure swing adsorption system of landfill is another way to remove hydrogen sulfide. Selective adsorption maybe accomplished once a pressure applied to a sieve and molecule of hydrogen sulfide loses its bond. In a typical scheme, four filters are exploited in tandem, allowing a pressure transfer from one vessel to another, while each carbon bed approaches saturation. Basically when air is added to the LFG to promote adsorption of hydrogen sulfide (H_2S), the reaction goes further and forms simple sulfur and water ingredients. The sulfur is subsequently adsorbed by activated carbon. An activated carbon sieve process occurs at the pressure range of 100~115psi and temperature variation of 122~158^{O}F. The operating life of the carbon bed fluctuates between 4000 and 8000 hours and possibly longer at low hydrogen sulfide levels.

5.2.4 Water scrubbing

A simple technology that is available today for removal of both hydrogen sulfide and carbon dioxide from LFG gas is water scrubbing. The packed bed (plastic media) allows for efficient connection between water and gas phases in a countercurrent absorption environment. A whole system consists of two-stage gauge compressors and tall vertical columns. A LFG is placed at the bottom of column and flows upward, whereas clean water is introduced at the top of column and flows downward over the packed bed. Water is always circulated at the bottom of contact column and LFG passes trough its layers in the form of bubbles. At the final stage, carbon dioxide saturated in water is gradually withdrawn from the bottom of the column and collected gas exits from the top. After scrubbing, water may undergo regeneration process stocking in the pond or stripping of CO_2 with air at atmospheric pressure. A purity of treated methane at 95% can easily be succeeded with the above described technique. A water scrubbing technique itself is a practical, low cost process for upgrading daily LFG to bio-methane. Although, this process is not universal or superior, it is yet less efficient than other processes in terms of methane loss and energy.

5.2.5 Chemical scrubbing with polyethylene glycols

Chemical polyethylene glycol scrubbing is the physical process using specific solvent (Selexol liquid) in the natural gas industry. Selexol liquid has a greater influence than water on carbon dioxide and hydrogen sulfide by virtue of particular properties. Selexol, usually stripped with steam, is typically preserved under pressure, which improves its ability to absorb carbon dioxide, hydrogen sulfide and other impurities. Selexol solvent stripped with air is also available, but is not as popular due to the formation of simple sulfur during its use. The chemical scrubbing process with Selexol solvent has seized growing recognition after successful upgrading LFG in several landfills in United States. However, it should be mentioned that the process is more expensive for small-scale applications than water scrubbing or pressure swing adsorption.

5.2.6 Biological filter

Biofiltration of LFG is basically comprised of employed microorganisms implemented on a suitable media through which LFG passes. A microbe metabolizes within gas volume, in particular the contaminated odorous compounds, either to remove them or to reduce their concentration to an acceptable level. Usually, LFG is mixed within 4% to 6% with air before entry into the filter bed. A filter media provides the required surface area for scrubbing as well as the attachment of the oxidizing hydrogen sulfide. A well designed and operated biofilter can often accomplish removal efficiencies of 95% or more at low and moderate concentration of contaminants such as hydrogen sulfide, ammonia and volatile organic compounds.

5.3 Trace gas removal

The term 'trace gas' refers to a gas or gases that are composed from less than 1% of earth's atmosphere. Nitrogen forms approximately 78% of atmosphere with oxygen accounting for approximately a further 21%. Other gases such as sulfur compounds, non-methane organic compounds and volatile organic compounds are considered as trace gases. These trace compounds maybe removed by selective solvents, iron sponges or granular activated carbon. The granular activated carbon (GAC) is the most widely used substance to deal with hydrocarbon and volatile organic compounds (VOC). One of the substantial drawbacks of using GAC for LFG polishing application is its high similarity for moisture factor. Therefore a preliminary moisture removal process is desirable following GAC use.

5.4 Water vapor removal

As we learned from past, degeneration of organic waste is an exothermic process and therefore LFG eventually becomes saturated with vapor water. A combination of high moisture content with carbon dioxide, hydrogen sulfide and VOCs produces a potentially corrosive gas. The amount of saturated water vapor in a gas basically depends on temperature and pressure. Water vapor removal is an important process because hydrogen sulfide and water vapor react to form sulfuric acid (H_2SO_4), which then stimulates corrosion in the pipe network. Moreover, water vapor may react with carbon dioxide to form carbonic acid (H_2CO_3), which is also corrosive. Beside corrosion process, these corrosive substances can result in clogging of the pipes when water vapor condenses within the system. There are several techniques for moisture reduction today including the following: moisture separators, mist eliminators, direct cooling, compression followed by cooling, absorption and adsorption. More details on the above techniques can be found in Conestoga Rovers & Associates (2004).

Along with moisture reduction techniques, there are several methods including tees, U-pipes, or siphons that can be used to remove water vapor. A horizontal pipe network that runs with slope 1:100 is the simplest technique to remove condensate. Another method is a 'refrigeration' unit, applied for removing excess water vapor to dew points. In 'refrigeration' units, water vapor is condensed on the cooling coils and then captured in the trap. Scrubbing LFG to remove hydrogen sulfide prior to refrigeration will greatly extend durability of the refrigeration unit. Power required running refrigeration unit is usually often less than 2% of LFG energy content.

5.5 Particle removal

Particulates of various sizes are entrained in the gas stream and must be filtered out prior to gas use. Particles may be controlled in two ways: by passing through a filter pad (made of stainless steel wire) or alternatively using a cyclone separator. The filtering systems employed in LFG cleanup are much the same as those found on large-scale IC engine and gas turbine air cleaners. Filter types include particle size cutoff and coalescing models. Filter pads are capable of removing particles down to $2\mu n$ whereas cyclone separator is able of removing particles down to 15μn Dimethyl siloxane, a gaseous silicon compound, whose combustion products include silica particles, is not removed by conventional gas cleaning methods. Refrigeration, normally used for condensate removal, is the only method of removal for dimethyl siloxane (Pacey, et al., 1994).

6. CONCLUSIONS

The purpose of this project is to study and examine landfill gas generation, extraction and purification techniques. As we learned from past, LFG is typically composed of about 50% methane, 45% carbon dioxide, and 5% of other gases including hydrogen sulfides and volatile organic compounds. Methane is a powerful greenhouse gas, with 21 times the global warming potential of carbon dioxide. Estimates indicate that about 13% of methane emissions released to the atmosphere in the year 2000 were from landfills.

Produced by the biological degradation of refuses placed in a landfill site, LFG represents both an environmental liability and a unique renewable energy resource. However, the amount of energy that can be produced and recovered from landfill waste is still indistinct and subject for further research.

The principal and essential substances in generation of LFG are microorganisms and bacteria. They release methane and carbon dioxide from waste during the biodegradation process of organic materials. Methane, once produced can be extremely explosive when concentration of LFG between 5%-15% in an air. Moreover, disorderly discharge of LFG to the atmosphere adds significant problems to the environment, transforming some volatile organic, nitrogen oxides compounds.

There are many complex factors that effect landfill gas generation, extraction and purification. These factors are interrelated to each other including physical, chemical, biological characteristics, landfill design and construction techniques, weather conditions, waste type and composition. For example, on the one hand, the rate of waste stabilizing and biological degradation is function of the amount of gas produced. On the other hand, the dynamics of landfill gas and atmospheric conditions influence the efficiency of the LFG recovery system. Moreover, gas permeability, gas flow pattern and the transport mechanism, which is a physical properties of waste, type of daily cover, material of cell liners influence not only effectiveness of gas collection system but magnitude of gas that can be captured. To recover its energy value and minimize its pollutant effects, many landfill sites have installed LFG recovery and utilization systems.

Governed extraction and utilization of LFG using up-to-date technology of the landfill's aphorism gas-to-energy could replete benefits to environmental protection, air quality improvements and economic returns. Concerns that often come along with landfill gas relate to odour, air quality impacts and explosion risks. If emitted to the atmosphere untreated, LFG is yet a mighty greenhouse gas contributing to global climate change. Collection of LFG to control impacts also results in the generation of a source of green energy. The methane constituent of LFG confines energy that can be used to generate electricity, heat buildings, fuel industrial processes, or run vehicles. Utilization of energy from LFG not only assists in the control of local environmental impacts, but also avoids consumption of fossil fuels that would otherwise be required to generate an equal amount of energy. Collection and utilization of LFG represents a very significant opportunity to reduce greenhouse gas emissions to the atmosphere.

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