# EFFECT OF LEACHATE RECIRCULATION
# ON METHANE GENERATION OF A
# BIOREACTOR LANDFILL

By

SHAHED R MANZUR

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

AUGUST 2010

# ACKNOWLEDGEMENTS

First of all, I would like to acknowledge my advisor, mentor and guide, Dr. Md. Sahadat Hossain with my earnest appreciation and admiration for his valuable suggestion, encouragement and support throughout this journey. None of this work would have been possible without his motivation and guidance. I would also like to express my sincere gratitude to Dr. Laureano R Hoyos and Dr. Melanie L Sattler for their valuable time, priceless advice and bighearted assistance in the preparation of this document.

I would like to express my sincere gratitude to the City of Denton, TX, MSW Landfill authority for their financial support throughout this project. Special appreciation goes to Mr. Vance Kemler (Director of Solid Waste), Mr. David Dugger (Landfill Manager) & Mr. Mike Fogle (Landfill Supervisor) from City of Denton MSW Landfill for their readily available help during the field investigation. I must appreciate Jubair Hossain, Md. Sadik Khan, Golam Kibria, Tashfeena Taufiq, Huda Shihada, S. M. Ashfaqul Hoq, Md. Mustafizur Rahman and Mousumi Ahmed for their friendship, cooperation and support in all stages of this study.

Most important of all, I express my infinite gratitude to my parents, siblings, uncles and my entire family for their support and faith in me. Thanks a lot to Khondoker Huq & family for being the most wonderful cousin anyone can have.

Finally, this work is dedicated to my mother, Farida Manzur for her endless love and uncountable sacrifices throughout my life. Without your support, it was simply impossible for me to achieve this milestone.

June 16, 2010

# ABSTRACT

# EFFECT OF LEACHATE RECIRCULATION FOR METHANE GENERATION IN BIOREACTOR LANDFILL

Shahed R. Manzur, M.S.

The University of Texas at Arlington, 2010

Supervising Professor: Md. Sahadat Hossain

Municipal solid waste (MSW) disposal is of current concern due to the green-house effect and rising temperature all around the globe. Landfill gas is generated from aerobic & anaerobic biodegradation of organic materials in municipal solid waste (MSW) landfill. Along with leachate, generation of Methane happens to be a by-product of the entire biodegradation process in MSW landfills. Conventional landfilling or dry cell concept minimizes the amount of moisture infiltration into the waste. In contrast, Enhanced Leachate Recirculation (ELR) or bioreactor operation facilitates leachate recirculation and distribution through the landfill that leads both reduction of time for waste stabilization and enhancement of gas generation.

The influence of leachate recirculation was investigated from a US municipal solid waste landfill (City of Denton, TX) where landfill gas generation and gas composition data were monitored for ten (10) individual lateral pipes H1 to H10. Three (3) from those ten (10) pipes from current working area A were considered for this research to determine the influence of moisture injection for a period of 365 days. MSW landfill gas composition and landfill gas flow were measured from each individual pipe (H2, H7 and H6). The average flow rate from the bio-reaction beneath the recirculation pipes (H2 and H7) was close to 15 ft$^3$/min whereas, for the non recirculating pipe (H6), the average flow rate was around 10 ft$^3$/min. From the gas composition test results, the recirculated gas pipes H2 and H7 provided methane percentage (%$CH_4$) close to 60% whereas the non-recirculating pipe provided around 45%. In addition, the distribution of methane concentration was fairly even for the recirculaing pipes compared to the non-recirculating pipes. Gas flow rate and composition were highly affected with additional moisture intrusion into refuse mass in the form of recirculated leachate. The field flow rate was compared with the predicted flow rate to evaluate the efficiency of the leachate recirculation system and gas collection system.

# TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

# LIST OF TABLES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Municipal solid waste (MSW), commonly known as trash or garbage, is made up of the household type of waste including such items as package wrappings, food scraps, and grass clippings, computers, refrigerators. In 2005, 245 million tons of municipal solid waste was generated in the U.S., with approximately 54% of this waste buried in landfills (U.S. EPA, 2005). While portions of this waste are recycled, composted, and converted to energy, landfills will remain a significant aspect of MSW management for the foreseeable future.

Conventional MSW landfills are designed and operated in accordance with RCRA Subtitle D, which minimizes amount of moisture entering and retained in the landfill waste. The absence of moisture in the waste prolongs the decomposition, and complete decomposition can as long as 50 to 100 years. This complicates the post closure monitoring period, which is currently set as 30 years, and future development. Also, due to rapid growth and urbanization of cities beyond city limits, many of these landfills are now within city limits. However, finding a suitable new location for landfilling of MSW within the city limit is becoming a predominant problem, as conventional MSW landfills may occupy an area ranging from several acres to hundreds of acres. Therefore, waste minimization or increasing the capacity of landfills within the same area is becoming a major consideration for the state agencies and federal regulatory bodies.

Accordingly, there have been substantial changes in the design and operation of landfills over the past twenty years. Though first suggested in the mid 1970s (Pohland, 1975), the concept of operating a landfill as a bioreactor or enhanced leachate recirculation (ELR) landfill has recently received increased attention (Pacey et al., 1999). An ELR landfill is operated to enhance refuse decomposition, gas production, and waste stabilization.

An ELR landfill operates to rapidly transform and degrade the organic matter within the MSW stream. A major aspect of ELR landfill operation is the addition of liquid and recirculation of collected leachate back through the refuse mass. The idea of liquid addition differs from the conventional landfill approach, where the objective was to minimize moisture intrusion into the landfill. According to the Solid Waste Association of North America (SWANA), a bioreactor landfill can be classified as "a controlled landfill or landfill cell where liquid and gas conditions are actively managed in order to accelerate or enhance bio-stabilization of the waste. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates, and process effectiveness over what would otherwise occur with the landfill." Moreover, the USEPA Clean Air Act regulations (40 CFR 63.1990), National Emissions Standards for Hazardous Air Pollutants) define a bioreactor landfill as: "a MSW landfill or a portion of a MSW landfill where any liquid, other than leachate or landfill gas condensate, is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40% by weight to accelerate or enhance the anaerobic biodegradation of the waste."

## 1.2 Performance Assessments for Leachate Recirculation

The leachate recirculation systems can be designed to accommodate both surface and subsurface leachate distribution. Leachare recirculation involves containment, collection and return of leachate back through the landfill media in a well designed system. Leachate recirculation through sanitary landfills has been shown to treat leachate partially and enhance the stabilization rate of organic compounds within the landfill (Pohland, 1980).

There are several benefits associated with the operation of landfills as bioreactors, including:

- Increased stabilization rates for organic compounds in the landfills. More rapid settlement results in increased effective refuse density and air space as presented in Figure 1.1.

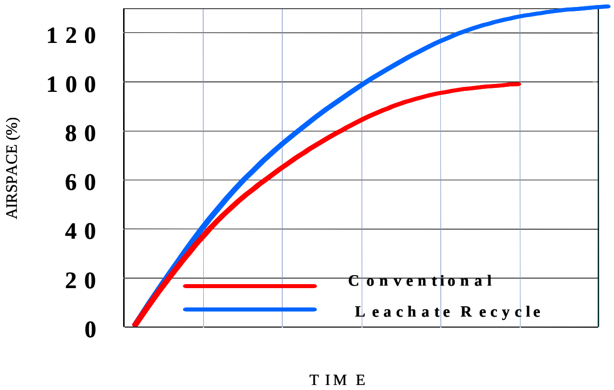


Figure 1.1: Increases air space in bioreactor or ERL landfill

- In-situ leachate treatment and the reduction of leachate handling cost ,
- Increased gas production which can improve the economics of energy recovery,
- The rapid stabilization of a landfill to a more environmentally benign state, and

- Acceleration of refuse decomposition, which may shorten the regulated post closure monitoring period and reduce the overall cost of the landfill,
- Efficient and effective use of landfill space because of refuse consolidation.

As a result of these benefits, there has been a significant increase in the number of landfills that are being operated with leachate recycle. A review of literature in 1993 identified less than 20 leachate recirculating landfills located in US, Germany, UK, and Sweden. By 1998, over 200 landfills were practicing leachate recirculation with little engineering input to design and operation (Reinhart et. al., 2002).

Leachate recirculation system design requires critical considerations for landfill stability for the local and global conditions. The shear strength of the MSW with the presence of the cover soil tends to decrease with time due to the degradation. According to a study by Miller & Emge (1997), several design considerations for the design of recirculation systems are adopted:

- Depositional blockages in the leachate collection system (drainage layers and piping) need to be anticipated and the considerations should be given to enlarging critical components (over sizing), system cleaning, and component replacement.
- Aerated leachate may introduce oxygen concentrations into the landfill that are inhibitory to methanogens, thereby resulting in decreased gas quality. Introducing aerated leachate may also hinder the anaerobic processes that leachate recirculation is intended to promote. Therefore, aeration should not be used in combination with subsurface leachate recirculation, but should be provided before surface application to reduce odors.

- Spraying leachate on the landfill surface over a vegetated cap may be used to reduce volume by evaporation and evapo-transpiration. However, winter freezing may prohibit operation during certain months. Therefore, surface application of leachate should be limited to areas with intermediate cover to ensure complete containment of leachate within the landfill and the collection or storage systems.

### 1.3 Problems with Leachate Recirculation

The design and operation of a landfill as ELR raises some concerns for stability analysis. Kavazanjian (1999) reported that the advent of ELR landfills, in which liquids are re-circulated by injection into the waste mass, not only raises questions about changes in mechanical properties but also heightens concerns about the stability of saturated waste. Therefore, waste stability is a critical component of ELR landfill design and operation. Injection of leachate and other liquids into an ELR landfill can endanger the stability of slopes due to the following reasons (Kavazanjian et al., 2001, Townsend et al., 2008):

- Increased driving force due to the increase in weight of the waste mass following liquid injections,
- Decreased strength due to decrease in the effective stress corresponding to the increase in pore pressure that results from liquid injection (both leachate head build-up and localized decrease in effective stress),
- Decreased strength due to the transformation of waste mass by the biological and chemical process that enhances degradation, turning the waste mass into an inherently weaker material.

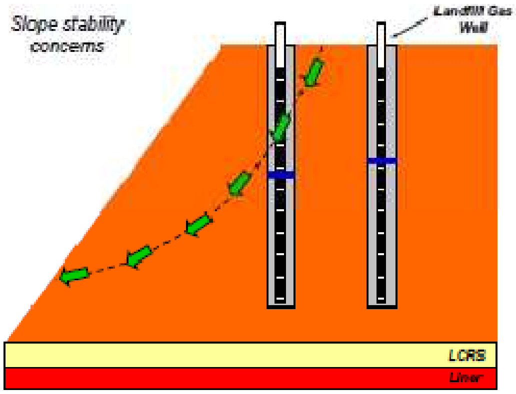


Figure 1.2: Slope stability concerns at MSW landfill (Townsend et al., 2008)

The daily cover soil may affect the stability of slopes in ELR landfills. As suggested by ITRC (2006), the use of relatively low permeability daily cover materials may result in perched leachate conditions. This can result in a build-up of pore water pressure within an isolated zone (Figure 1.3). Eventually this may cause slope failure. Therefore, extensive slope stability analyses are required for successful operation of ELR lansfills.

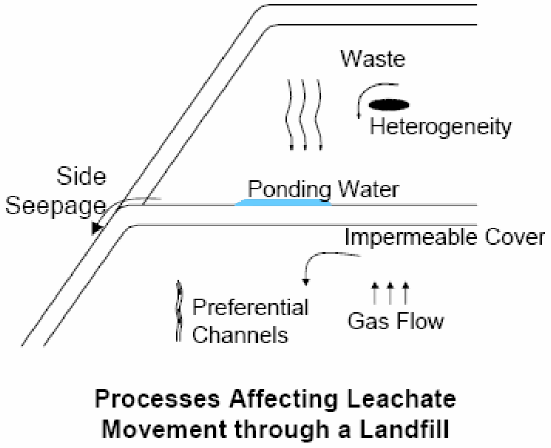


Figure 1.3: Affects of impermeable daily cover soils on slope (ITRC, 2006)

From another research by Townsend et al. (2008), the slope stability problem was reported due to the low conductivity of cover soil. Interception of leachate by low permeability cover layers and subsequent transmission of leachate to the side slope of the landfill can result in seeps as shown in Figure 1.4.

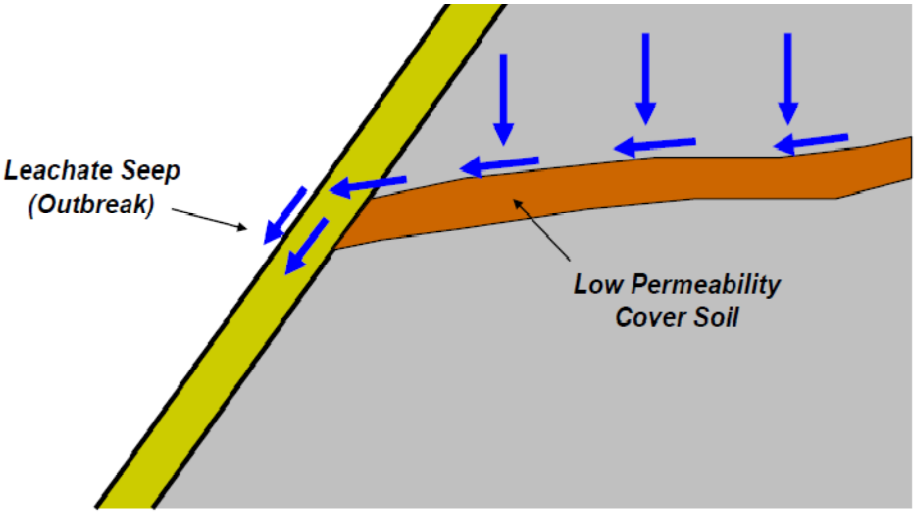


Figure 1.4: Affects of impermeable daily cover soils on slope (Townsend et al., 2008)

Using low permeable soil (clay materials) as a cover soil has adverse effects on the gas generation for MSW landfills. Due to the low permeability, leachate takes longer to percolate into the solid waste, resulting in a perched condition. Presence of additional leachate slows down biodegradation of MSW or even can cease biodegradation. Operating trenches concurrently for gas extraction and leachate recirculation can be a problematic issue for bioreactor operations. The perched leachate tends to blind the the bottom of the trench and thus reduce the effectiveness of gas extraction. The presence of stagnant leachate thus affects into gas generation, as well as creates progressive slope failure into the MSW landfill as shown in Figure 1.5.

Figure 1.5: Progressive failure pattern in landfill slope

## 1.4 Objective

The primary goal of this study is to determine the influence of leachate recirculation on gas production. The major objectives are:

- To determine influence area within the MSW of leachate recirculation using Resistivity Imaging (RI) for a period of six months starting from June 2009 to December 2009.
- To monitor landfill gas composition and gas flow rate during the leachate recirculation period.
- To determine the influence of leachate recirculation by comparing gas flow rate data from leachate recirculation pipes and non recirculation gas pipes.
- To predict the gas flow rate using US EPA's 1st order kinetic gas generation model.
- To compare modeled gas flow rate with actual field gas flow rate to study the effect of leachate recirculation on gas generation.

### 1.5 Organization

This thesis report is comprised of five (5) chapters: Introduction (Chapter 1), Literature Review (Chapter 2), Methodology & Field Studies (Chapter 3), Results & Discussion (Chapter 4) and Conclusions & Recommendation for Future Work (Chapter 5).

Chapter 2 covers literature review and the background behind this work. Several literatures were reviewed regarding leachate recirculation methodologies and current practices along with different phases of decomposition for landfill gas generation and gas composition. US EPA's first order gas generation model and the parameters behind gas generation have also been studied in detail.

Chapter 3 describes the history and geological information of the study area and step-by-step approach behind this study. The test locations for the RI tests and the procedure have been discussed to determine the influence area.

Chapter 4 focuses on the analysis and prediction of the landfill gas flow rate from the influence area obtained from RI test results. The field gas composition and flow rate data were represented for different pipes. The predicted gas generation rate and the composition were compared with the actual field data. The gas generation rate was predicted using the UE EPA's 1st order gas generation equation with the aid of the field HRRI images of the redrawn landfill geometry.

Chapter 5 finally summarizes the results and outcomes for the present work and recommendations for future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

A MSW landfill can be described as a relatively long term biochemical reactor where solid waste and water are the inputs and landfill gas and leachate are the primary outputs. Fresh solid waste along with partially biodegraded organic material and other inorganic waste materials are placed in landfill. Methane emissions and leachate disposal are recognized as the two major concerns of municipal solid waste landfills. Methane gas is a by-product of landfilling municipal solid wastes. Most of the global MSW is dumped into non-regulated landfills and the generated methane is emitted to the atmosphere. Some of the modern regulated landfills attempt to capture and utilize landfill biogas, a renewable energy source, to generate electricity or heat. As of 2001, there were about one thousand landfills collecting landfill biogas worldwide. The landfills that capture biogas in the US collect about 2.6 million tones of methane annually, 70% of which is used to generate heat and/or electricity. The landfill gas situation in the US was used to estimate the potential for additional collection and utilization of landfill gas in the US and worldwide.

Recently, leachate recirculation has been used to accelerate landfilled waste biodegradation to enhance landfill gas generation. In addition, leachate irrigation was also conducted for volume reduction in an effective manner. However, the impacts of leachate recirculation on landfill $CH_4$ emissions have not been previously reported. So, the main objectives of this chapter are to reviewing the effect of recirculation inside the landfill that leads to the enhancement of gas generation. Landfill settlement is also another issue that comes upfront once the leachate recirculation is conducted. So, several landfills in different climate zone have been reviewed and the effects are described in this chapter.

## 2.2 Methane, a Primary Constituent of Landfill Emissions

Methane ($CH_4$) is an important greenhouse gas, because its global warming potential is 21 times more effective than that of $CO_2$ on a 100 year time horizon (IPCC, 2001). Atmospheric $CH_4$ concentration has more than doubled during the past several 100 years and continues to rise due to human actions (IPCC, 2001). Of the global anthropogenic $CH_4$ emissions, more than 10% originate from municipal solid waste (MSW) landfills (IPCC, 2001). Studies from Bogner et al., 1995 and Kumar et al., 2004 suggested that landfill $CH_4$ is produced from anaerobic biodegradation of organic matter inside the land-filled waste. $CH_4$ emissions vary significantly among the landfill sites and are affected by gas recovery, microbial $CH_4$ oxidation, landfill age, the thickness of landfill cover, and meteorological conditions. A recent study by Lohila et al. (2007) stated that, gas recovery has been reported to control $CH_4$ emissions from the landfill sites effectively. Microbial oxidation of $CH_4$ in cover soils provides a complementary strategy for minimizing landfill $CH_4$ emissions (Barlaz et al., 2004; Berger et al., 2005; Abichou et al., 2006).

The United States Environmental Protection Agency (US EPA) estimated that the total anthropogenic emissions of methane were 282.6 million tonnes in 2000, where 36.7 million tonnes (13%) were due to landfill emissions (Figure. 2.1).

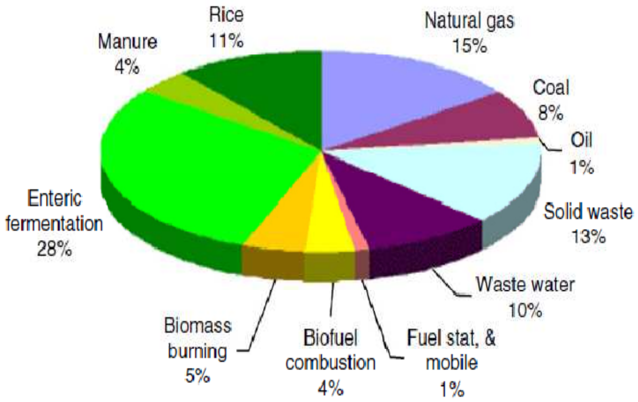
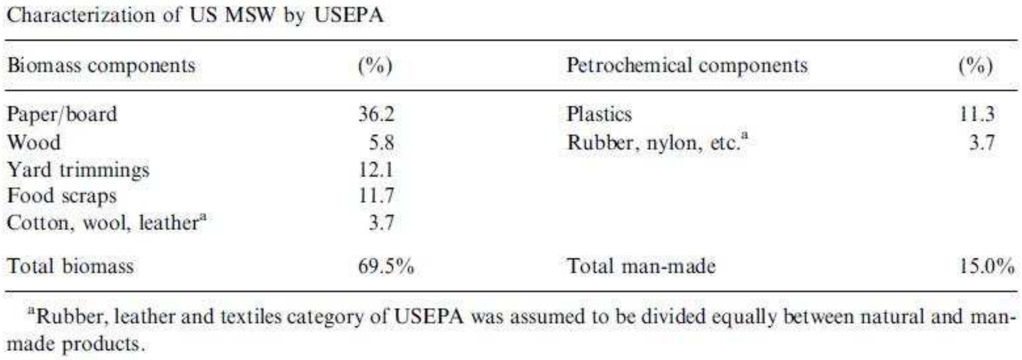


Figure 2.1: Global anthropogenic methane (Themelis & Ulloa, 2007).

From a research by US EPA (2003), the characterization of US MSW is shown in Table 2.1. The typical MSW of Table 2.1 contains 69.5% of biomass materials. This includes the contained moisture and inorganic dirt particles

Table 2.1: Characterization of MSW in USA (US EPA, 2003)



Characterization of US MSW by USEPA

| Biomass components | (%) | Petrochemical components | (%) |
|---|---|---|---|
| Paper/board | 36.2 | Plastics | 11.3 |
| Wood | 5.8 | Rubber, nylon, etc.[a] | 3.7 |
| Yard trimmings | 12.1 | | |
| Food scraps | 11.7 | | |
| Cotton, wool, leather[a] | 3.7 | | |
| Total biomass | 69.5% | Total man-made | 15.0% |

[a] Rubber, leather and textiles category of USEPA was assumed to be divided equally between natural and man-made products.

From the simple balance equation,

$$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2$$

complete reaction of one tonne of MSW would generate 208 standard cubic meters of methane biogas or 0.149 tonnes of methane.  The rate of biodegradation of MSW in landfills was studied by Barlaz et al. in small pilot plant columns that provided ideal temperature and concentration conditions for bio-reaction. As shown in Figure. 2.2, the reaction peaked at less than one hundred days and was nearly complete after about 320 days. Barlaz (2006) estimated that the total amount of gas generated during this period was 213 $Mm^3$ methane/dry tonne of biomass reacted.

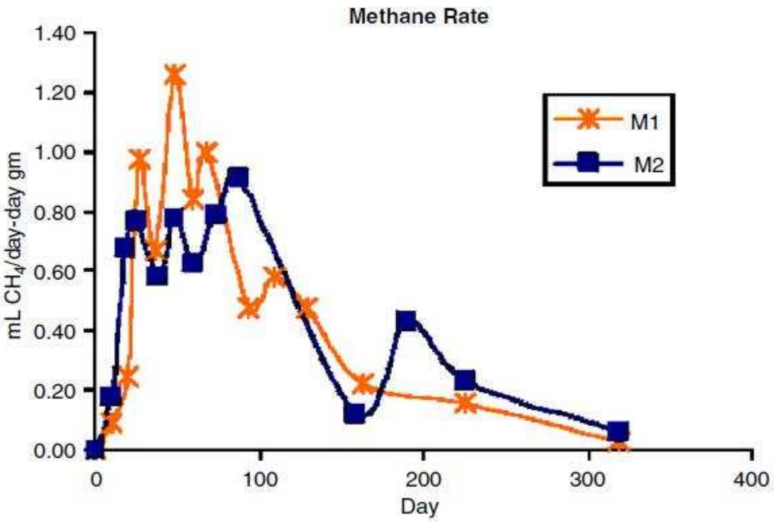


Figure 2.2: Generation of methane in experimental apparatus simulating landfill bio-reactions in two different tests M1 and M2 (Barlaz et al., 2004)

## 2.3 Landfill Gas Composition

Landfill gas is primarily the by-product of anaerobic biodegradation of organic materials in landfills. Municipal solid waste generally generates tremendous quantities of gas during its decomposition. Landfill gas generation is a biological processes in which microorganisms decompose organic waste to produce carbon dioxide, methane, hydrogen sulfide and other gases. The landfill gases are categorized into two distinct groups as principal gases and trace gases. Principal gases are present in landfill gas in higher quantities (i.e. $CH_4$, $CO_2$), whereas the trace gases (i.e. $H_2S$) have lower amount. Although the trace gases are present in small quantities, these may be toxic and pose a risk in public health. A research by Energy Information Administration, US Department of Energy, 1996, have represented that the main compounds and their composition of landfill gas from anaerobic biodegradation as-

Table 2.2: Composition of landfill gas (US DOE, 1996)

| Compound | Average concentration (%) |
|---|---|
| Methane ($CH_4$) | 50 |
| Carbon dioxide ($H_2S$) | 45 |
| Nitrogen ($N_2$) | 5 |
| Hydrogen sulfide ($H_2S$) | <1 |
| Non-methane organic compound (NMOC) | 2700 ppmv |

## 2.4 Different Phases of Bio-reaction

After the MSW is landfilled, the organic components start to decompose in presence of microorganisms. Near the surface of the landfill, the natural organic compounds are oxidized aerobically with the presence of atmospheric oxygen. The main end products with this biochemical reaction are methane carbon dioxide and water vapor. However, the principal bioreaction in the landfill is anaerobic digestion, which takes place in three steps:

First, fermentative bacteria hydrolyze the complex organic matter into soluble molecules.

Second, these molecules are converted by acid-forming bacteria to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are acetic acid, propionic acid, butric acid and ethanol.

Last, methane is formed by the methanogenic bacteria, either by breaking down the acids to methane and carbon dioxide, or by reducing carbon dioxide with oxygen. Representative forms of reactions can be shown as:

Acetogenesis

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$$

Methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO$$

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$

The maximum amount of methane or natural gas that may be generated during anaerobic decomposition of cellulose can be shown by the equation:

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$$

$$C_6H_{10}O_4 + 1.5\ H_2O \rightarrow 3.25\ CH_4 + 2.75\ CO_2$$

This reaction produces a very small amount of heat and the product gas contains about 54% methane and 46% carbon dioxide. The landfill gas also contains water vapor near the saturation point corresponding to the cell temperature, plus small amounts of ammonia, hydrogen sulphide and other minor constituents. So, in order to keep the anaerobic reaction active, water needs to be added as the principal agent. From several studies by He et al. (2007) and Benson et al. (2007), leachate recirculation plays a vital role to accelerate the methanogenesis of the landfilled waste in the lab scale landfill column.

The landfill gas generation occurs in several phases which are shown in Figure 2.3 from the researched conducted by United Kingdom Department of Environment (UKDOE). Initially, the distribution of the gases in the landfill is representative of the distribution of gases in the atmosphere - about 79% nitrogen and 21% oxygen, with a small amount of carbon dioxide and other compounds. Aerobic decomposition begins soon after the waste is placed in a landfill and it continues until all of entrained oxygen is depleted from the voids in the waste and from within the organic material itself. Aerobic bacteria produce a gaseous product characterized by relatively high temperatures (130 to $160^0$ F or 54 to $71^0$C), high carbon dioxide and no methane content. Other bi-products include water, residual organics and heat. According to several studies by EMCON Associates (1980, 1981, 1998), aerobic decomposition may continue from 6 to as long as 18 months in the upper lifts if methane-rich landfill gas from below flushes oxygen from voids in the disposed waste.

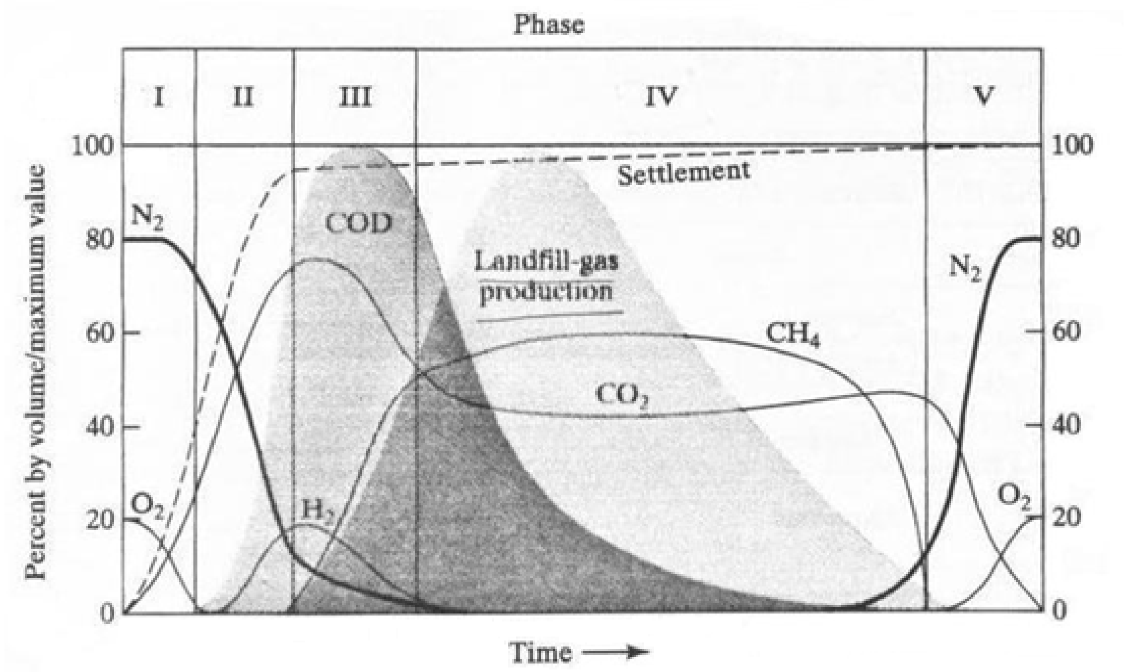


Figure 2.3: Changes in landfill gas composition over time (UK DOE, 1993)

Waste decomposition undergoes several distinct changes with time. After all entrained oxygen is depleted, decomposition comes to a transitional phase where acid forming bacteria begin to hydrolyze and ferment the complex organic compounds in the waste. Decomposition then enters into an anaerobic phase, during which methane forming bacteria, which thrive in an oxygen deficient environment, become dominant. Studies (EMCON, 1998) have shown that the anaerobic gas production is typified by lower temperatures (100 to $130^0$ F or 38 to $54^0$ C), significantly higher methane concentrations (45 to 57%) and lower carbon dioxide concentrations (40 to 48%). Anaerobic gas production will continue until all the carbonaceous material is depleted or until oxygen is re-introduced into the waste, which would then return the decomposition process in aerobic conditions. A return to aerobic decomposition does not stop landfill gas production, but it will retard the process until anaerobic conditions prevail again (EMCON, 1998). All the five phases with the indication of end of phases are shown in Table 2.3. The total time duration of gas generation for a landfill can be as high as 10 to 80 years or even more. The time duration for bioreactor landfill is normally less than that for the conventional landfill.

Table 2.3: Summary of MSW Landfill Gas Generation Phases
(According to EMCON, 1998)

| Phase | Name | Primary activity signaling the end of phase |
|---|---|---|
| I | Aerobic | No oxygen in the landfill gas (several hours to 1 week) |
| II | Aerobic/Acid Generation | Formation of free fatty acids is at its peak and methane generation begins (1 to 6 months) |
| III | Transition to Anaerobic | Methane and carbon dioxide concentrations stabilize and no nitrogen in the landfill gas (3 months to 3 years) |
| IV | Anaerobic | Methane and carbon dioxide concentrations begins to reduce and some nitrogen (air) returns to the system (8 to 40 years) |
| V | Transition to Stabilization | Gas is primary air and all anaerobic decomposition is complete (1 to 40 or more years) |

## 2.5 Factors Affecting Gas generation

The amount of generated gas from a MSW landfill depends on several factors including the waste composition, moisture content, particle size, age of waste, pH, and temperature. From several researches (McBean et al., EMCON 1998) it is evident that, the decomposition and gas generation are expected to continue for 30-100 years but in practice gas generation occurs at a high level for a much shorter period of time.

### *2.5.1 Waste Composition*

The residential and commercial waste placed into the landfill can be divided by two groups: decomposable and nondecomposable/inert materials. Decomposable materials include food waste, clothes, papers, woods (slowly decomposable materials) whereas glass, metals, plastics, construction and demolition waste fall in the category of inert materials. The more easily the organic fraction of the waste decomposes, the faster will be the landfill gas generation rate. Food wastes typically fall into this category. Thus, a high percentage of food wastes in a landfill likely will lead to a faster landfill gas generation rate. Some decomposable wastes, such as large pieces of wood, are not inert, but decompose so slowly that for most practical purposes they do not contribute significantly to landfill gas generation.

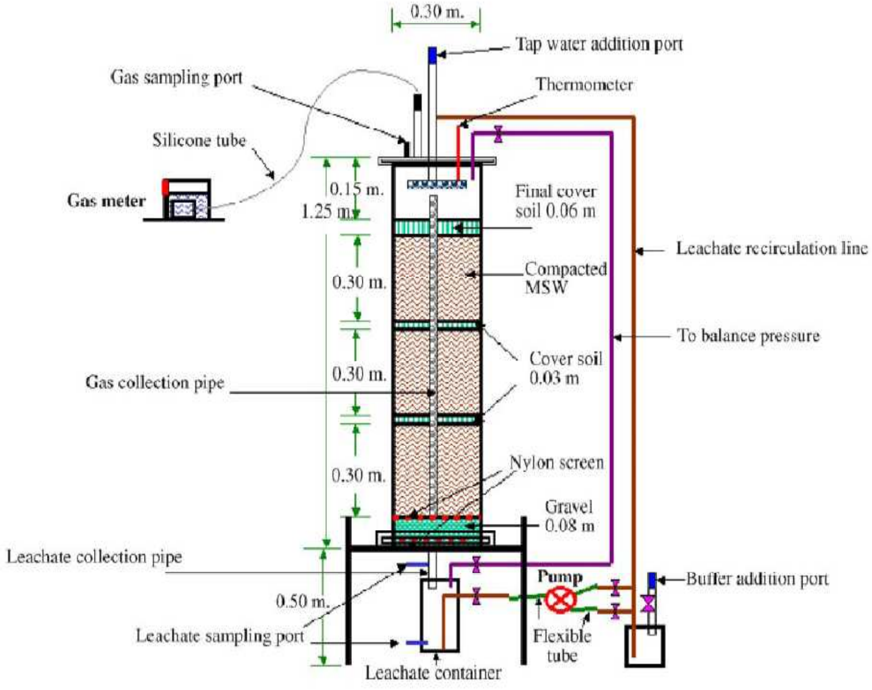
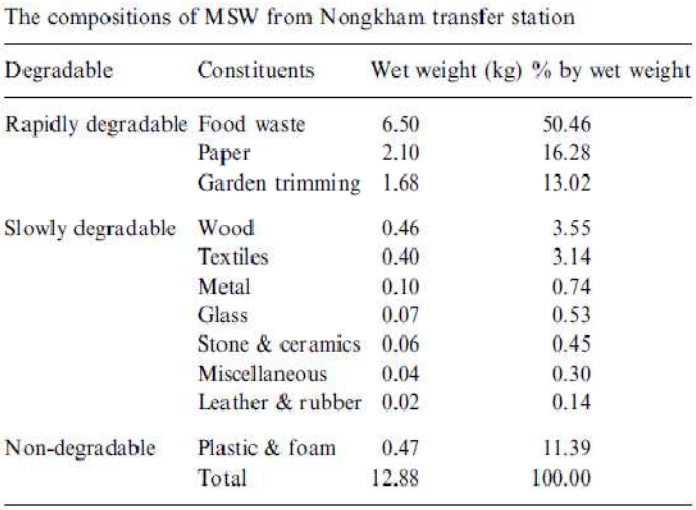


Figure 2.4: Simulated Landfill Reactor (Sanphoti et al., 2006)

From a research by Sanphoti et al. (2006), the MSW sample reactor setup as shown in Figure 2.4 provided a methane generation of 9.02 l/kg dry weight at a rate of 0.10 l/kg dry weight/d, and reached the stabilization phase on day 270.

Table 2.4: MSW Composition (Sanphoti et al., 2006)



The compositions of MSW from Nongkham transfer station

| Degradable | Constituents | Wet weight (kg) | % by wet weight |
|---|---|---|---|
| Rapidly degradable | Food waste | 6.50 | 50.46 |
| | Paper | 2.10 | 16.28 |
| | Garden trimming | 1.68 | 13.02 |
| Slowly degradable | Wood | 0.46 | 3.55 |
| | Textiles | 0.40 | 3.14 |
| | Metal | 0.10 | 0.74 |
| | Glass | 0.07 | 0.53 |
| | Stone & ceramics | 0.06 | 0.45 |
| | Miscellaneous | 0.04 | 0.30 |
| | Leather & rubber | 0.02 | 0.14 |
| Non-degradable | Plastic & foam | 0.47 | 11.39 |
| | Total | 12.88 | 100.00 |

*2.5.2 Moisture Content of the Waste*

For most landfills, after waste composition the moisture content of the waste is the most significant factor in prediction of landfill gas. The higher the moisture content, the greater the gas generation rate up to a point. Afterwards, with high moisture content methane production rate actively decreases. Moisture content in a conventional landfill changes over time whereas for the bioreactor landfill, the moisture content is kept at an optimum amount to maximize the gas generation. Conventional landfills are operated to minimize the amount of moisture infiltrating into the waste (dry cell concept). Landfill bioreactors are designed and operated to enhance the biodegradation process by increasing waste moisture levels within the landfill (Reinhart and Townsend, 1997). The moisture content (MC) of solid waste is increased by the addition of water and/or recirculation of the collected leachate. While the relationship between increased MC and rapid waste decomposition has been well established through laboratory studies (Rees, 1980), increasing the moisture content of solid waste in a full scale operating landfill is a challenge. Changes in landfill moisture content may result from changes in surface water infiltration and/or groundwater inflow, release of water as a result of waste decomposition, seasonal variations in the moisture content of the waste, and managed additions of liquids. Theoretically, the optimum condition for gas generation is total waste saturation.

Another research by Mehta & Barlaz et al. (2002) in conjunction with Yolo County, California Department of Public Works showed the performance of two full scale test cells, one operated with and another without controlled moisture addition. The methane production rate in the control and enhanced cells are presented in Figure 2.5.

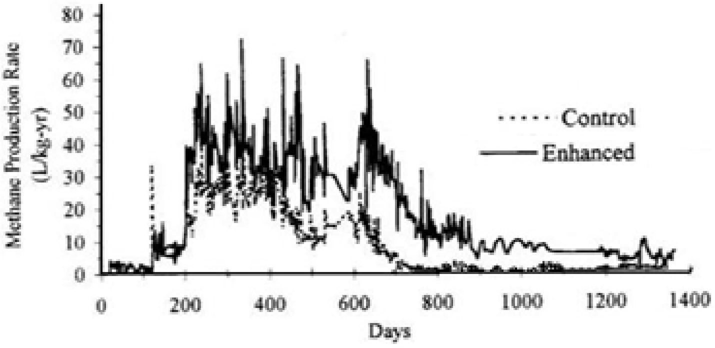


Figure 2.5: Methane production rate in enhanced and control cells (Mehta et al., 2002)

The measured methane yields through day 1,231 were 27.9 and 63.1 L CH4 /wet-kg in the control and enhanced cells, respectively. Day 1,231 is the day on which solid samples were collected. Between days 1,231 and 1,365 yields increased to 28.1 and 64.6 L-CH4 /wet-kg, respectively. Refuse excavated from the control cell was drier than that from the enhanced cell. The moisture contents from the control cell were 14.6% and 19.2% where from the enhanced cell the values were 38.8, 31.7 and 34.8%.

Generally, the volumetric moisture content of any fresh solid waste at placement is less than the required moisture content for the optimum gas generation. For fresh MSW, typical moisture content can be 20-40%. Whenever the moisture content is less than the field saturation condition, additional water is added with the leachate to increase the rate of degradation. Research by Morris et al. (2000), reports that a waste with volumetric moisture content of 20% and degree of saturation of 40%, was recorded with leachate and additional water to represent 90% of the required to saturate the waste to its field capacity in order to overcome the waste moisture deficit. The field capacity is a target moisture content at which significantly accelerated degradation takes place.

Figure 2.6 illustrates mass of waste placed and volume of leachate recycled into the landfill. It also reflects the landfill settlement respect to the total volume of landfill at closure. It clearly indicates that the degradation that takes place during the operating period what cause the volumetric reduction. Settlement increases the capacity of the landfill so that it can take more waste at the time during the time of operation.

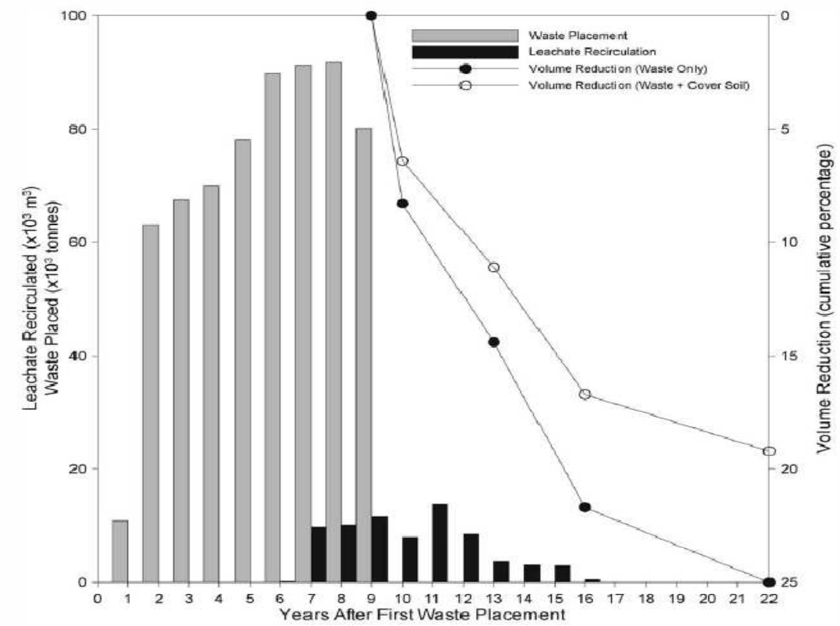


Figure 2.6: Waste placement, leachate recirculation and settlement by Morris et al. (2003)

However, Figure 2.7 denotes that the volume of leachate generated did not increase significantly during the period of leachate recirculation. It also decreased noticeably after the closure of the landfill. The leachate generation varies seasonally and one of the influencing factors is the rainwater. The landfill top cover with loose soil cover ($10^{-2}$ cm/sec) allowed rainwater to percolate into the waste. Both leachate recirculation and the high amount of infiltration have certainly played a vital role in saturating the waste beyond the field capacity which resulted in considerable flushing. Two test cells were created to study the effects with different amount of leachate recirculation. The collected leachate was measured as shown in Figure 2.8.

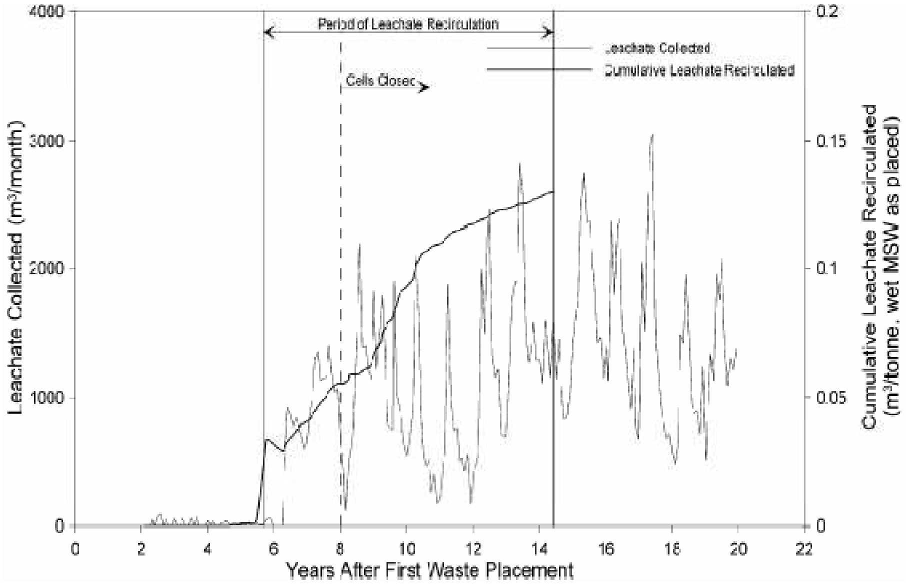


Figure 2.7: Leachate production at landfill (Delaware) by Morris et al. (2003)

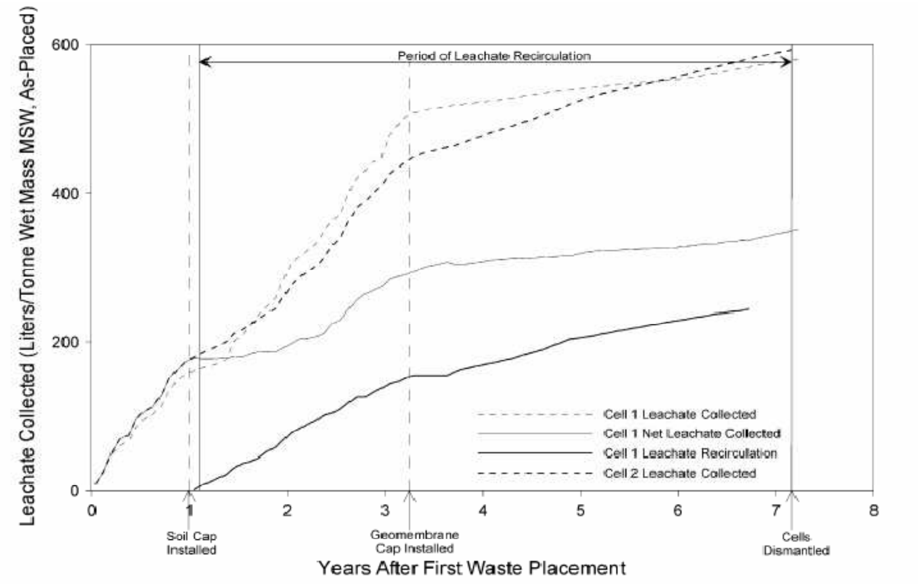


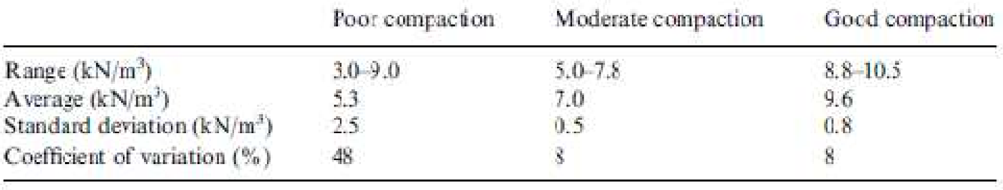
Figure 2.8: Cumulative leachate flow volume from test by Morris et al. (2003)

### *2.5.3 Unit Weight of MSW*

Unit weight of municipal solid waste is another very important parameter related to gas generation. Unit weight of MSW depends on several factors, such as compaction efforts and layer thickness, overburden pressure and moisture content of the MSW (Dixon & Jones, 2005). The unit weight of MSW varies due to the large variation in MSW composition, density of MSW, level of compaction, level of decomposition, types and amount of daily cover soil used in different sites. A layer thickness of 0.5-1.0 m will provide good compaction that leads to high unit weights; however, layer thickness up to 2-3 m can also be found in MSW landfills.

A detailed study by Fassett et al. (1994) reported statistical analyses data on bulk unit weight of MSW collected from different international locations. Differences in unit weights for different condition are shown in Table 2.5.

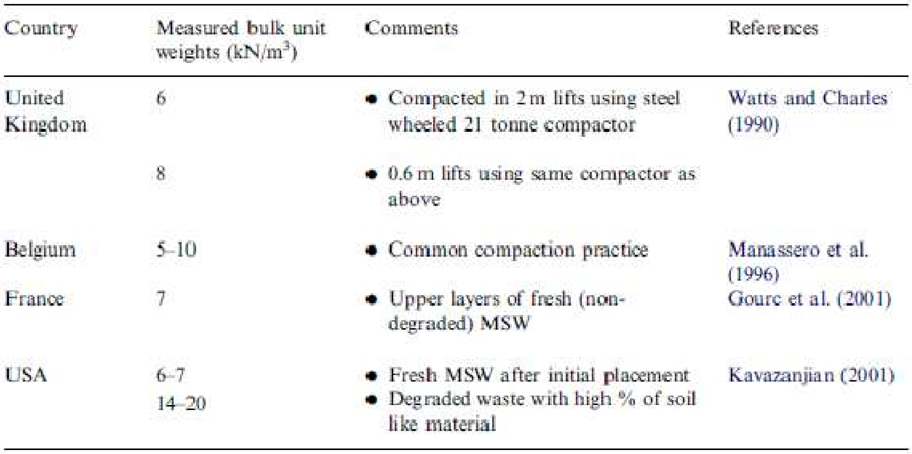
Table 2.5: Statistical summaries of bulk unit weight data for fresh MSW (Fassett et al., 1994)



| | Poor compaction | Moderate compaction | Good compaction |
|---|---|---|---|
| Range (kN/m$^3$) | 3.0–9.0 | 5.0–7.8 | 8.8–10.5 |
| Average (kN/m$^3$) | 5.3 | 7.0 | 9.6 |
| Standard deviation (kN/m$^3$) | 2.5 | 0.5 | 0.8 |
| Coefficient of variation (%) | 48 | 8 | 8 |

Other studies by Landva and Clark (1990) and Oweis and Khera (1986) also reported similar range for bulk unit weights. The bulk unit weight for fresh MSW has been reported from different countries as presented in Table 2.6.

Table 2.6: Bulk unit weights from international literature (Dixon and Jones, 2005)



| Country | Measured bulk unit weights (kN/m$^3$) | Comments | References |
|---|---|---|---|
| United Kingdom | 6 | • Compacted in 2 m lifts using steel wheeled 21 tonne compactor | Watts and Charles (1990) |
| | 8 | • 0.6 m lifts using same compactor as above | |
| Belgium | 5–10 | • Common compaction practice | Manassero et al. (1996) |
| France | 7 | • Upper layers of fresh (non-degraded) MSW | Gourc et al. (2001) |
| USA | 6–7<br>14–20 | • Fresh MSW after initial placement<br>• Degraded waste with high % of soil like material | Kavazanjian (2001) |

If the waste is very highly compacted during placement, it will have higher unit weight and subsequently the permeability becomes lower. With time progression of time, the particles will be break down into finer particles. It will take even longer time percolate moisture after recirculation. Similarly, the gas movement will also be affected if the compaction level is is very high.

### *2.5.4 Particle Size of the Waste*

The smaller the size of disposed waste units or particles, the larger its specific surface area. A particle of waste with a larger specific surface area will decompose faster than a particle with a smaller one because, more surface area is available for microbes to access. For example, a disposed tree stump will decompose more quickly if it is ground into wood chips, than if disposed whole. Therefore, a landfill that accepts shredded waste will have a faster overall decomposition rate (i.e., faster gas generation rate) than a landfill that accepts only non-shredded waste.

### *2.5.5 Age of the Waste*

Landfill gas (methane) generation has two primary time-dependent variables: lag time and conversion time. Lag time is the period from waste placement to the start of methane generation (see Figure 2.3, start of Phase III). The conversion time is the period from waste placement to the end of methane generation (Figure 2.3, end of Phase V). For example, yard waste has very short lag and conversion times, while leather and plastic have very long lag and conversion times.

### *2.5.6 pH*

The optimum pH range for most anaerobic bacteria is 6.7 to 7.5,or close to neutral pH of 7.0 (Mcbean et al., 1995). Within the optimum pH range, methanogens grow at a high rate so that methane production is maximized. Outside the optimum range pH<6.0 or pH>8.0 methane production is severely limited. This effect has been presented in a research by Morris et al. (2003) as shown in Figure 2.9. The onsite methanogenic condition can be represented by increasing pH value and decreasing leachate BOD concentration (Figures 2.9 and 2.10). It is significant to note that this occurred while the landfill was still operational. The beginning of the final maturation phase of waste degradation generally seems to occur between years 10 and 13, very soon after closure, as illustrated by stable neutral pH, very low BOD concentration (generally between 20 and 100 mg/l) and a BOD/COD ratio below 0.1. For comparison, the average monthly and maximum daily values for BOD permitted under the USEPA’s point-source effluent limitations for discharges from MSW landfills (USEPA, 2000) are 37 and 140 mg/l, respectively.

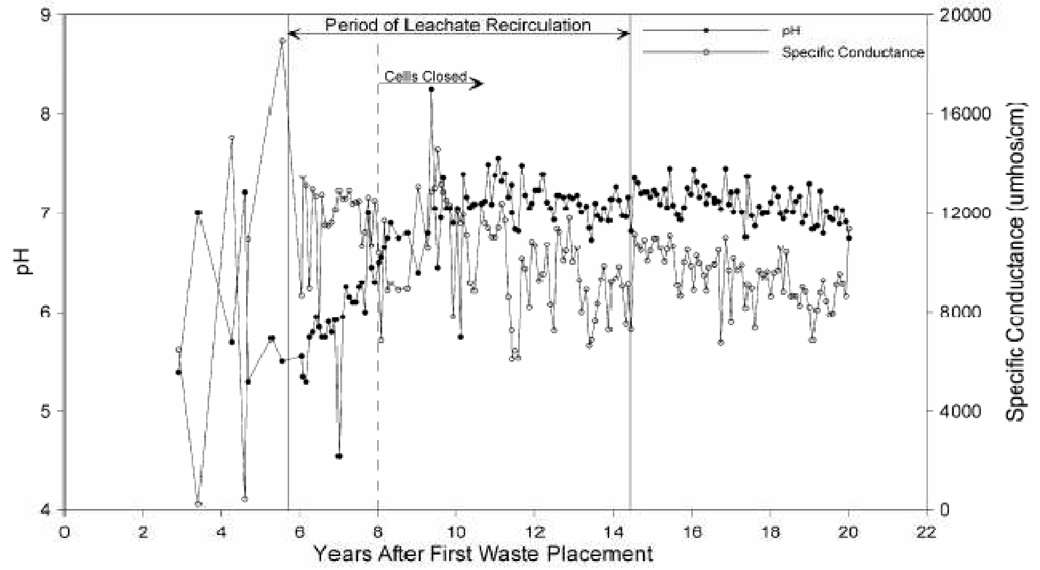


Figure 2.9: pH and conductivity at landfill (Delaware) by Morris et al. (2003)

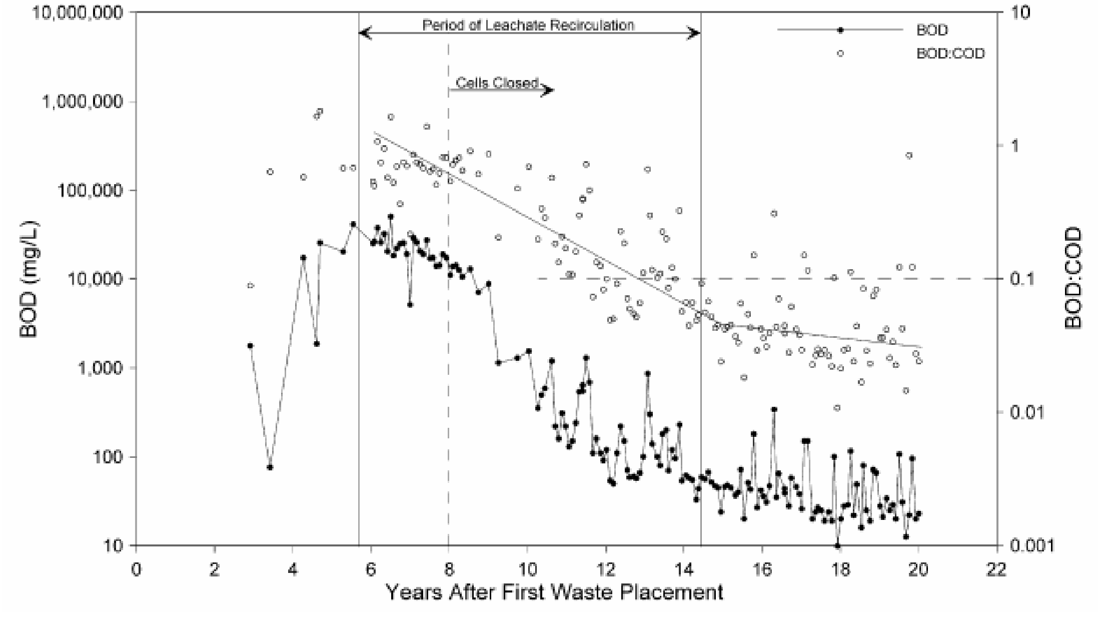


Figure 2.10: BOD concentration and BOD/COD at landfill (Delaware) by Morris et al. (2003)

### *2.5.7 Temperature*

Temperature conditions within a landfill influence the type of bacteria that are predominant and the level of gas production. The optimum temperature range for mesophilic bacteria is 30 to 35°C (86 to 95°F), whereas the optimum for thermophilic bacteria is 45 to 65°C (113 to 149°F). Thermophiles generally produce higher gas generation rates; however, most landfills exist in the mesophilic range. Landfill temperatures often reach a maximum within 45 days after placement of wastes as a result of the aerobic microbial activity. Landfill temperature then decreases once anaerobic conditions develop. Greater temperature fluctuations are typical in the upper zones of a landfill as a result of changing ambient air temperature. Landfill waste at a depth of 15 m (50 ft) or more is relatively unaffected by ambient air temperatures. Temperatures as high as 70°C (158°F) have been observed (McBean et al., 1995). Elevated gas temperatures within a landfill are a result of biological activity. Landfill gas temperatures typically are reported to be in the range from 30 to 60°C (86 to 140°F) (EMCON, 1980 and 1981). Optimum temperature ranges from 30 to 40°C (86 to 104°F); whereas temperatures below 15°C (59°F) severely limit methanogenic activity in the landfill (McBean et al., 1995).

## 2.6 Leachate Recirculation to Accelerate Biodegradation

Leachate recirculation is an option for inexpensive leachate disposal (Kinman et al., 1987), in reducing the cost of post closure care and long term liability (Diamadopoulous, 1994; Westlake, 1995; Reinhart and Al-Yousif, 1996). It also reduces waste stabilization time. Leachate recirculation is also effective in enhancing gas production and improving leachate quality, especially in terms of leachate COD. Results from Chan et al (2002) indicate that leachate recirculation can maximize the efficiency and waste volume reduction rate of landfill sites. The potential advantages of leachate recirculation include:

a. Improvement in leachate quality;
b. Providing leachate treatment in situ, which will decrease offsite treatment costs;
c. Reduction in volume of leachate to be treated by biochemical methods;
d. Enhancement of gas production;
e. Accelerated subsidence, permitting recovery of valuable landfill air space (Reinhart, 1996; Sulisti et al., 1996, Mostafa et al., 1999, Warith et al., 1999);
f. Promotion of settlement before placement of the final cover, which decreases the risk of damage to the final cover;
g. Acceleration of refuse decomposition, which may shorten the regulated postclosure monitoring period and reduce the overall cost of the landfill (Barlaz et al. 1990; Reinhart and Townsend 1998; Pohland and Kim 1999).

The effect of leachate recirculation has been successfully shown by Morris et al. (2003) in the laboratory scale. The difference of the gas produced in the recirculated cell (1) and the dry cell (2) shows the level of degradation of MSW inside the cells. The particles inside the cell 1 were more degraded and the fine contents were higher compared to the degraded waste at the cell 2. The waste inside cell 1 was less odorous than the waste inside cell 2, according to Figure 2.11.

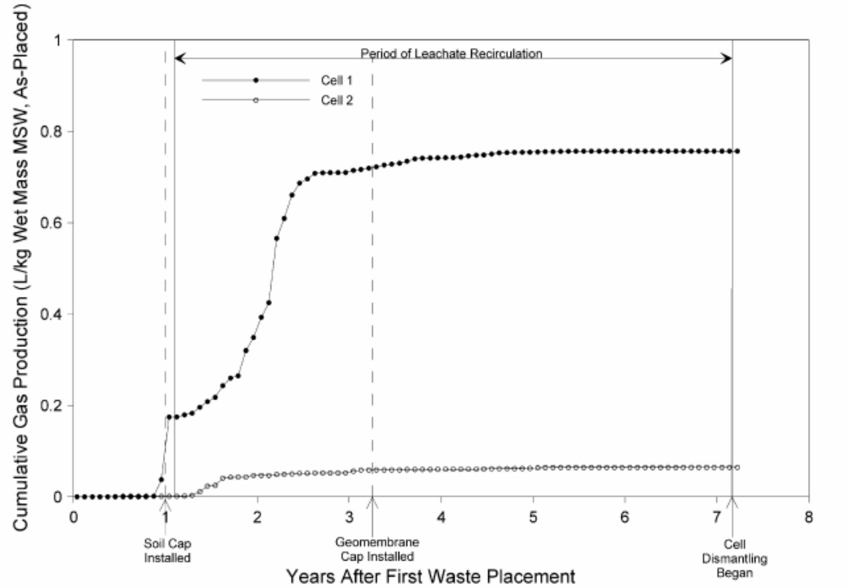


Figure 2.11: Cumulative LFG generation at test cell by Morris et al. (2003)

Leachate recirculation enhances the degradation of MSW, as it provides an aqueous environment that facilitates the provision of nutrients and microbes within landfill cells. It is also an effective way to mobilize nutrients and microorganisms in waste, together with improved mass transfer to prevent the development of stagnant zones in landfill cells (Chugh et al., 1998). The results from Chan et al. (2002) provided evidence that leachate recirculation can shorten the transitional period to active methane production and boost the methanogenesis of a landfill cell containing MSW. In leachate recirculated columns, maximal gas production was observed 9 weeks after the commencement of anaerobic digestion (Figure 2.12).

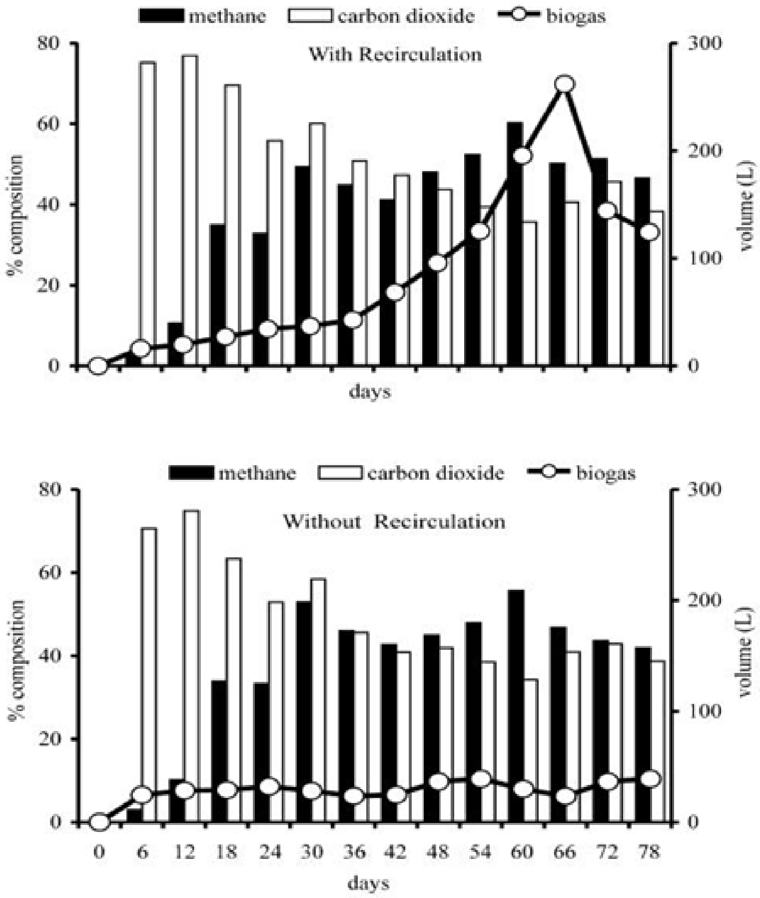


Figure 2.12: Gas production and compositions of methane and carbon dioxide (%) collected from treatment with and without leachate recirculation (Chan et al., 2002)

In columns without leachate recirculation, the gas generation was slow and peak generation rate could not be detected within the 11 week experimental period (Figure 2.12). Other studies by Pohland and Harper (1987) reported that it took a longer time to go through the initial adjustment, transition and acid formation stages before entering the methane production stages if the anaerobic degradation process were not maximized at landfill site. From studies by Kinman et al. (1987), unless better degradation conditions were provided, it took a long period of over a year to achieve maximum gas production in experimental cells. The organic content was high (61%) comparing to the studies in Brazil (60%, Kuajara et al., 1997) and in other temperate cities, such as UK (30%; Westlake, 1995). In order to maximize the anaerobic degradation process, the pH of waste must be neutral or slightly acidic; otherwise the gas production will cease if pH drops below 5.5 (Ruskin, 1982). In this study as the individual pH of the three kinds of waste was slightly alkaline (pH = 8.3-8.9), the mixture of them was highly susceptible to biodegradation. Leachate recirculation had further enhanced the degradation process as indicated by the improved rates of gas production and nutrient removal from the test column.

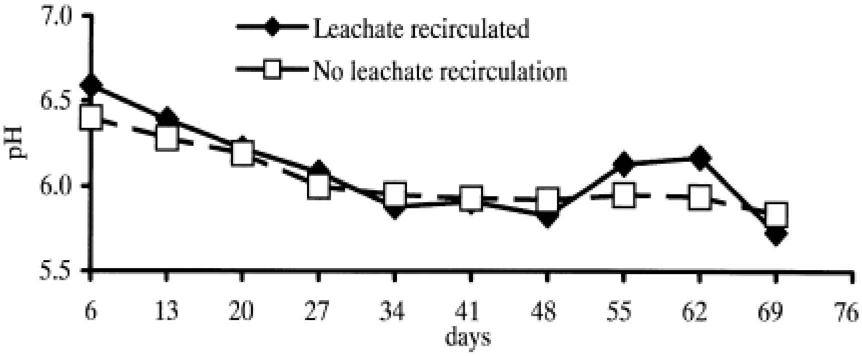
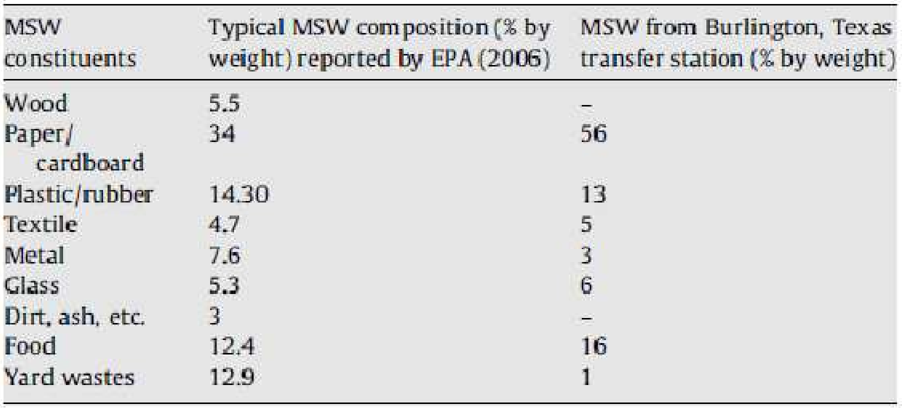


Figure 2.13: Change in pH of leachate with respect to time (Chan et al., 2002)

Research by Hossain and Haque (2009) successfully reported refuse decomposition in laboratory scale. Paper constituted the major portion of MSW in all of the collected solid waste samples. Paper constituted about 56% and food waste was about 13% by weight of the total MSW. The average value of each of the constituents present in MSW is presented in Table 2.7. These values mostly compared well with the physical composition of residential MSW reported by the US EPA (2005).

Table 2.7: Comparison between typical and observed physical composition of MSW (Hossain & Haque, 2009)



| MSW constituents | Typical MSW composition (% by weight) reported by EPA (2006) | MSW from Burlington, Texas transfer station (% by weight) |
|---|---|---|
| Wood | 5.5 | – |
| Paper/ cardboard | 34 | 56 |
| Plastic/rubber | 14.30 | 13 |
| Textile | 4.7 | 5 |
| Metal | 7.6 | 3 |
| Glass | 5.3 | 6 |
| Dirt, ash, etc. | 3 | – |
| Food | 12.4 | 16 |
| Yard wastes | 12.9 | 1 |

Two sets of bioreactors were simulated with four 16l reactors to represent samples at different stages of decomposition. The reactors were sampled destructively to obtain refuse at different stages of degradation based on the generated methane rate. The stages of decomposition were also shown by the pH and volatile solids content. Results were obtained as shown in Figures 2.14 and 2.15.

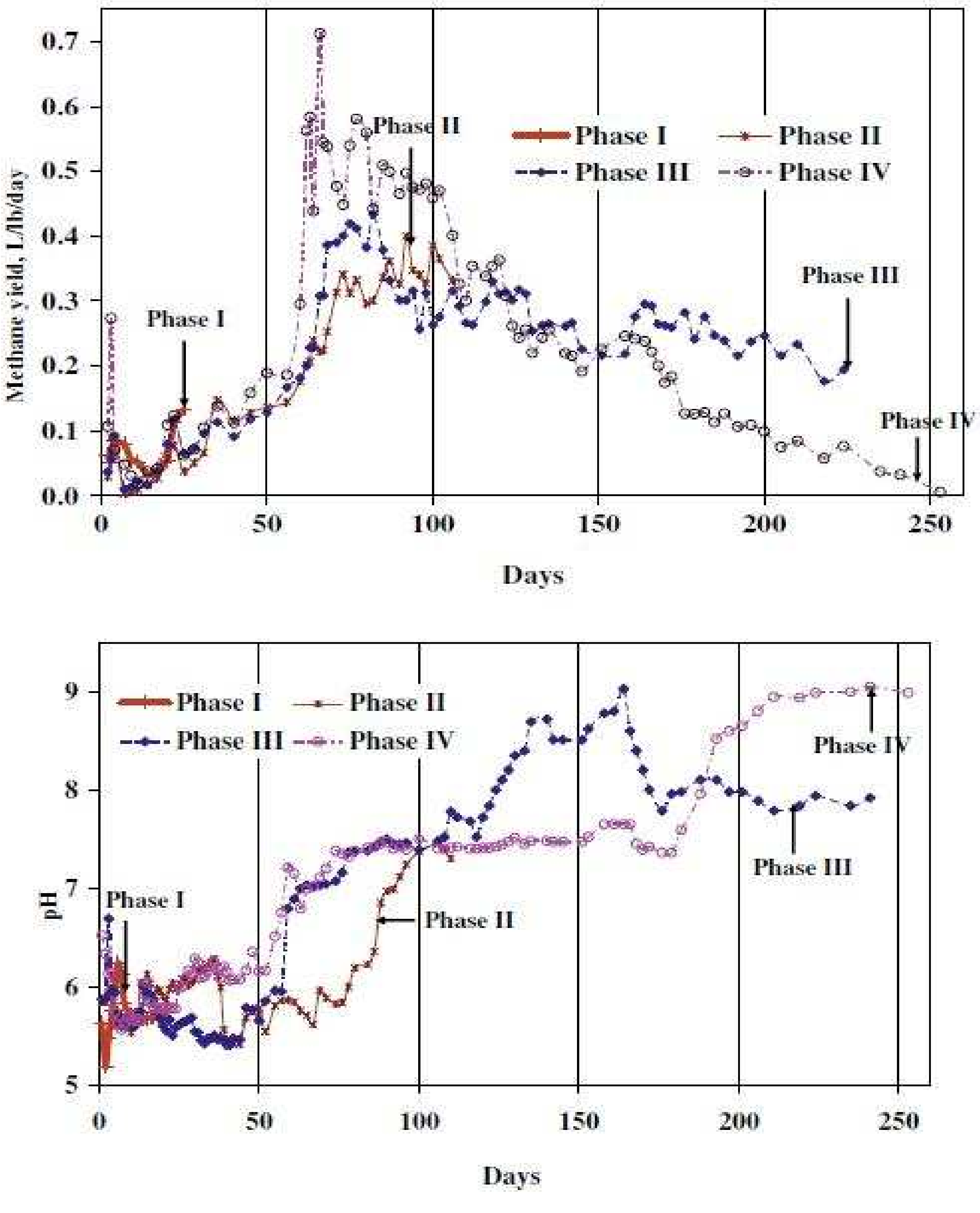


Figure 2.14: Rate of gas production and pH data at each (Hossain and Haque, 2009)

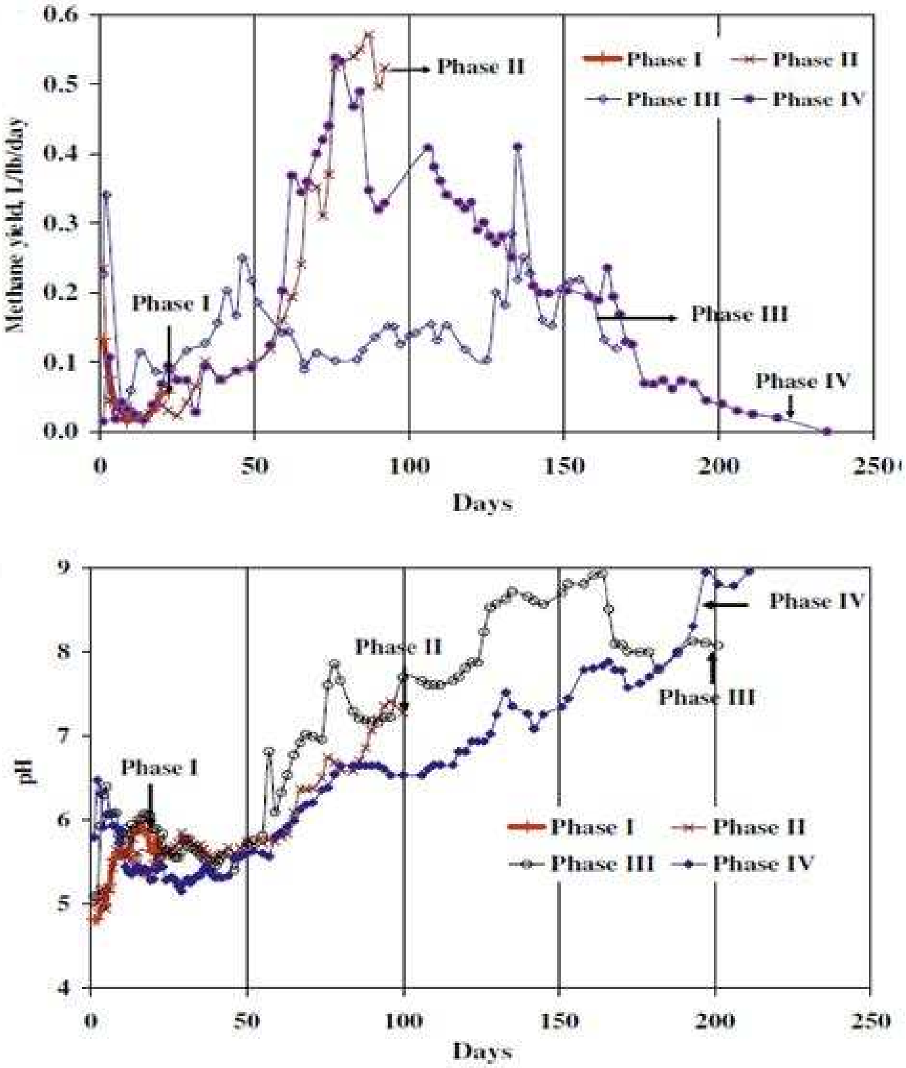
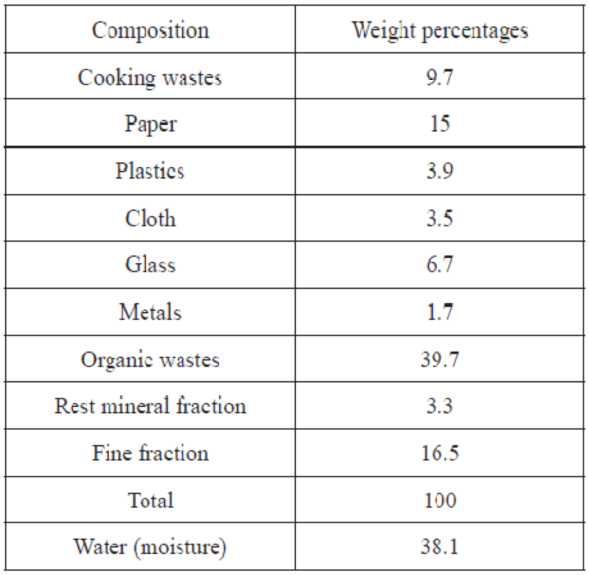


Figure 2.15: Rate of gas production and pH data at each phase
(Hossain and Haque, 2009)

The anaerobic digester sludge and leachate neutralization along with leachate recirculation enhanced the refuse decomposition. The reactors were destructively sampled at days 25, 106, 225, and 253. Based on the methane and pH data in Figure 2.14, at day 25 the sample was in the anaerobic acid phase (Phase I). At day 106, when the rate of methane production was at its peak and pH was about neutral, the sample was in accelerated methane production phase (Phase II). Finally, at days 225 and 253, the samples were in decelerated methane production (Phase III) and complete stabilization phases (Phase IV), respectively. Similarly, for the second set (Setup 2) of reactors at 22, 92, 167, and 235 days, the samples were at Phases I–IV of decomposition, respectively; the results are presented in Figure 2.15.

Research by Filipkowska and Agopsowicz (2004) described the effect of the presence of moisture on decomposition of MSW. Gas production (total gas volume, production rates and methane concentration) was monitored for 311 days. The quality and quantity of biogas were determined as for waste deposition without irrigation and with irrigation with the addition of water and leachate. The lowest biogas production was observed for waste deposition without water and leachate irrigation (dry wastes) and for totally flooded wastes.

Table 2.8: Average refuse composition used in lysimeter by
Filipkowska and Agopsowicz (2004)



| Composition | Weight percentages |
|---|---|
| Cooking wastes | 9.7 |
| Paper | 15 |
| Plastics | 3.9 |
| Cloth | 3.5 |
| Glass | 6.7 |
| Metals | 1.7 |
| Organic wastes | 39.7 |
| Rest mineral fraction | 3.3 |
| Fine fraction | 16.5 |
| Total | 100 |
| Water (moisture) | 38.1 |

The highest amount of biogas production per gm dry wasre and highest methane concentration were achieved for wastes irrigated by leachate in the amount corresponding to atmospheric precipitation. There were 6 lysimeters used with different moisture to determine the quantity of methane present in the generated gas. The composition used in this research was as shown in Table 2.8.

The duration of this research was 311 days. During the experimental period the wastes in lysimeters were supplied with water or leachate as:

Lysimeter 1 – Without Water or leachate (control)
Lysimeter 2 – Water 2.15 mm/day
Lysimeter 3 – Water 4.30 mm/day
Lysimeter 4 – Flooded with water
Lysimeter 5 – Leahcate 2.15 mm/day
Lysimeter 6 – Leachate 4.30 mm/day

In control lysimeter (lysimeter 1) from the beginning of the experiment biogas production increased systematically Fig 2.16. The highest effectiveness of biogas production in this lysimeter (0.01 $cm^3/g$ d.m. of organic fraction per day) was observed between 100 and 180 days of the experimental period. Using water in lysimeters 2 and 3 inhibited biochemical changes and biogas production during 40-60 days of the experiment. After this time, biogas production increased to 0.016-0.024 $cm^3/g$ dry mass of organic fraction per day.

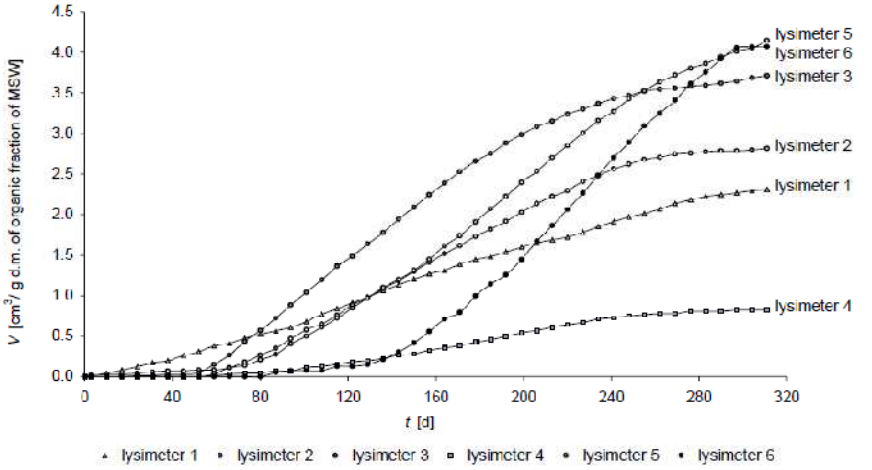


Figure 2.16: Cumulative gas production during observation period (Filipkowska and Agopsowicz, 2004)

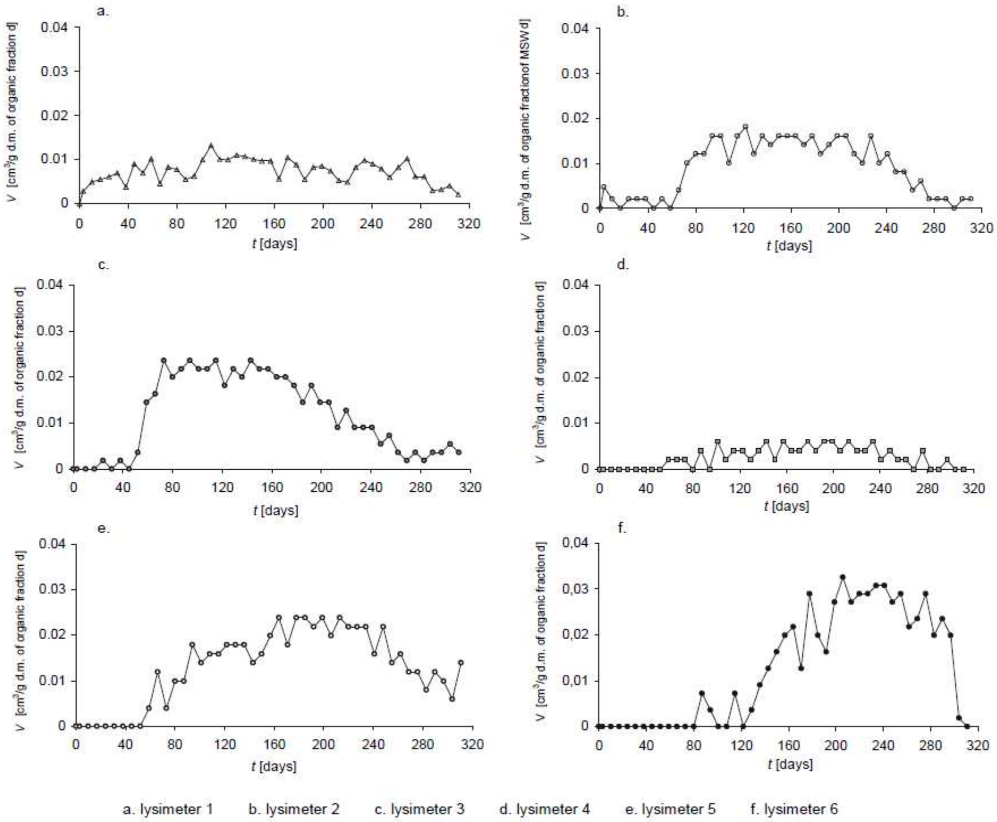


Figure 2.17: Daily amount of produced biogas during experiment period (Filipkowska and Agopsowicz, 2004)

Using landfill leachate (in lysimeter 5 and 6) initiated biochemical changes during the initial 60-80 days of the experiment. The highest effectiveness of biogas production in these lysimeters was obtained between days 180 and 280 of the experiment, about 80-100 days later than in the control lysimeter. After this period biogas production increased to the amount of 0.024-0.031 $cm^3$/g d.m. of organic fraction per day, a 3-fold higher production compared with control lysimeter.

### *2.6.1 Leachate Recirculation Methods*

Leachate recirculation can be conducted at different stages of landfilling depending upon the site specific requirements. For the warm and drier temperatures, leachate can be added during the active landfilling stage, whereas for the other areas, leachate can be injected whenever required through the previously installed recirculation systems. Leachate recirculation can be conducted by two categories as described by Qian, Koerner & Gray (2002) and Townsend, Kumar & Ho (2008),

a. Surface systems
   - Spray irrigation
   - Drip irrigation
   - Tanker truck application
   - Infiltration ponds
   - Leach field
   - Surface trench

b. Subsurface systems
   - Vertical injection wells
   - Horizontal trenches
   - Buried infiltration galleries
   - Combination of horizontal lines and vertical wells

The method suitable for any specific site depends on several factors such as:

- Current condition of landfill (a new one or a completed one)

- Sources of liquids
- Goals of the owner/operator
- Available equipment
- Cost
- Interference with landfill operations
- Regulatory concerns

- Surface Spraying (Spray Irrigation, Drip Irrigation and Tanker Truck Application): Generally, these methods are adopted during pre-cap stages as shown in Figure 2.18. Surface spraying utilizes tank trucks with an attached spray bar applying leachate to the surface of the wet mass. Leachate can be applied to each individual lift as required at the working face. Although this method is very economical and convenient from both operational and delivery perspectives, odors, vectors and litter are the concerns related to this method.

Figure 2.18: Surface irrigation methods using tanker truck, Townsend et al., (2008)

- Surface Ponding: A temporary pond may be created using waste berms with the aid of a geomembrane as presented in Figure 2.19. This method is well adapted to delivering large quantities of leachate with excellent coverage at the pre-cap stages. Once the ponding is undertaken after full height has been reached, this method becomes most effective. Depending on site specific considerations, odors, vectors and litter may pose a limited concern.

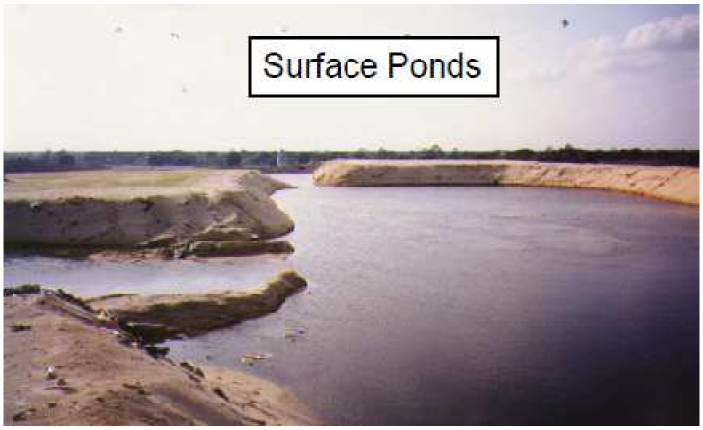


Figure 2.19: Surface ponding (Infiltration ponds) method, Townsend (2008)

- Leach Fields and Trenches: Leach fields are a variation of surface ponding where leachate is delivered through well defined drainage paths (Figure 2.20). This method is adopted during the post-cap period. Generally, rectangular or square patterned leach fields are placed beneath temporary or final cover systems. Although problems with

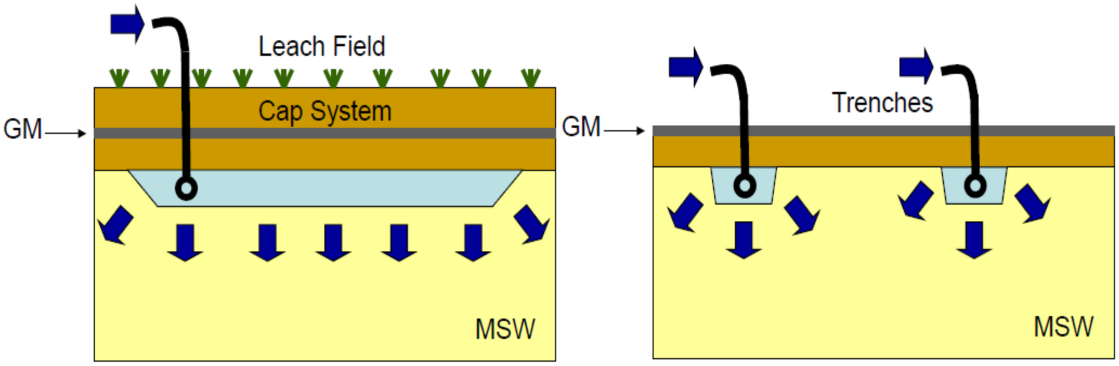


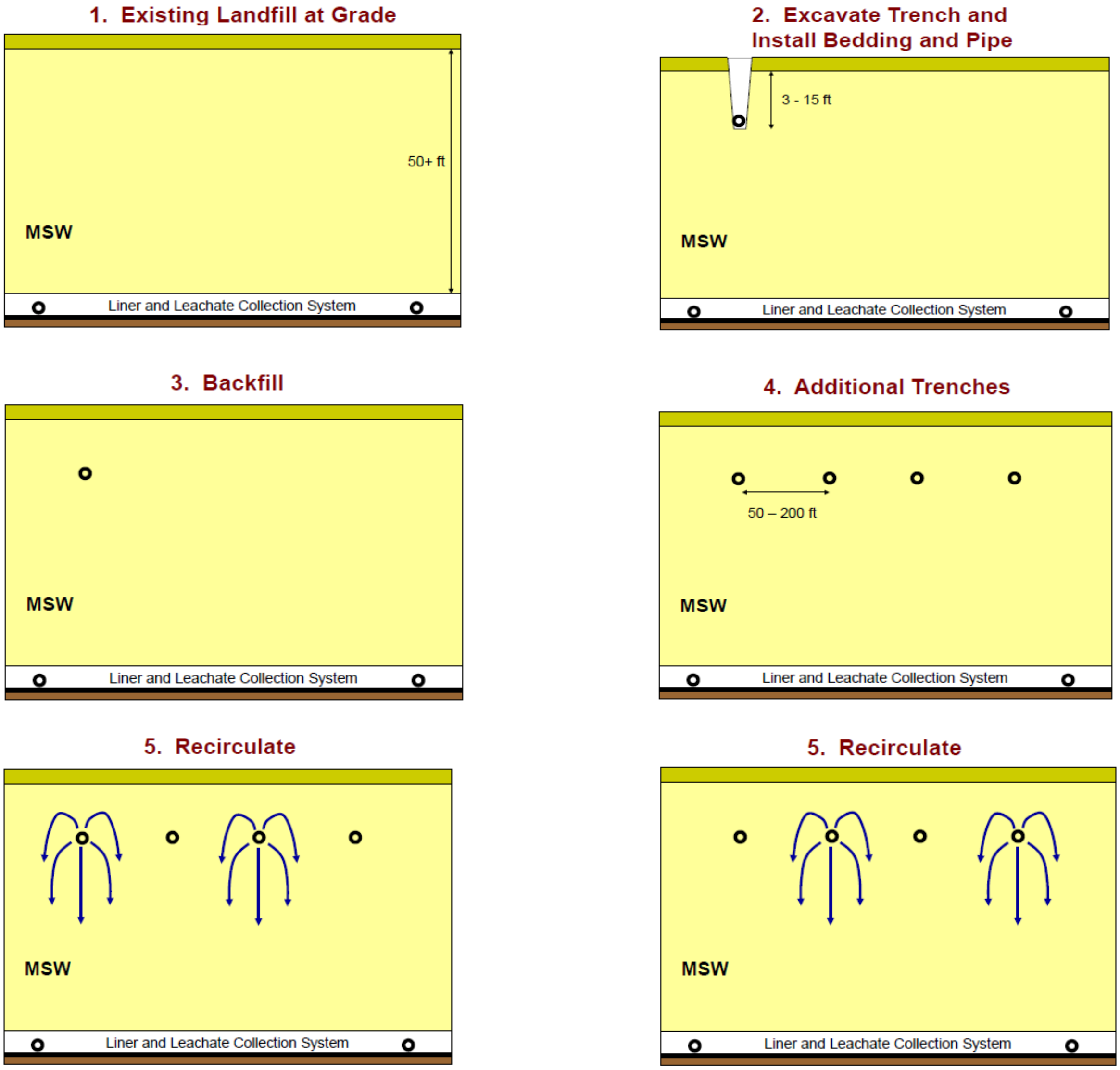
Figure 2.20: Leach Fields and Trenches for leachate recirculation, Townsend (2008)

odors, vectors and litter may be controlled by this process, the injection rate is limited and the implementation cost is normally high for these systems.

- Shallow Trenches and Wells: Shallow wells penetrate waste mass beneath temporary or final covers as shown in Figure 2.21. These wells are perforated and placed at a spacing of 10-30 meters. The injection rate is limited but the injection cost is fairly high. If gas removal is practiced, short circuiting via leachate in gas wells can be easily occurred. Careful planning and experienced hands are needed to facilitate with this process. Odors, vectors and litters are completely controlled by this method.

Figure 2.21: Shallow Trenches and wells, Townsend (2008)

The step-by-step installation procedure of the shallow horizontal trenches has been discussed in a detailed study by Townsend (2008). The entire procedure can be illustrated as in Figure 2.22.



1. Existing Landfill at Grade

2. Excavate Trench and Install Bedding and Pipe

3. Backfill

4. Additional Trenches

5. Recirculate

5. Recirculate

Figure 2.22: Installation and application of leachate using Shallow Horizontal Trenches (Townsend, 2008)

- Deep Wells: Deep wells are installed throughout the waste mass. These wells are perforated along the length of the pipe to facilitate leachate injection. Coverage depends upon well spacing that generally ranges from 20-50 m. Care must be exercised to avoid penetration of the bottom liner system to prevent leachate from going outside to the natural stream. Normally, the elevations of the deep wells are near the bottom of the landfill cell what cover less amount of waste inside the landfill. For gas collection purpose, shallow wells are the most preferable ones. For the City of Denton MSW landfills, the leachate recirculation system is comprised of a combination of deep wells and shallow wells as shown in Figure 2.23.

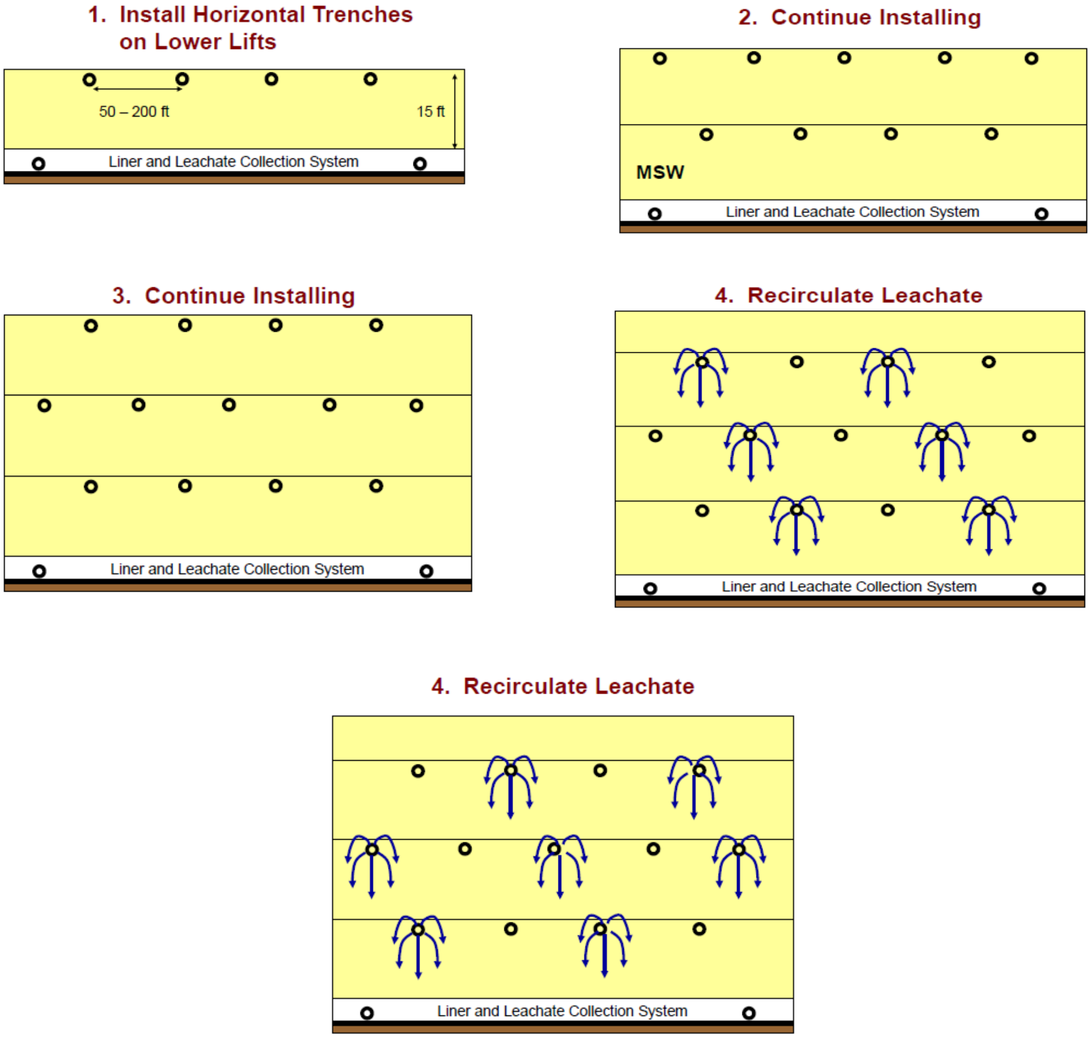


Figure 2.23: Installation and application of leachate using Deep Horizontal Trenches (Townsend, 2008)

- Permeable Blanket: This is another recently developed technology to facilitate leachate injection inside the solid mass. From the detailed study by Haydar & Khire

(2006), permeable blankets as shown in Figure 2.24 are constructed by laying a relatively thin layer of permeable material having relatively high hydraulic conductivity on a horizontal or inclined waste surface in a landfill. Geotextiles placed directly above and below the blanket separate the permeable material from the surrounding porous materials e.g., soil, waste to prevent clogging of the blanket. The thickness of such blankets can vary depending upon the material used like shredded tires, pea gravel, crushed glass, geocomposite, drainage layer, etc._ and site-specific design and operational variables. A perforated pipe is embedded in the blanket in the transverse or longitudinal direction parallel to the shorter or longer plan view dimension of the blanket where leachate is injected under a positive pressure. The relatively high hydraulic conductivity of the blanket allows preferential travel of injected leachate or liquids within the blanket and wetting of the underlying waste as the injected leachate infiltrates. The aerial dimensions and the shape of the permeable blanket can vary depending upon the leachate recirculation needs, shape of the landfill cell, relative contrast in the hydraulic

Figure 2.24: Permeable bed consists of shredded tire and crushed glass in Polk County Bioreactor Landfill (Townsend et al., 2008)

conductivities of the blanket and underlying waste, and leachate injection pressure or leachate injection rates. Several key advantages of permeable blankets over conventional leachate recirculation methods are: excavation of waste is not needed during the construction of blanket, resulting in no odors; a permeable blanket can substitute for multiple horizontal trenches or vertical wells, resulting in lower installation cost for an equivalent design performance; relatively uniform distribution of injected leachate below the permeable blanket, resulting in potential reduction in differential settlement and related post closure maintenance costs; and permeable blankets made up of granular materials like pea gravel, crushed glass, to provide an ideal platform to embed sensors for monitoring the pressure, temperature, and other physical, chemical, or biological parameters associated with the migration of injected liquids.

## 2.7 Landfill Gas Generation Models

There are two life stages in a landfill, its operating stage, where municipal solid waste (MSW) is being disposed of, and its closed stage, where storage capacity is reached. Operating landfills emit more $CH_4$ than closed landfills due to the majority of degradation occurring in the first few years following disposal, with decreasing emission rates with time after closure (Fourie and Morris, 2004; Humer and Lechner, 1999a). Following closure, a landfill continues to emit GHG, possibly for several hundreds of years (Borjesson et al., 2004). The general trend of GHG emissions from landfills can be seen in Figure 2.25. Various independent theoretical and experimental studies suggest a large variation of GHG generation from 1 ton of waste, ranging from 40 $m^3$ to 250 $m^3$ (Humer and Lechner, 1999a; Ayalon et al., 2000; Bogner et al., 1997; Themelis and

Ulloa, 2006). This is understandable as LFG generation is highly dependent on a variety of factors, which are reported by Komilis et al. (1999a) and described in section 2.5.

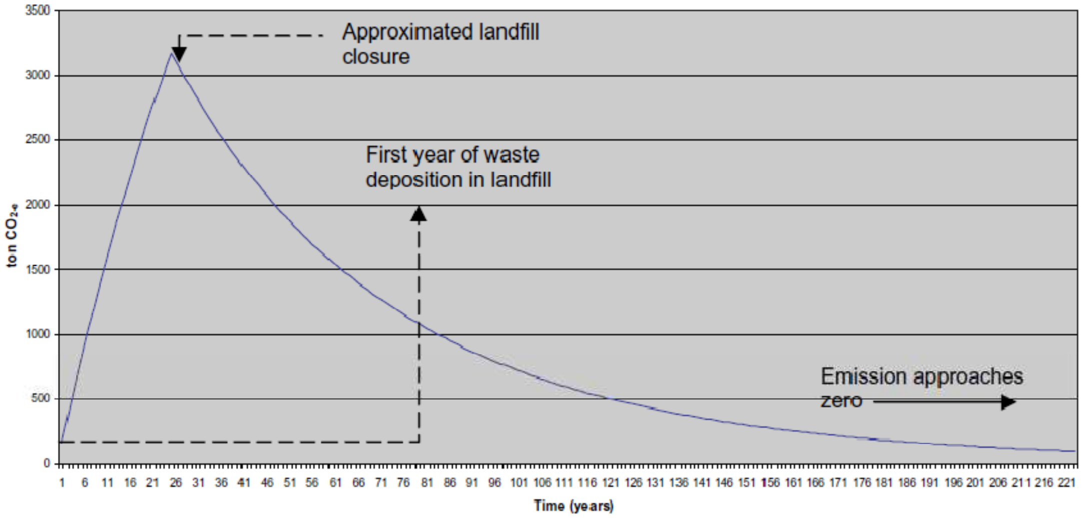


Figure 2.25: General trend of $CH_4$ emission from landfills in their operating post closure years using IPCC 1st order decay model (Lou & Nair 2009)

The landfill gas can be estimated by using first order decay (FOD) in two phases. In the first phase, the rate of generation keeps on increasing till the peak is reached; later on it keeps declining till the material is stabilized. From the guidelines adopted by IPCC (1996), the National GHG Inventories Default method and FOD methods are used to estimate methane emission from MSW disposal sites.

### *2.7.1 Default Method*

The default method was developed by Bingemer and Crutzen (1987) and it is still being used in the revised IPCC (1996) guidelines as the default methodology for estimating methane emissions from solid waste disposal sites. It is based upon the mass balance approach. The equation used in this method can be shown as:

Methane Generation (Gg/yr) = $MSW_T$ * $MSW_F$ *MCF *DOC * $DOC_F$ *F * (16/12 - R) * (1 - OX)

where,

$MSW_T$ = Total MSW generated (Gg/yr)

$MSW_F$= Fraction of MSW disposed of at the disposal sites. The percentage of 70% is based on field investigative studies. The remaining 30% is assumed to be lost due to recycling, waste burning at source as well as at disposal site, waste thrown into the drains and waste not reaching the landfills due to inefficient solid waste management systems.

MCF= Methane correction factor (fraction) that depends upon the method of disposal and depth available at landfills. The IPCC document indicated the value of 0.4 m for open dumps .5 m depth and hence used for computation.

DOC= Degradable organic carbon (fraction). DOC content is essential in computing methane generation. It depends on the composition of waste and varies from city to city. Equation to determine DOC values = 0.4A + 0.17B + 0.15C + 0.3D

where,

A = Paper + rags

B = leaves + hay + straw

C = fruits and vegetables

D = wood

$DOC_F$= Fraction DOC dissimilated. It is a portion of DOC that is converted to LFG. The estimates are based on a theoretical model that varies only with the temperature in the anaerobic zone of a landfill site. The model is described as $0.014T+0.28$, where T=temperature in $^{o}$C (Tabasaran, IPCC document 1996).

F= Fraction of methane in LFG (default is 0.5).

R= Recovered methane (Gg/yr).

OX= Oxidation factor (default is 0). It accounts for the methane that is oxidized in the upper layer of waste mass where oxygen is present. Oxidation may reduce the quantity of methane generated that is ultimately emitted. However, there is no internationally accepted factor and can be assumed as zero.

### *2.7.2 FOD Method*

Kumar et al. described FOD as a time dependent emission profile that reflects the true pattern of the degradation process over time. The FOD method requires data on current, as well as historic waste quantities, composition and disposal practices for several decades. A modified approach is proposed wherein the biogas release is based on FOD in a triangular form as shown in Figure 2.26, where the area of the triangle would be equivalent to the gas released over the period from every tonne of solid waste deposited. In the absence of detailed data, this area (volume of gas) is assumed to be equal to the volume computed using the default methodology. It is also assumed that the degradation takes place in two phases. The first phase starts after 1 year of deposition and the rate increases for 6 years. Thereafter the second phase starts when the gas generation rate decreases and becomes zero after 15 years. Research by Kumar et al. (2004) compared methane emissions from solid waste landfill using these two methodologies.

The values estimated using default methodology were larger compared to the values estimated using the triangular methodology from 1980 to 1999.

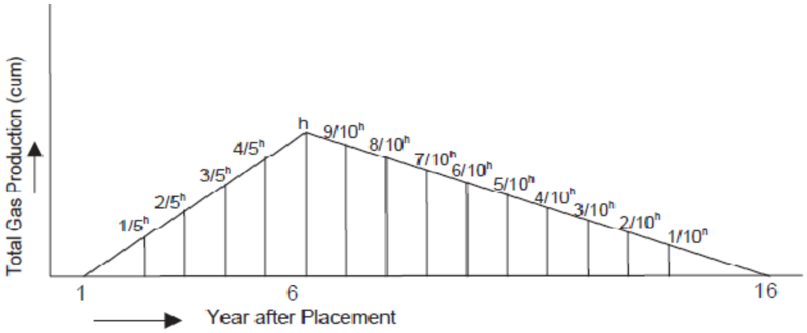


Figure 2.26: Triangular form for gas production

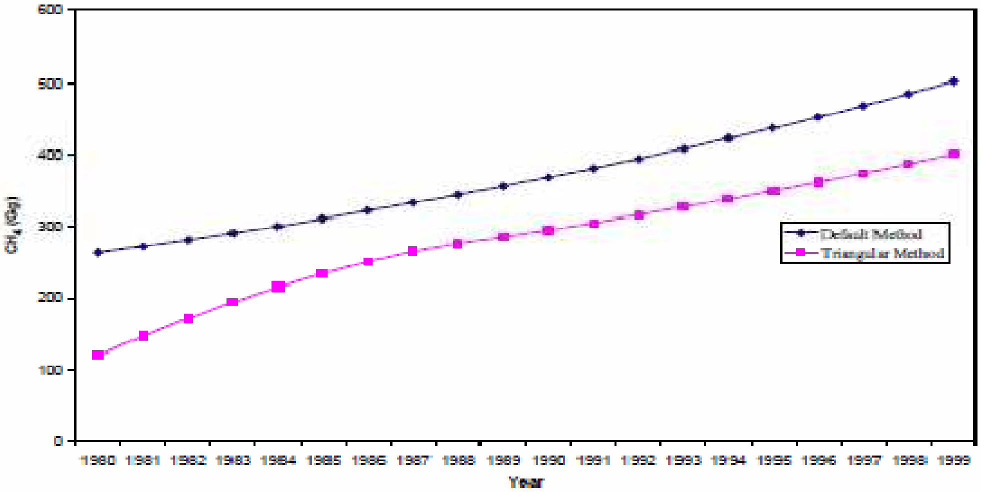


Figure 2.27: Comparison of methane emission vs. year using both the default method and triangular method by Kumar et al. (2004)

The assumption made in the default methodology is that, methane emitted is the same years from 1980 to 1999, which may not be realistic. The values estimated using triangular form gives more realistic value as the form is based on the assumption that the gas generation follows triangular form and the gas keeps on generating the next 15 years. Every year the methane is generated due to the waste disposal in the past 15 years.

# CHAPTER 3

# METHODOLOGY & FIELD STUDIES

## 3.1 Background & Site Description

### *3.1.1 Background*

The city of Denton is the county seat of Denton County, TX in the United States. Geographically, it is situated 40 miles (64 km) south of the Oklahoma-Texas Border and 40 miles (64 km) northwest of Dallas. From 2000 census data, the population for the city of Denton was 80,537 and the total population for the Denton County was 432,976. According to the July 2008 census, current population of Denton is 636554, making it the 207th largest city in the U.S and 23rd largest city in TX. The landfill footprint and the present area of interest were shown in figures 3.1 and 3.2.

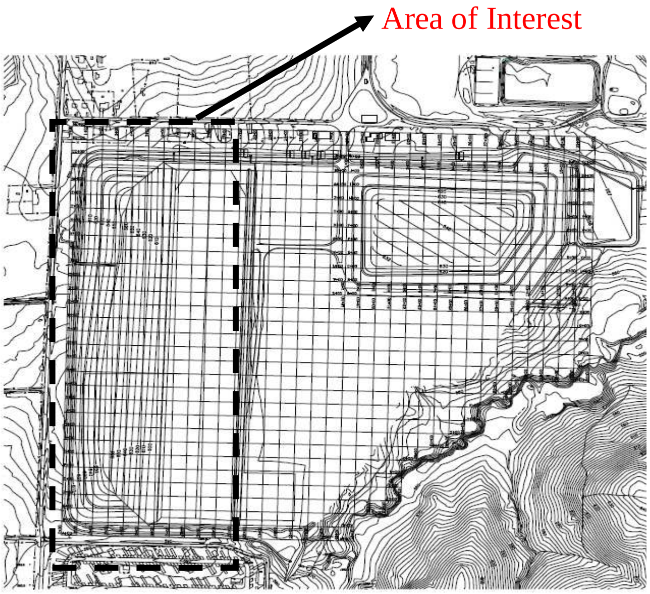


Figure 3.1: Landfill layout and area of interest (City of Denton, MSW Landfill)

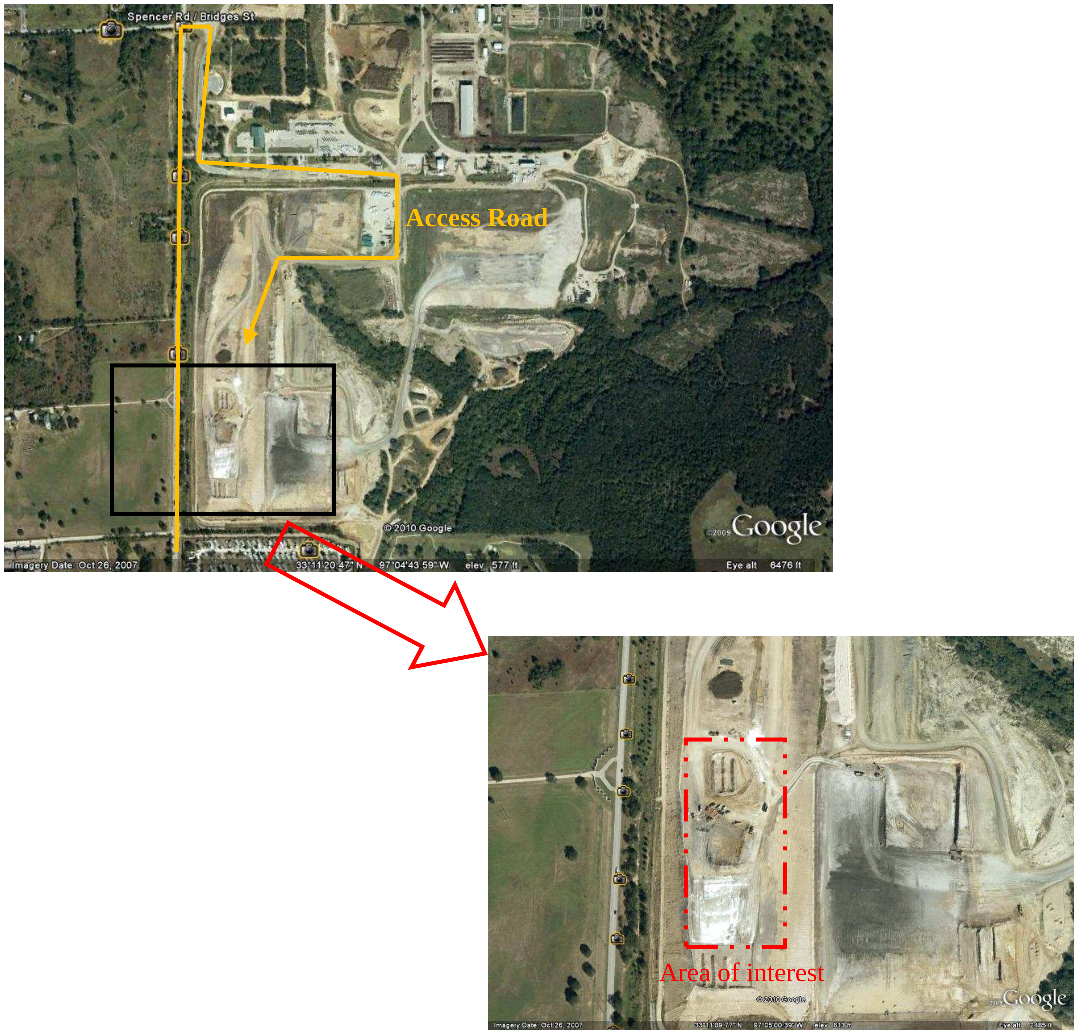


Figure 3.2: Area of interest in MSW landfill, City of Denton, TX (using google earth$^{TM}$)

### *3.1.2 Site Description*

The City of Denton Type I landfill received approximately 300 tons/day of waste in the past. It occupies almost 36.08 acres and was permitted by Texas Department of Health Services in March, 1984. Later, a revised permit area of 239.87 acres with a waste footprint of 152 acres was approved in 1996. The city of Denton MSW Landfill started receiving municipal solid waste in 1984. From the beginning stage, this landfill adopted the conventional landfilling process for MSW. In 2009, this landfill initiated leachate recirculation for the present working cell. The first landfill cell was on the east section of the current working cell and it was closed on 1998. These two cells are completely separate from each other.

## 3.2 Description of Leachate Recirculation System

The study area Cell 2 covered thirty six (36) interconnected horizontal pipes from H1 to H36 at different elevations to collect landfill gas. On top of gas collection, these pipes are extensively used for recirculation. The pipe locations and line elevations are presented in Table 1.

Table 3.1: Lateral pipes at current area of interest

| Pipe | Location | Elev. ft | Pipe | Location | Elev. ft | Pipe | Location | Elev. ft |
|---|---|---|---|---|---|---|---|---|
| H1 | D+00 | 620 | H13 | L+50 | 605 | H25 | Q+00 | 590 |
| H2 | E+00 | 620 | H14 | M+00 | 620 | H26 | Q+50 | 610 |
| H3 | F+00 | 620 | H15 | M+50 | 605 | H27 | R+00 | 590 |
| H4 | F+60 | 605 | H16 | N+00 | 620 | H28 | R+00 | 620 |
| H5 | G+00 | 620 | H17 | N+50 | 605 | H29 | R+50 | 610 |
| H6 | H+50 | 605 | H18 | O+00 | 620 | H30 | S+00 | 590 |
| H7 | H+60 | 605 | H19 | O+00 | 590 | H31 | S+50 | 608 |
| H8 | I+50 | 605 | H20 | O+50 | 605 | H32 | T+50 | 605 |
| H9 | J+20 | 620 | H21 | P+00 | 620 | H33 | U+50V | 605 |
| H10 | J+50 | 605 | H22 | P+00 | 590 | H34 | V+00 | 620 |
| H11 | K+50 | 605 | H23 | P+60 | 605 | H35 | W+00 | 620 |
| H12 | L+00 | 620 | H24 | Q+00 | 620 | H36 | W+50 | 620 |

The interconnected gas collection system and recirculation system are presented in Figure 3.3.

Figure 3.3: Interconnected leachate recirculation and gas collection system

For the City of Denton MSW Landfill, subsurface systems have been adopted to inject leachate inside the landfill. The horizontal gas collection pipes at different locations as presented in Figure 3.4 have been successfully used as leachate recirculation systems. These pipes have been utilized for gas collections as well as leachate recirculation purposes. The injected leachate percolates through these pipes to the bottom of the landfill. Later, the leachate is collected from the leachate sump located on the southern side of the current cell and pumped into the leachate storage tank. Then, leachate is resent back to different locations inside the landfill using different pipes from the leachate storage tank.

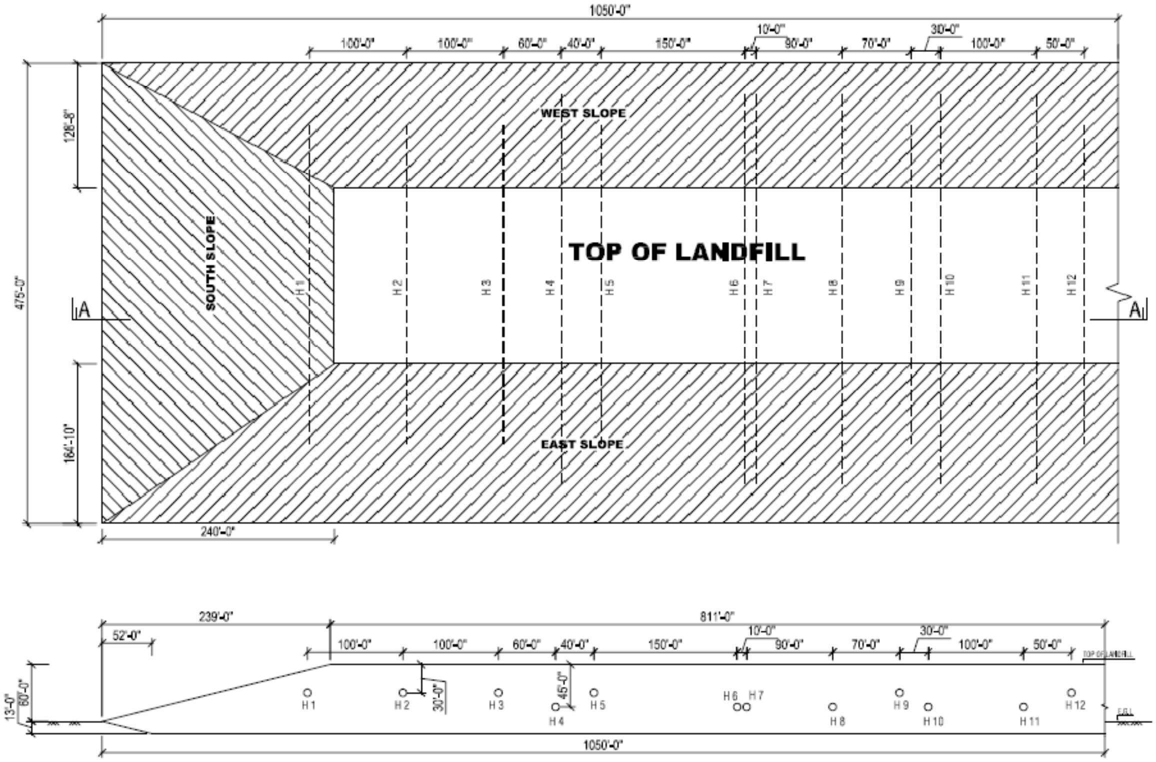


Figure 3.4: Plan and longitudinal section of the landfill cell

Figure 3.5: Leachate storage tank and pumping station (City of Denton, MSW landfill)

## 3.3 Step-by-step approach

The work flow chart for the current study is presented in the Figure 3.6.

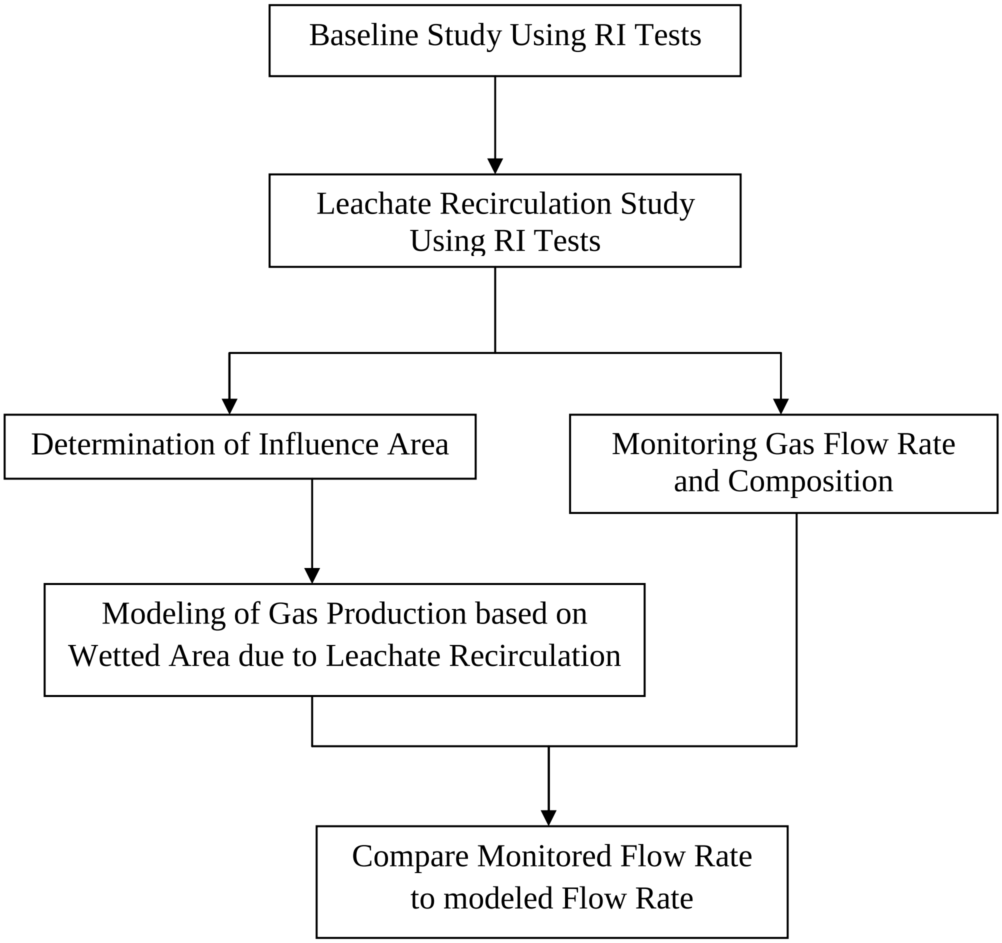


Figure 3.6: Work flow chart for the study.

## 3.4 Area Selected for this Study

The area under Cell 2 was divided into three areas (Area A, Area B & Area C) as shown in Figure 3.7. Due to the ongoing active landfilling process, this study area was confined to the leachate recirculation systems present under Area A. Active landfilling was closed in April 2009 for Area A, September 2009 for Area B and December 2009 for Area C. This study was initiated from the beginning of May 2009 and Area A was readily available for the field studies; but, later on field studies were also conducted at the other areas B and C. However, for this thesis our study was confined into Area A.

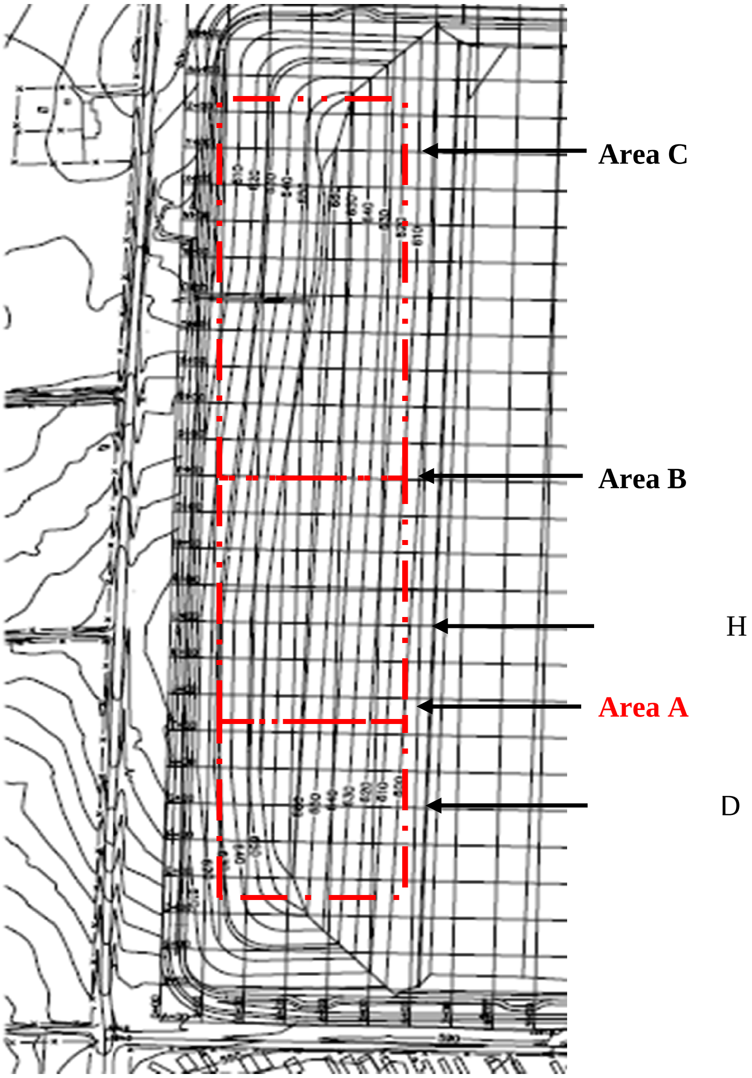


Figure 3.7: Area of interest in Cell 2 (City of Denton, MSW landfill)

The locations of the lateral pipes are shown in Figure 3.8.

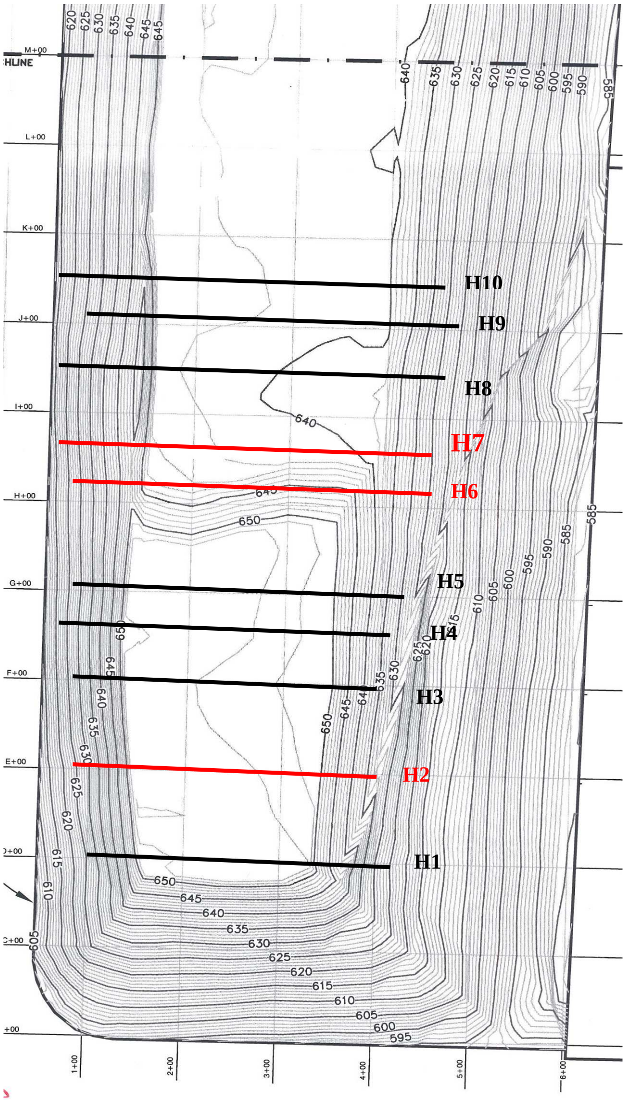


Figure 3.8: Location of the lateral pipes from area of interest

Area A covers a total footprint of 850 x 550 ft$^2$.The height of the waste is 73 ft (from the top to the bottom of the landfill). For the purposes of this study, Pipe H2, H6 and H7 are monitored starting May 2009. The locations and elevations of pipes are presented in Table 3.2.

Table 3.2: Locations of horizontal pipes under Area A

| Pipe | Location | Elevation, ft From bottom | Pipe | Location | Elevation, ft From bottom |
|---|---|---|---|---|---|
| H1 | D+00 | 43 | H6 | H+50 | 28 |
| H2 | E+00 | 43 | H7 | H+60 | 28 |
| H3 | F+00 | 43 | H8 | I+50 | 28 |
| H4 | F+60 | 28 | H9 | J+20 | 43 |
| H5 | G+00 | 43 | H10 | J+50 | 28 |

## 3.5 Determination of Influence Area

Determination of the influence area due to leachate recirculation was the most crucial part of this study. The preliminary assessment or the baseline study of the current moisture distribution in the City of Denton's landfill was conducted by using Resistivity Imaging (RI). The objective of the baseline investigations was to study the current areas of moisture accumulation before leachate recirculation in the landfill.

### 3.5.1 *Test Equipment*

Resistivity Imaging was conducted using the SUPER STING R8 IP meter. There were 56 electrodes spaced at 6 ft intervals for all of the tests. The test sections covered a 2D section of 330 m. The electrodes were connected with the cables and late attached to the eight channel switch box. The switch box was attached to the resistivity meter. A 12V marine battery was used as the power source during the tests. The entire resistivity test procedure and the resistivity equipment used are shown in the Figure 3.9.

Figure 3.9: a. Installation of the electrodes at 6 ft spacing, b. connection of the electrodes with the cable, c. connection of the cables with switch box and the Resistivity meter, d. sample test section, e. Resistivity meter (Super Sting R8 IP meter)

### 3.5.2 *Common Test Methods*

There are several methods which can be adopted for Resistivity Imaging.

- Pole-Pole Method

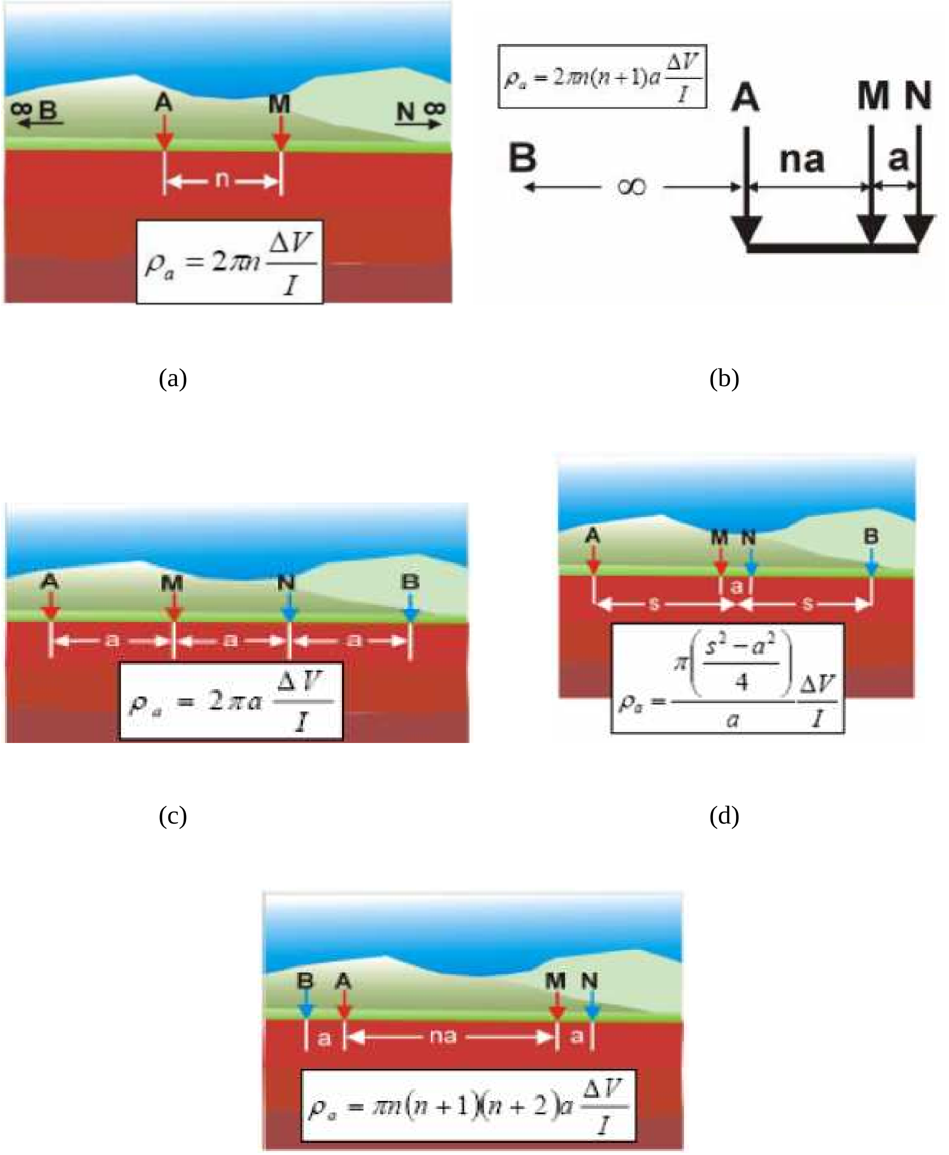
The simplest array is one in which one of the current electrodes and one of the potential electrodes are placed so far away that they can be considered at infinity. This array can actually be achieved for surveys of small overall dimensions when it is possible to put the distant electrodes some practical distance away. For a survey in an area of a few square meters, "infinity" can be on the order of a hundred meters. The error can be less than 5% using this method. This method also has a very strong signal and good resolution; however, handling two electrodes becomes difficult. The array layout is presented in Figure 3.10 a.

- Pole-Dipole Method

This array is used frequently in resistivity surveying and the spacing is usually described, and taken, in integer multiples of the voltage electrode spacing "a" as shown in Figure 3.10 b. The error can be less than 5% using this method. This method also has a very strong signal but has difficulty handling infinity electrodes in the field.

- Wenner Method

The Wenner array is now seen to be a simple variant of the pole-dipole in which the distant pole at infinity is brought in and all the electrodes are given the same spacing, "a", as presented in Figure 3.10 c. This method has highest signal to noise ratio, excellent vertical resolution but poor lateral resolution. The method cannot take advantage of a multi-channel system; only single channel is used during the testing.



(a)

(b)

(c)

(d)

(e)

Figure 3.10: Different Imaging Methods (a) Pole-Pole Method, (b) Pole-Dipole Method, (c) Wenner Method, (d) Schlumberger Method and (e) Dipole-Dipole Method

- Schlumberger Method

One of the first arrays used in the 1920's and still popular today is the Schlumberger array, as shown in Figure 3.10 d. This method is very similar to the Wenner array and cannot take advantage of a multi-channel system, because only single channel is used during the testing. However, inverse Schlumberger may use up to four channels. In a Schlumberger sounding, the voltage electrodes are usually kept small and fixed while only the "s" spacing is changed.

- Dipole-Dipole Method

The dipole-dipole array is logistically the most convenient in the field, especially for large spacings. All the other arrays require significant lengths of wire to connect the power supply and voltmeter to their respective electrodes and these wires must be moved for every change in spacing, as the array is either expanded for a sounding or moved along a line. The convention for the dipole-dipole array is shown in Figure 3.10. The current and voltage spacing are the same, "a", and the spacing between them is an integer multiple of "a". This method has the best resolution but poor signal to noise ratio. This array is excellent for multi-channel equipment.

The Dipole-Dipole (DD) method is best for the multi-channel system and to investigate large areas. Also, DD array can detect both vertical and horizontal structures and gives better resolution compared to other arrays. Therefore, considering its advantages, Dipole-Dipole array was used for the current study.

### 3.5.3 *Baseline Study of PipeS H2, H6 and H7*

The tests to determine the baseline conditions for pipes H2, H6 and H7 were conducted on 05/23/2009 and 05/29/2009. These test sections had 56 electrodes at 6 ft spacing with a total length of 330 ft. The test location has been shown in Figure 3.11.

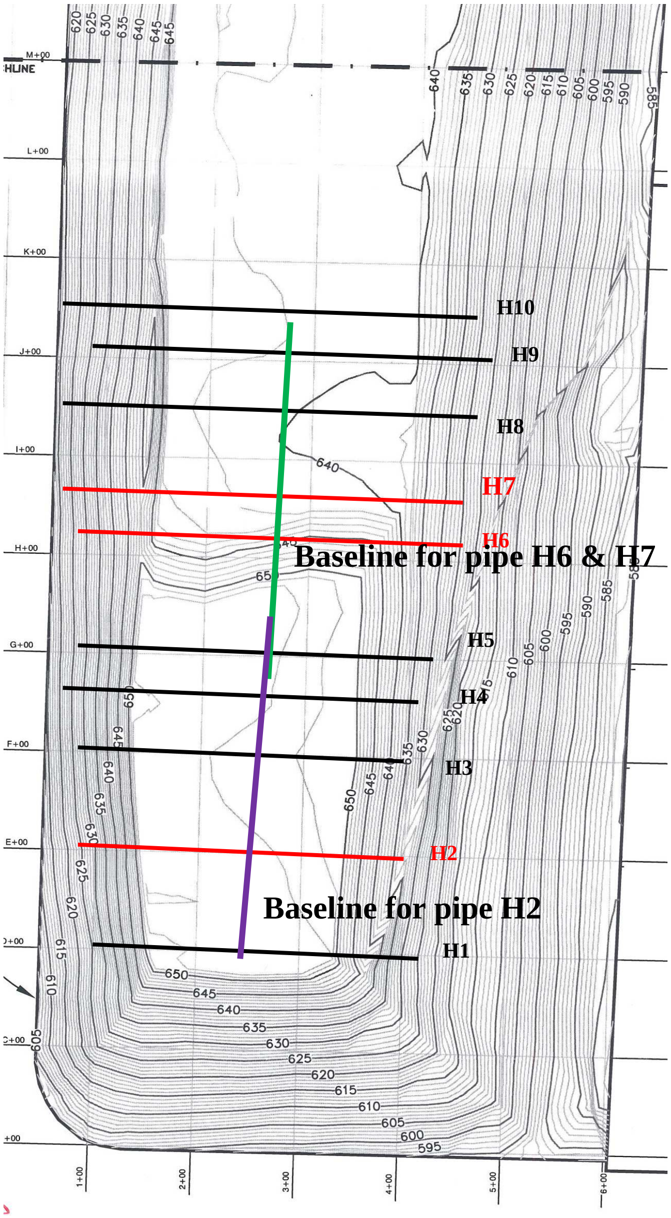


Figure 3.11: Baseline study location for Area A

## 3.6 Leachate Recirculation

To accelerate the decomposition of MSW, leachate recirculation was carried out using the interconnected horizontal pipes as described in Section 3.2. The horizontal pipes are connected together as shown in Figure 3.12 and attached with the leachate storage tank shown in Figure 3.5. The effect of the leachate recirculation was watchfully observed using RI tests at those sections previously studied during the baseline study. The leachate injected through the pipe went inside the landfill and seeped through the solid waste through the perforations. The waste moisture content increased due to the injection of leachate, which presumably resulted higher degradation rates for the MSW.

Figure 3.12: Interconnected leachate recirculation pipes in landfill

Among the pipes on Area A, H2 and H7 have been performing efficiently in leachate injection. Pipe H6 is a representative of the non-recirculating pipes. The total injected leachate volume was recorded by City of Denton, MSW landfill authority and was shared for this research purpose.

*3.6.1 Leachate Recirculation through Pipe H2*

The first day of leachate injection through the pipe H2 was May 8, 2009. Later, 2500 gallons of leachate was injected through the pipe H1 on 05/26/2009. Since the first day of recirculation, this pipe had excellent performance in injecting leachate on a regular basis. The test location for pipe H2 is shown in Figure 3.13.

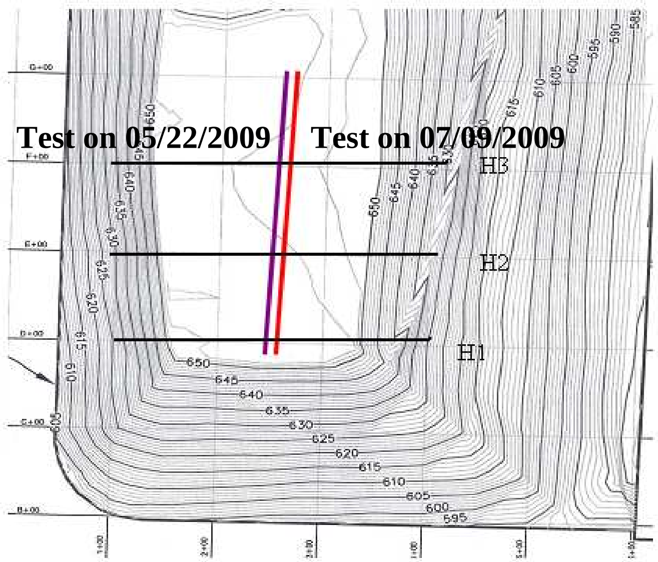


Figure 3.13: Leachate recirculation study location on pipe H2

Later, six vertical wells were placed into the south end of the Area A to collect landfill gas. Leachate recirculation was not facilitated through these wells. Leachate recirculation studies were also conducted through these wells using RI tests. The locations of the vertical are presented in Figure 3.14.

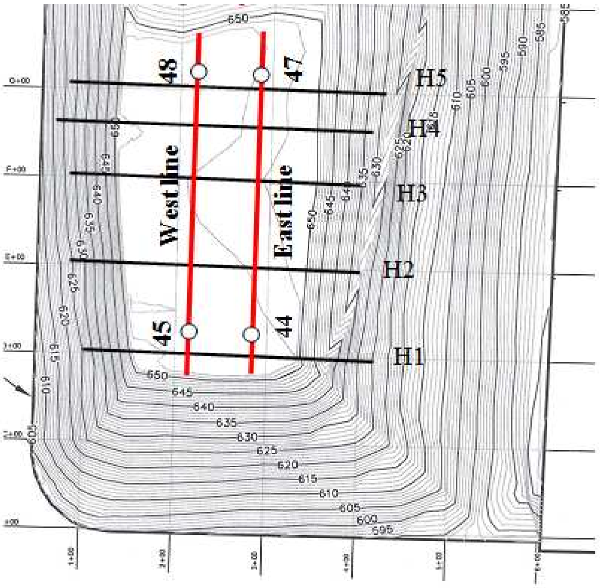


Figure 3.14: Leachate recirculation study location through vertical wells for pipe H2

### *3.6.2 Leachate Recirculation through Pipe H7*

The first day of leachate injection through the pipe H7 was February 5, 2009. Since the first day of recirculation, this pipe was efficient in leachate recirculation. Initially it injected a high amount of leachate but later on, since August 2009, line H7 did not deliver large volume of leachate. In this regard, pipe H7 was kept under rest in October and December, 2009 whereas, in November, 2009 it took an insignificant amount of leachate. The test locations are presented in Figure 3.15.

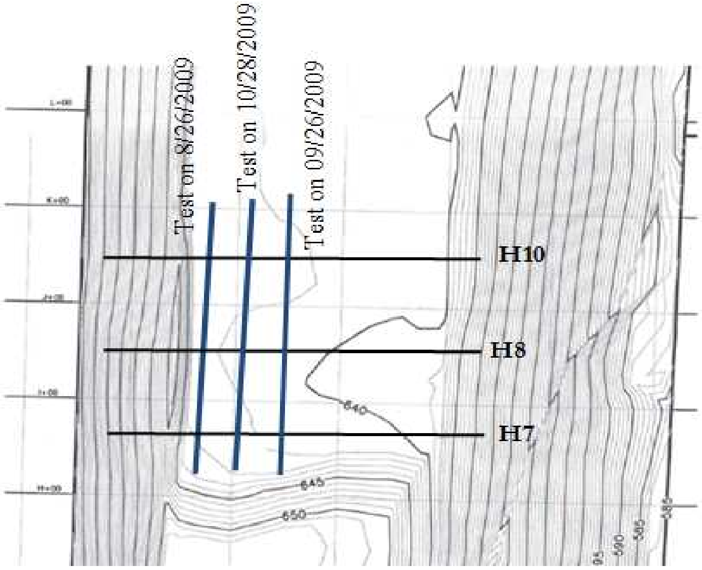


Figure 3.15: Leachate recirculation study location on pipe H7

## 3.7 Landfill Gas

Landfill gas data is comprised of gas composition data and gas flow rate data from the landfill. Several tests were conducted on site to measure the flow rate and the quantity of methane present in the LFG from City of Denton MSW landfill.

### *3.7.1 Landfill Gas Composition*

Gas composition is very significant data for the emitted landfill gas. Generally, it contains the percentage of readily available methane, carbon dioxide, oxygen and other trace gasses. The percentage of methane indicates whether the present gas can be readily useful to generate electricity through the generator. If the percentage of methane is very low, that gas cannot be used for electricity generation, but must rather be burned through the gas flare station, as shown in Figure 3.16.

Figure 3.16: Landfill gas flare station, MSW Landfill, City of Denton

Landfill gas composition data was recorded by DTE Energy starting January 2009, twice in every month. DTE Energy has determined the composition using gas analyzer LANDTEC GEM 2000. In addition to the gas composition data provided by DTE energy, several gas composition tests were conducted on site using gas analyzer LANDTEC GEM 2000 present in Geo-environmental Laboratory at UTA.

### *3.7.2 Landfill Gas Volume*

Landfill gas volume is also another very important parameter for the current study. The total volume of generated gas was determined from the gas flow rate collected from each individual well head at the landfill. Similar to gas composition data, landfill gas flow rate data were recorded by DTE Energy starting January 2009 for each individual gas well. The gas flow rate was also recorded from the flare station once in every month in order to determine the average total gas flow rate. All the gas pipes are connected together, as shown in Figure 3.20. This connected pipe was attached to the flare station. In addition to the gas flow rate rata provided by DTE Energy, several tests were conducted to measure the gas flow rate for the purpose of this study.

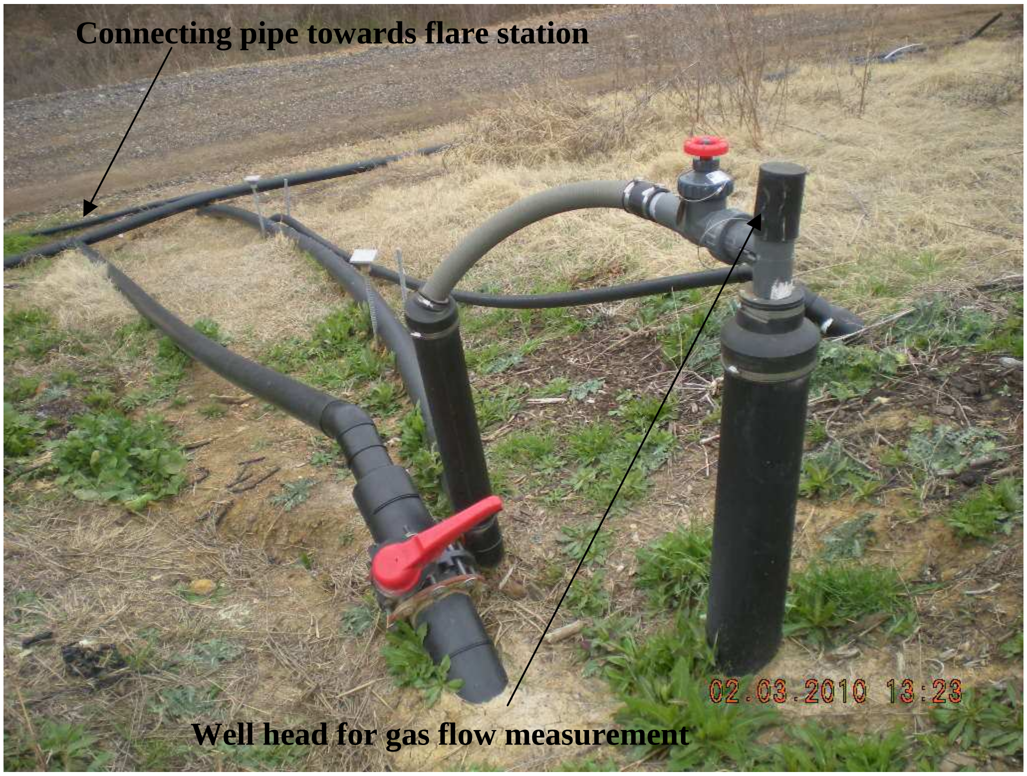


Figure 3.17: Gas well head and connection pipe towards well head

In order to measure landfill gas composition and gas volume, LANDTEC GEM 2000 was employed. The GEM™2000 was designed by ESLANDTEC specifically for use on landfills to monitor landfill gas (LFG) extraction systems, flares, and migration control systems. The GEM™2000 samples and analyzes the methane, carbon dioxide and oxygen content of landfill gas. The easy-to-read LCD screen shows the results as percentages of $CH_4$, $CO_2$, $O_2$ and balance gas. The GEM™2000 calculates and displays gas flow rate using the built in flow meter. It also measures and displays Btu content, temperature (with optional probe), relative and atmospheric pressures and $CH_4$ at LEL (Lower Explosive Limit).

Figure 3.18: LANDTEC GEM 2000 used for landfill gas studies

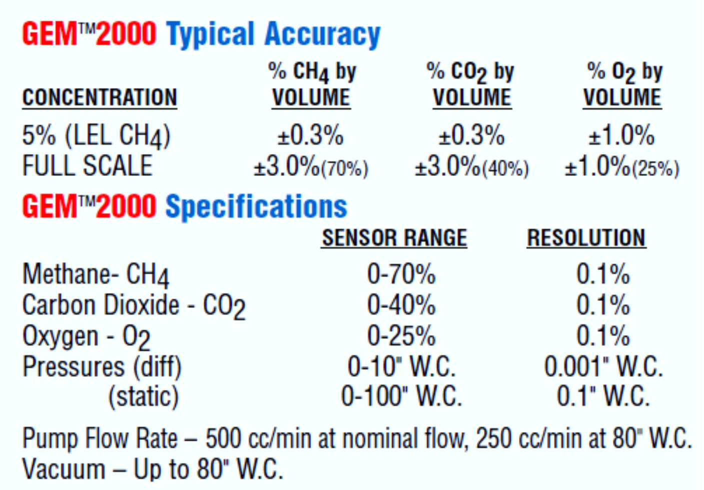
Several features and benefits of using LANDTC GEM 2000 are:

- It provides automatic sampling and analysis of gas composition % by volume of $CH_4$, $CO_2$, $O_2$ and balance gas, % LEL $CH_4$, temperature (with optional probe), static pressure, differential pressure, and barometric pressure. Calculates gas flow rates (SCFM) as well as Btu content.
- It provides onsite calibration. Rapid field calibration checking or adjustment can be carried out on site.

- It consists of 'Infrared Gas Analyzer' that provides accurate measurements of methane ($CH_4$) and carbon dioxide ($CO_2$).
- Durable Oxygen Sensor is provided by the galvanic cell principle; it is not influenced by other gases (i.e. $CH_4$, $CO_2$, CO, $SO_2$ or $H_2S$).
- It can display methane analysis as either % CH4 by volume or LEL $CH_4$ during Landfill Gas Analyzer Mode.
- It can be used during different weather conditions. It is designed to operate in extremes from 32°F to 104°F.
- It is a light-weight instrument (less than 5 lbs) that can be carried very easily into landfills.

LANDTEC GEM 2000 provides fairly accurate results in gas analyzing and gas flow rate determination. The level of accuracy as provided into the user manual is shown in Table 3.3.

Table 3.3: Typical accuracy level for LANDTEC GEM 2000



**GEM™2000 Typical Accuracy**

| CONCENTRATION | % $CH_4$ by VOLUME | % $CO_2$ by VOLUME | % $O_2$ by VOLUME |
|---|---|---|---|
| 5% (LEL $CH_4$) | ±0.3% | ±0.3% | ±1.0% |
| FULL SCALE | ±3.0%(70%) | ±3.0%(40%) | ±1.0%(25%) |

**GEM™2000 Specifications**

| | SENSOR RANGE | RESOLUTION |
|---|---|---|
| Methane- $CH_4$ | 0-70% | 0.1% |
| Carbon Dioxide - $CO_2$ | 0-40% | 0.1% |
| Oxygen - $O_2$ | 0-25% | 0.1% |
| Pressures (diff) | 0-10" W.C. | 0.001" W.C. |
| (static) | 0-100" W.C. | 0.1" W.C. |

Pump Flow Rate – 500 cc/min at nominal flow, 250 cc/min at 80" W.C.
Vacuum – Up to 80" W.C.

## 3.8 Modeling of Gas Flow Rate

Gas generation rate is a function of many site-specific variables, including waste generation rate, waste composition, climate, nutrient availability, and moisture content of the waste. Mathematical and computer gas-yield prediction models considering these variables are widely available but vary significantly in sophistication. Four parameters must be known if gas production is to be estimated: gas yield per unit weight of waste, the lag time prior to gas production, the shape of the lifetime gas production curve, and the duration of gas production.

Estimation of gas generation rate is very significant in terms of gas collection and control systems for a new landfill. According to New Source Performance Standards (NSPS) and the Emission Guidelines (EG), the gas collection and control system need to be sized for the maximum flow rate in accordance with EPA's landfill gas generation modeling equation, LandGEM (USEPA, 1997).

According to USEPA (1997), the total gas generation from the landfill for each year during either active period or closure period should be calculated based on each year's waste mass and waste age to determine the maximum expected gas generation flow rate from the landfill. Then, the maximum annual gas generation rate can be found by comparing each year's amount of gas generation.

### *3.8.1 First Order Kinetic Gas Generation Model*

For a landfill with a constant or unknown year-to-year solid waste acceptance rate, the annual gas generation rate can be calculated using EPA's gas modeling equation (USEPA, 1997),

$$Q_t = 2 \,.\, L_0 \,.\, m_0 \,.\, (e^{-k.c} - e^{-k.t}) \qquad (3.1)$$

where, $Q_t$ = expected gas generation rate in the $t^{th}$ year, $ft^3/yr$ or $m^3/yr$

$L_0$ = methane generation potential, $ft^3/lb$ or $m^3/Mg$

$m_0$ = constant or average annual solid waste acceptance rate, lb/yr, Mg/yr

k = Methane generation rate constant, $yr^{-1}$

t = Age of the landfill, yr

c = time since closure, yr (For active landfill, c =0; hence, $e^{-k.c} = 1$)

According to different period of landfill operations, it can be stated that,

For active landfill period,

$$Q_t = 2 \,.\, L_0 .\, M_0 \,.\, (1-e^{-k.t}) \qquad (3.2)$$

For closed landfill period,

$$Q_t = 2 \,.\, L_0 \,.\, m_0 \,.\, (e^{-kta} - 1) \,.\, e^{-kt} \qquad (3.3)$$

where, $Q_t$ = expected gas generation rate in the $t^{th}$ year, $ft^3/yr$ or $m^3/yr$

$L_0$ = methane generation potential, $ft^3/lb$ or $m^3/Mg$

$m_0$ = constant or average annual solid waste acceptance rate, lb/yr, Mg/yr

k = Methane generation rate constant, $yr^{-1}$

t = Age of the landfill, yr

$t_a$ = total years of active period of landfill, yr.

According to USEPA (1997), the expected gas generation rate from any waste mass, Mi, in the $t^{th}$ year can be calculated by,

$(Q_i)_t = 2 \,.\, k \,.\, L_0 \,.\, M_i \,.\, e^{-kti}$ ........................................................................(3.4)

where, $(Q_i)_t$ = expected gas generation rate for waste mass, $M_i$, in the $t^{th}$ year, $ft^3/yr$ or $m^3/yr$

$L_0$ = methane generation potential, $ft^3/lb$ or $m^3/Mg$

$M_i$ = mass of solid waste filled in the $i^{th}$ year, lb or Mg

k = Methane generation rate constant, $yr^{-1}$

$t_i$ = Age of the waste mass, $M_i$, in the $t^{th}$ year, yr

For a landfill with a known and changed year-to-year solid waste acceptance rate, annual gas generation rate can be calculated using EPA's modeling equation, (USEPA, 1997):

$$Q_t = \sum_{i=1}^{n} 2 \, . \, k \, . \, L_0 . \; M_i \, . \, (e^{-kt}) \text{..........} (3.5)$$

where, $Q_t$ = expected gas generation rate in the $t^{th}$ year, $ft^3/yr$ or $m^3/yr$

$L_0$ = methane generation potential, $ft^3/lb$ or $m^3/Mg$

$M_i$ = mass of solid waste filled in the $i^{th}$ year, lb or Mg

k = Methane generation rate constant, $yr^{-1}$

t = Age of the landfill, yr

$t_a$ = total years of active period of landfill, yr.

### *3.8.2 Model Parameters*

The Landfill Gas Emissions Model (LandGEM) is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emission rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills. LandGEM can use either site-specific data to estimate emissions or default parameters if no site-specific data are available. The model contains two sets of default parameters, CAA defaults and inventory defaults. The CAA defaults are based on federal regulations for MSW landfills laid out by the Clean Air Act (CAA) and can be used for determining whether a landfill is subject to the control requirements of these regulations. The inventory defaults are based on emission factors in EPA’s Compilation of Air Pollutant Emission Factors (AP-42) and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data. LandGEM is widely used to determine if a landfill is subject to the control requirements of the federal New Source Performance Standards (NSPS) for new MSW landfills, the federal Emission Guidelines (EG) for existing MSW landfills, or the National Emission Standards for Hazardous Air Pollutants (NESHAP) for MSW.

*Clean Air Act (CAA) Defaults:*

The CAA defaults are based on requirements for MSW landfills laid out by the Clean Air Act (CAA), including the New Source Performance Standards (NSPS) or federal Emissions Guideline (EG) and National Emission Standards for Hazardous Air Pollutants (NESHAP). This set of default parameters yields conservative emission estimates and can be used for determining whether a landfill is subject to the control requirements of the NSPS/EG or NESHAP.

*Inventory Defaults:*

With the exception of wet landfill defaults, the inventory defaults are based on emission factors in the U.S. Environmental Protection Agency's (USEPA) Compilation of Air Pollutant Emission Factors (AP-42). This set of defaults yields average emissions and can be used to generate emission estimates for use in emission inventories and air permits in the absence of site-specific test data.

*Determination of Model Parameters:*

Several model parameters associated with LandGEM are as follows:

- Methane generation rate (k),
- Potential methane generation capacity ($L_0$),
- NMOC concentration, and

- Methane content.

*Methane Generation Rate, (k)*

It determines the rate of methane generation for the mass of waste in the landfill. The higher the value of k, the faster the methane generation rate increases and then decays over time. The value of k is primarily a function of four factors:

a. Moisture content of the waste mass,
b. Availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide,
c. pH of the waste mass, and
d. Temperature of the waste mass.

The k value, as it is used in the first-order decomposition rate equation, is in units of year$^{-1}$. The five k values used by LandGEM are shown in Table 3.4. USEPA considered 'arid area landfills' are those located in areas that receive less than 25 inches of rainfall per year. The default k value is the CAA k value for conventional landfills.

Table 3.4: Values of Methane Generation rate (k), USEPA (1997)

| Default Type | Landfill Type | k value (yr$^{-1}$) |
|---|---|---|
| CAA | Conventional | 0.05 (default) |
| CAA | Arid Area | 0.02 |
| Inventory | Conventional | 0.04 |
| Inventory | Arid area | 0.02 |
| Inventory | Wet (Bioreactor) | 0.7 |

*The Potential Methane Generation Capacity, (Lo)*

$L_o$ depends only on the type and composition of waste placed in the landfill. The higher the cellulose content of the waste, the higher the value of Lo. The default Lo values used by LandGEM are representative of MSW. The Lo value, as it is used in the first-order decomposition rate equation, is measured in metric units of cubic meters per megagram to be consistent with the CAA. The five Lo values used by LandGEM are shown in Table 3.5. The default Lo value is the CAA Lo value for conventional landfills.

Table 3.5: Values for the potential Methane Generation Capacity ($L_o$), USEPA (1997)

| Emission Type | Landfill Type | $L_0$ value ($M^3$/Mg) |
|---|---|---|
| CAA | Conventional | 170 (default) |
| CAA | Arid Area | 170 |
| Inventory | Conventional | 100 |
| Inventory | Arid area | 100 |
| Inventory | Wet (Bioreactor) | 96 |

*Nonmethane Organic Compound Concentration (NMOC)*

The NMOC in landfill gas is a function of the types of waste in the landfill and the extent of the reactions that produce various compounds from the anaerobic decomposition of waste. NMOC is measured in units of parts per million by volume (ppmv) and is used by LandGEM only when NMOC emissions are being estimated. The NMOC Concentration for the CAA default is 4,000 ppmv as hexane. The NMOC Concentration for the inventory default is 600 ppmv where co-disposal of hazardous waste either has not occurred or is unknown and 2,400 ppmv where co-disposal of hazardous waste has occurred.

# CHAPTER 4

# RESULTS & DISCUSSION

## 4.1 Leachate Recirculation Influence Area

Influence area due to leachate recirculation was determined using RI tests for the Area A of the current working cell 2. RI tests were conducted generally after 1 day of leachate recirculation to determine the influence area. Initially RI tests were performed after every 24 hours of recirculation. From those test results, the extents of the recirculation were found maximum after one day of recirculation. After 24 hours, waste absorbed moisture supplied by recirculation. For that reason, RI tests were performed after 24 hours of recirculation. The leachate recirculation influence area was compared with the baseline test area, and thus the amount of the wetted solid waste was determined. In this section, Pipe H2 and H7 will be discussed for the leachate recirculation study purpose.

### *4.1.1 Leachate Recirculation Study for Pipe H2*

The leachate was injected through pipe H2 at regular intervals starting May 2009. The pipe is located on the grid line E+00 and the depth of the pipe was approximately 30 ft from the top of the surface. Initially, to evaluate the performance of the pipe, RI tests were conducted across the pipe. There were several RI tests conducted on the pipe H2 after the leachate recirculation.

- Baseline test result: The baseline test was conducted on May 22, 2009 and the test result is presented in Figure 4.1. The lower the ohm-m value, the wetter the area. Thus, blue indicates the wetter area of influence.

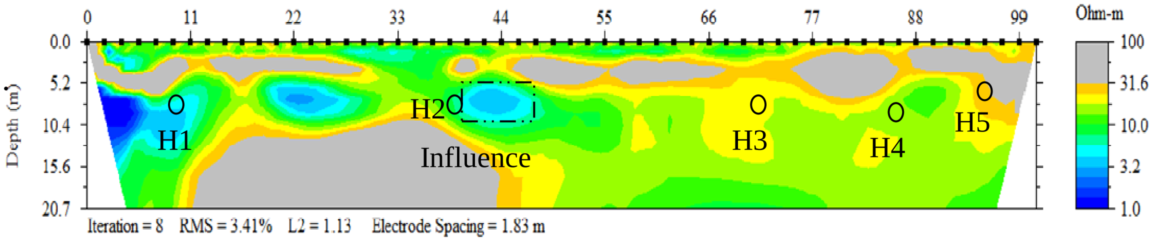


Figure 4.1: Baseline test result for pipe H2 on 05/22/2009

- Recirculation test result: Leachate recirculation test results are shown in the Figures 4.2, 4.3, 4.4 and 4.5 for pipe H2. Pipe H1 to pipe H4 were covered during the baseline study. But, the section was shifted towards the right of the initial lines during recirculation studies to focus area under pipe H2 to pipe H5. The resistivity numbers would be lower as an effect of the leachate recirculation into the waste mass. The influence zone increased from Figure 4.1 to Figure 4.2, slightly from Figure 4.2 to Figure 4.3 and slightly again from Figure 4.3 to Figure 4.4.

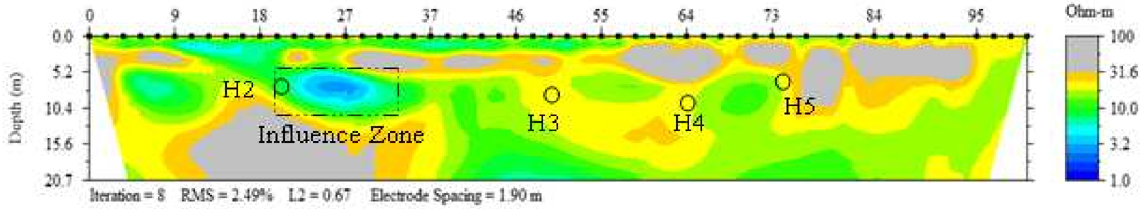


Figure 4.2: Recirculation test result for pipe H2 on 7/29/2009

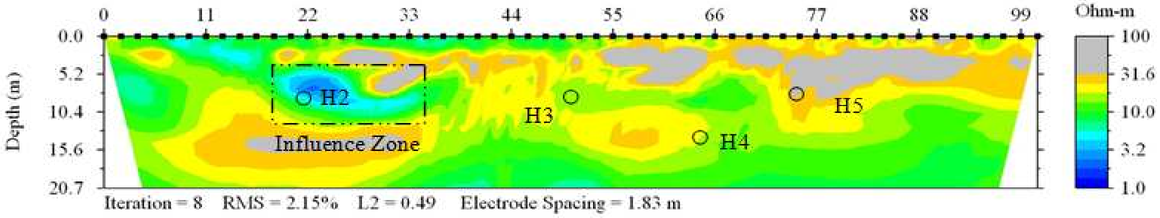


Figure 4.3: Recirculation test result for pipe H2 on 8/26/2009

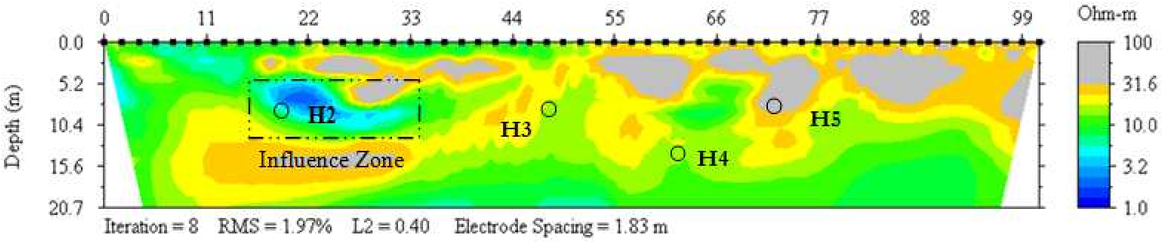


Figure 4.4: Recirculation test result for pipe H2 on 09/26/2009

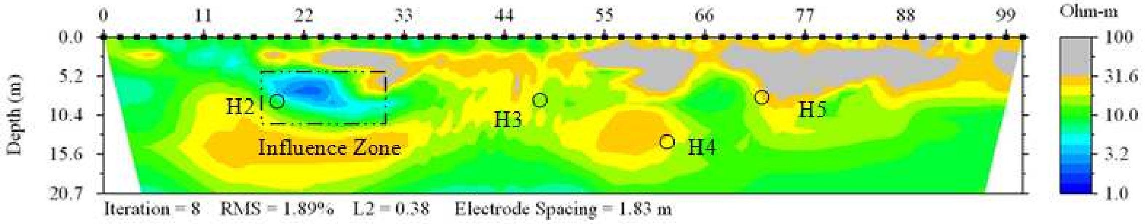


Figure 4.5: Recirculation test result for pipe H2 on 10/02/2009

- Influence Area: The influence area due to the leachate recirculation was determined based on the RI test results conducted at the pipe section. The influence area has been drawn using RI test results as shown in Figure 4.6.

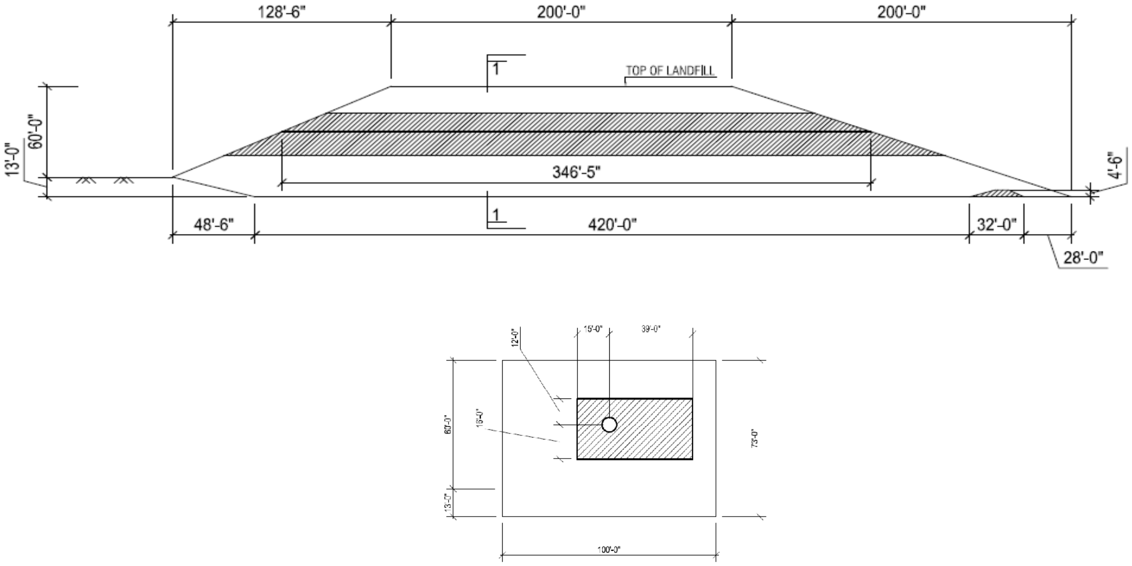


Figure 4.6: Influence area from leachate recirculation using RI for pipe H2

The effects of moisture intrusion have been modeled from the RI test results conducted for pipe H2 as presented to the Figure 4.7.

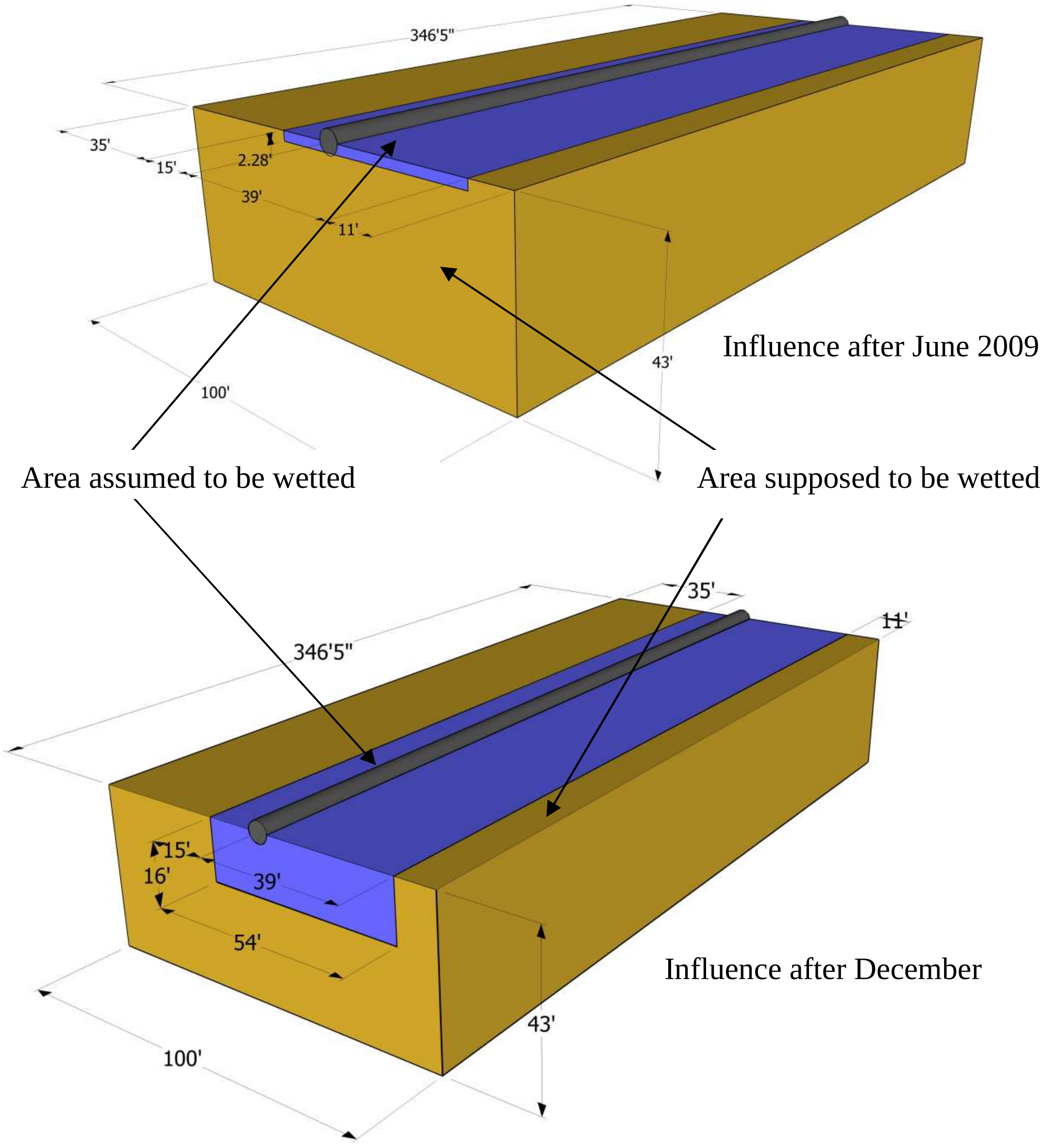


Figure 4.7: Increase of the influence area from leachate recirculation for Pipe H2

### *4.1.2 Leachate Recirculation Study for Pipe H7*

The leachate was injected through pipe H7 at regular intervals from June 05, 2009. The pipe is located on the grid line H+60 and the depth of the pipe was approximately 45 ft from the top of the surface. The depth from the pipe to the bottom of the landfill is approximately 28 ft. The horizontal pipe H6 was 10 ft away from pipe H7 with the same elevation.

- Baseline test result: The baseline test was conducted on May 29, 2009 at the center section shown in Figure 3.11. The test result is shown in Figure 4.8.

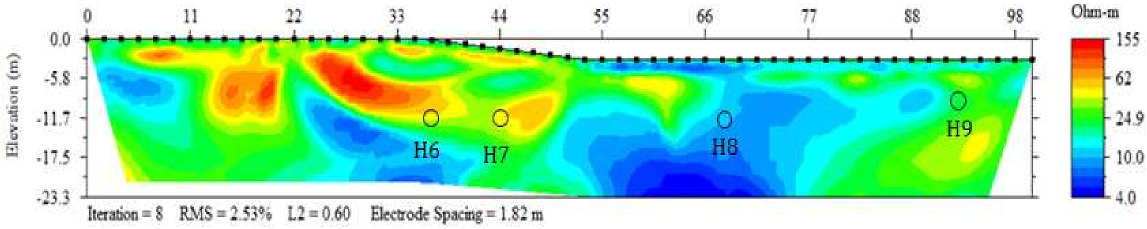


Figure 4.8: Baseline test result for pipe H7 on 05/29/2009

From the baseline test result, the resistivity numbers obtained were fairly low at different regions. During that period active landfilling were ongoing at that location. Pipes 7 and 8 were first pumped on February 2009. Due to the leachate recirculation, the resistivity numbers were fairly low for those regions.

- Recirculation test result: Leachate recirculation test results are shown in the Figures 4.9 to 4.11 for pipe H7. The locations of the tests were shown in Figure 3.18.

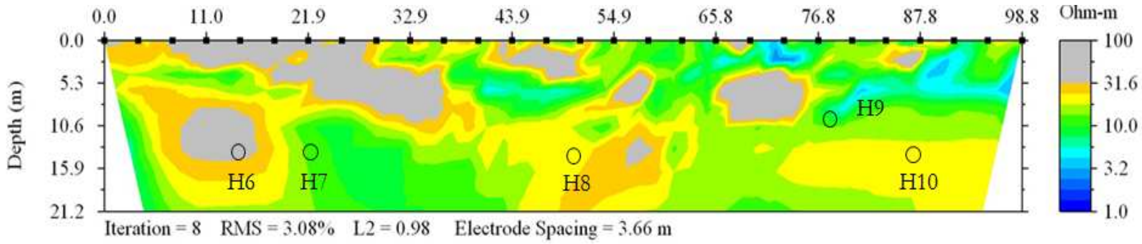


Figure 4.9: Recirculation test result for pipe H7 on 08/26/2009

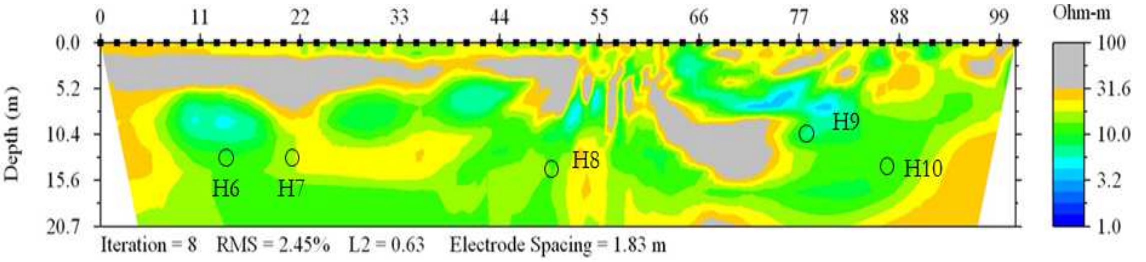


Figure 4.10: Recirculation test result for pipe H7 on 09/26/2009

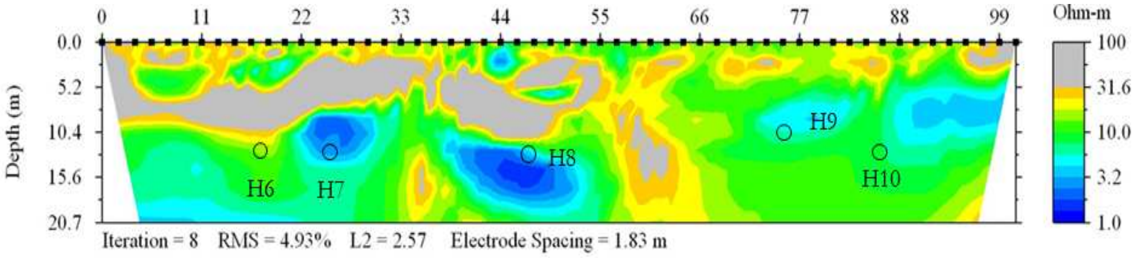


Figure 4.11: Recirculation test result for pipe H7 on 10/28/2009

The recirculation test results for pipe H7 are also similar to those of pipe H2. The influence area is increasing for pipe H7 as an effect of recirculation and the resistivity number is very low at those locations.

- Influence Area: The influence area due to the leachate recirculation was determined based from the RI test results conducted at the pipe section. The influence area has been redrawn using RI test results as shown in Figure 4.12.

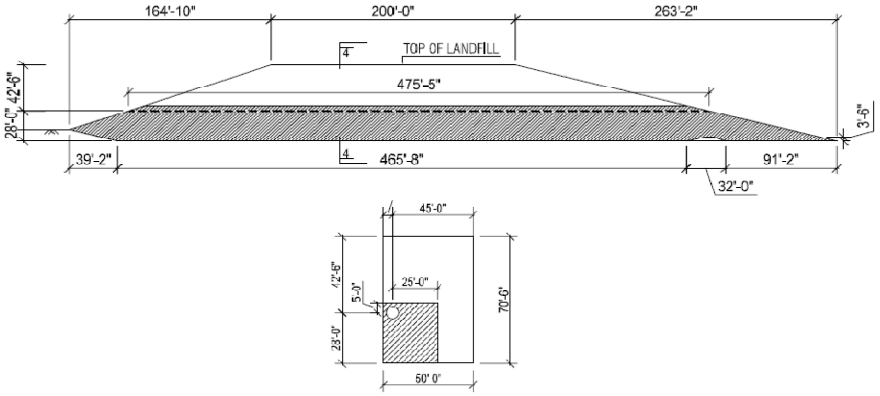


Figure 4.12: Influence area from leachate recirculation using RI for pipe H7

The effects of moisture intrusion have been modeled according to the Figure 4.13.

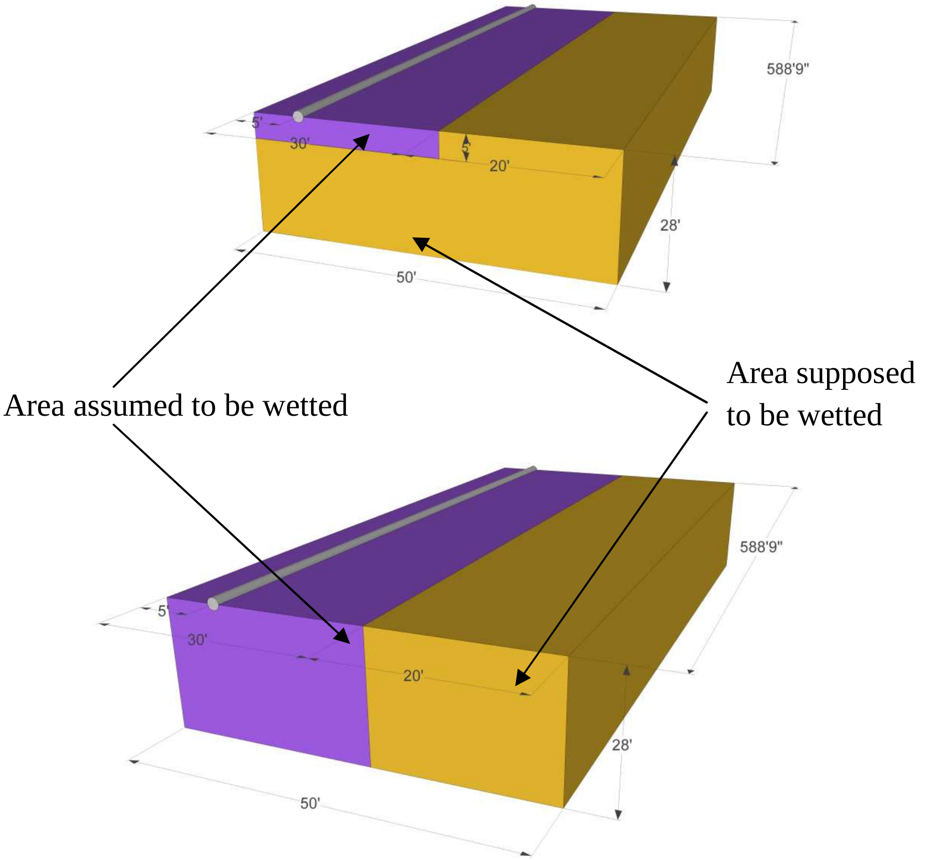


Figure 4.13: Increase of the influence area from leachate recirculation for pipe H7

## 4.2 Non Recirculation Influence Area

Pipe H6 was a representative for the non recirculation pipes. The Influence area under pipe H6 has been described in the following section.

### *4.2.1 Influence Zone beneath Pipe H6*

Pipe H6 covers a total width of 80 ft and it is located 45 ft below the top of the landfill. Pipe H7, which is in fact a leachate recirculation pipe at the same elevation of pipe H6, is located just 10 ft away from pipe H6. Thus, the gas generation for pipe H6 may be influenced by the recirculation conducted at pipe H7. The longitudinal and cross sections for the pipe H6 are shown in Figure 4.14.

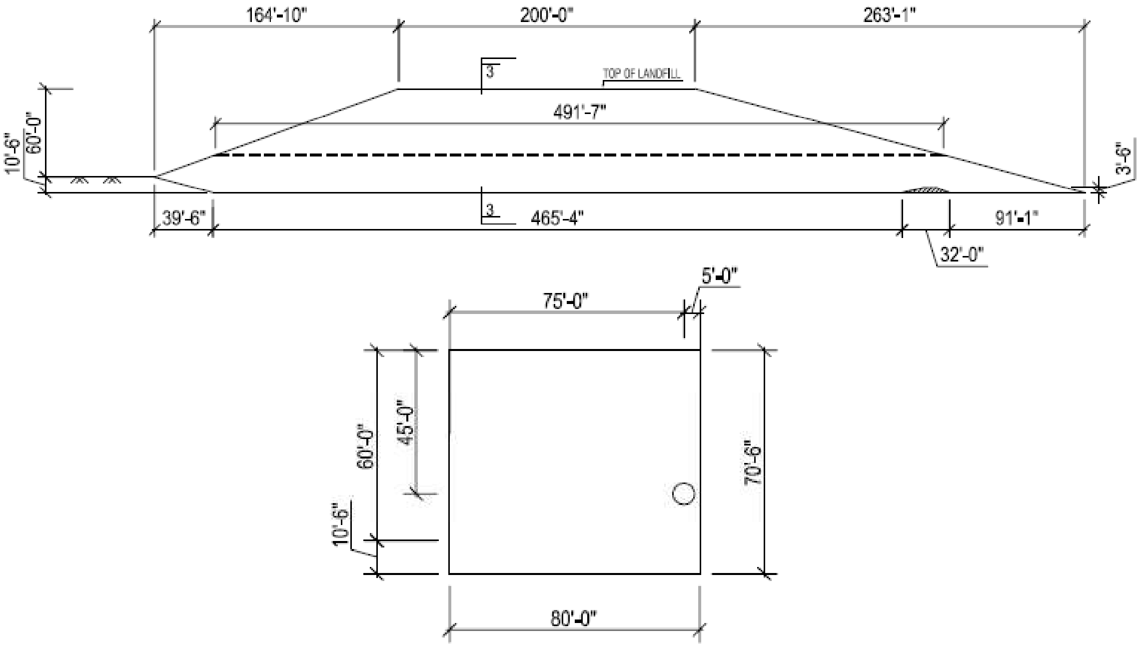


Figure: 4.14: Influence area under pipe H6

## 4.3 Recirculated Leachate Volume

Leachate was frequently recirculated starting May 2009. The amount of leachate pumped through the horizontal pipes was carefully recorded and the effect of leachate recirculation was carefully monitored over a period of time. For this study, pipes H2 and H7 were under consideration for leachate recirculation studies. Table 4.1 represents the total volume of leachate recirculated through different pipes through December 2009.

Table 4.1: Amount of leachate injected through horizontal pipes (City of Denton landfill)

| Month | Recirculated leachate volume in individual pipes (gallon) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | H1 | H2 | H3 | H4 | H5 | H7 | H8 | H10 |
| Jan’09 | - | - | - | - | - | - | - | - |
| Feb’09 | - | - | - | 30 | - | 12065 | 8500 | - |
| Mar’09 | - | - | - | - | - | 7895 | 8365 | 4540 |
| Apr’09 | - | - | - | 45 | - | - | - | 11422 |
| May’09 | 11847 | 7508 | 2387 | ** | - | - | - | - |
| Jun’09 | ** | - | - | | - | - | - | - |
| Jul’09 | | 14061 | 10145 | | 16542 | 6882 | 9383 | 10089 |
| Aug’09 | | 10154 | 10007 | | 9903 | 1069 | 1090 | 10177 |
| Sep’09 | | 10082 | 5518 | | 5095 | 1094 | 1273 | 10383 |
| Oct’09 | | 36204 | 34327 | | 19114 | - | - | 29558 |
| Nov’09 | | 20034 | 37417 | | 27886 | 1314 | 1512 | 10514 |
| Dec’09 | | 18247 | 14936 | | 5678 | - | - | 11100 |
| Total | 11847 | 116290 | 114737 | 75 | 84218 | 30319 | 30123 | 97783 |

** H1 and H4 were reported out of service due to bad cap and pinched respectively.

## 4.4 Gas Composition

Landfill gas composition is a very significant indicator that denotes the percentage of methane, carbon dioxide, oxygen and other trace gases present in landfill gas. The amount of carbon dioxide ($CO_2$) is greater at the beginning; it decreases with time due to the presence of oxygen ($O_2$) inside the landfill, whereas the amount of methane ($CH_4$) increases with respect to time.

### *4.4.1 Gas Composition for Recirculation Pipes H2 and H7*

Leachate recirculation started at the beginning of February, 2009 at pipe H7 and May, 2009 at pipe H2. The gas composition test results, starting from January 2009, for pipe H2 and pipe H7 have been presented in Table 4.2 and Table 4.3 respectively.

Table 4.2: Gas composition test results for pipe H2

| Test Conducted | Time | %$CH_4$ |
|---|---|---|
| 1/6/2009 | 0 | 53.8 |
| 1/9/2009 | 3 | 52.8 |
| 2/9/2009 | 34 | 56.8 |
| 3/20/2009 | 73 | 55.2 |
| 3/26/2009 | 79 | 37.4 |
| 4/6/2009 | 90 | 56 |
| 5/12/2009 | 126 | 28.7 |
| 5/18/2009 | 132 | 39.8 |
| 5/22/2009 | 136 | 55.4 |
| 6/3/2009 | 148 | 55.4 |
| 6/16/2009 | 161 | 55.1 |
| 6/18/2009 | 163 | 55.2 |
| 7/29/2009 | 204 | 47.6 |
| 8/5/2009 | 214 | 47 |
| 8/6/2009 | 215 | 56.5 |
| 8/19/2009 | 228 | 53.7 |
| 9/4/2009 | 244 | 56.4 |
| 9/23/2009 | 263 | 39.7 |
| 10/16/2009 | 286 | 54 |
| 10/22/2009 | 292 | 44.9 |
| 11/12/2009 | 307 | 58.2 |
| 12/3/2009 | 328 | 56.9 |
| 12/18/2009 | 343 | 38.2 |
| 12/21/2009 | 346 | 57.4 |

Table 4.3: Gas composition test result for pipe H7

| Test Conducted | Time | %$CH_4$ |
|---|---|---|
| 1/6/2009 | 0 | 57.8 |
| 1/9/2009 | 3 | 56.1 |
| 2/9/2009 | 34 | 47.3 |
| 3/20/2009 | 73 | 39.9 |
| 3/26/2009 | 79 | 55.5 |
| 4/6/2009 | 90 | 42.8 |
| 5/22/2009 | 136 | 53.2 |
| 6/3/2009 | 148 | 43 |
| 6/5/2009 | 150 | 43 |
| 6/10/2009 | 155 | 51.4 |
| 6/16/2009 | 161 | 54.8 |
| 6/18/2009 | 163 | 54.8 |
| 8/5/2009 | 214 | 45.5 |
| 8/6/2009 | 215 | 56.9 |
| 8/19/2009 | 228 | 57.2 |
| 9/28/2009 | 268 | 57.1 |
| 10/22/2009 | 292 | 53.2 |
| 11/12/2009 | 307 | 54.4 |
| 12/18/2009 | 343 | 46.3 |

### *4.4.2 Gas Composition for Non-Recirculation Pipe H6*

Pipe H6 was considered as a pipe without the influence of leachate injection. The gas composition tests started from January 2009 for this pipe as well. The test result are represented in Table 4.4.

Table 4.4: Gas composition test result for pipe H6

| Test Conducted | Time | %$CH_4$ |
|---|---|---|
| 1/6/2009 | 0 | 16.8 |
| 1/9/2009 | 3 | 45.7 |
| 2/9/2009 | 34 | 15 |
| 3/20/2009 | 73 | 53.2 |
| 3/26/2009 | 79 | 54.1 |
| 4/6/2009 | 90 | 46.6 |
| 5/22/2009 | 136 | 54.8 |
| 6/3/2009 | 148 | 44.6 |
| 6/10/2009 | 155 | 51.5 |
| 6/16/2009 | 161 | 55.6 |
| 6/18/2009 | 163 | 45.6 |
| 8/5/2009 | 214 | 48 |
| 8/6/2009 | 215 | 54.4 |
| 8/19/2009 | 228 | 51.7 |
| 9/28/2009 | 268 | 53.6 |
| 10/16/2009 | 286 | 56.2 |
| 10/22/2009 | 292 | 53.3 |
| 11/12/2009 | 307 | 54.8 |
| 12/18/2009 | 343 | 45.9 |

### *4.4.3 Change in Gas Composition with Time:*

Methane is the prime consideration from the gas composition data. The higher the concentration of methane, the better it is for power generation. For both leachate recirculation pipes and non-leachate recirculation pipes, the changes in gas composition with respect to time are quite comprehensible. From the field test data for the gas composition, there is an understandable relationship present between gas composition and leachate recirculation. The percentage of methane along with the rate of degradation increases with leachate recirculation. The influence of recirculation is quite evident from Figures 4.15 and 4.17.

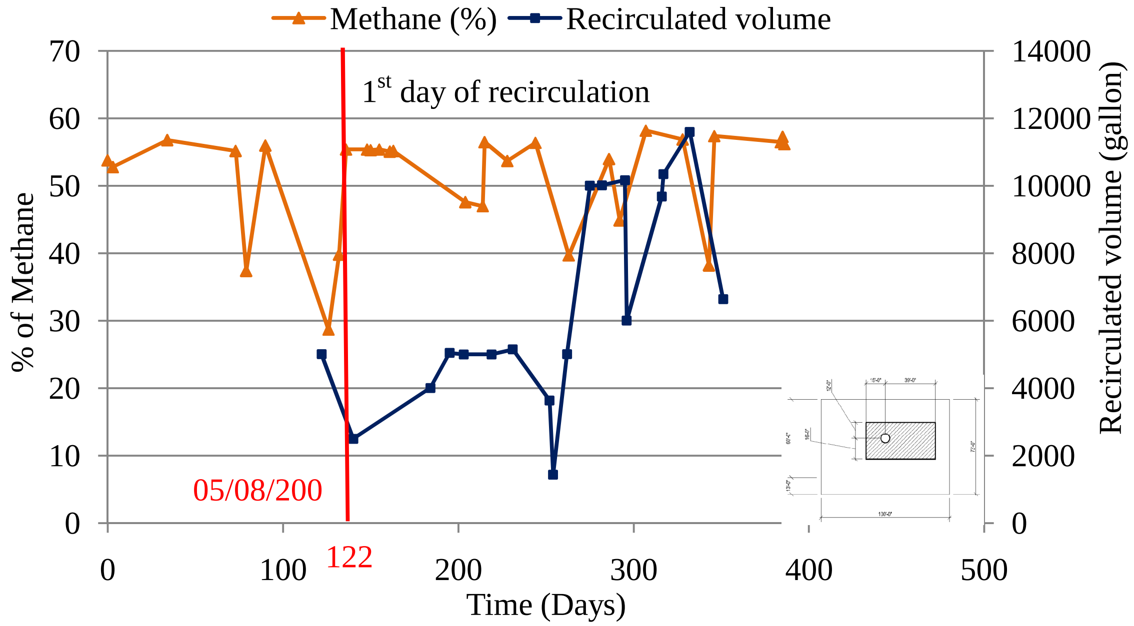


Figure 4.15: Methane concentration for pipe H2

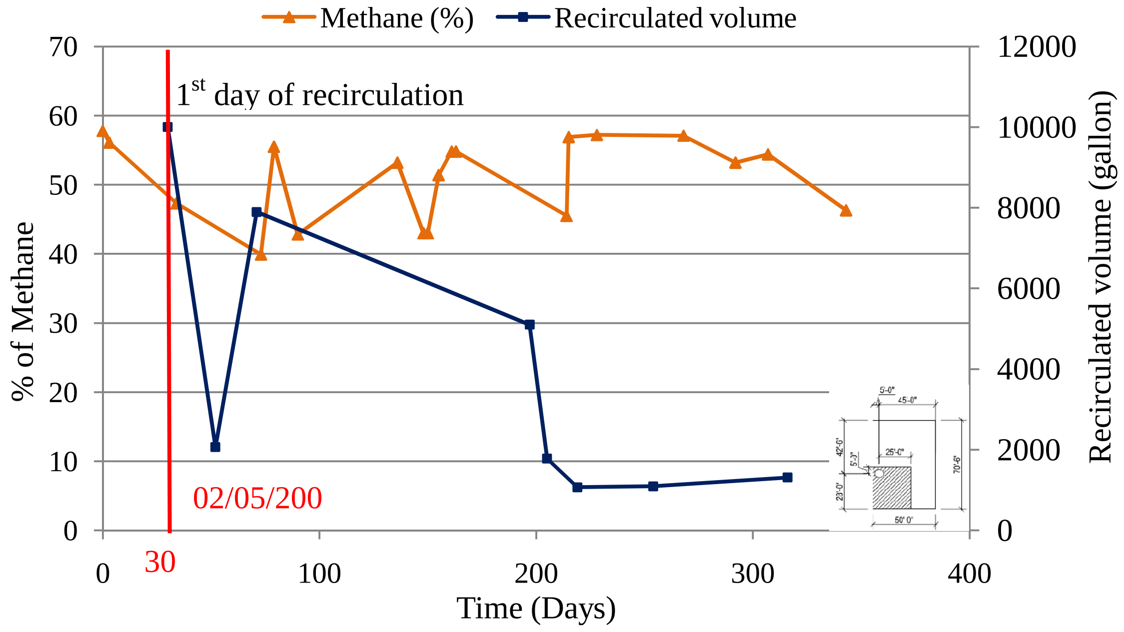


Figure 4.16: Methane concentration for pipe H7

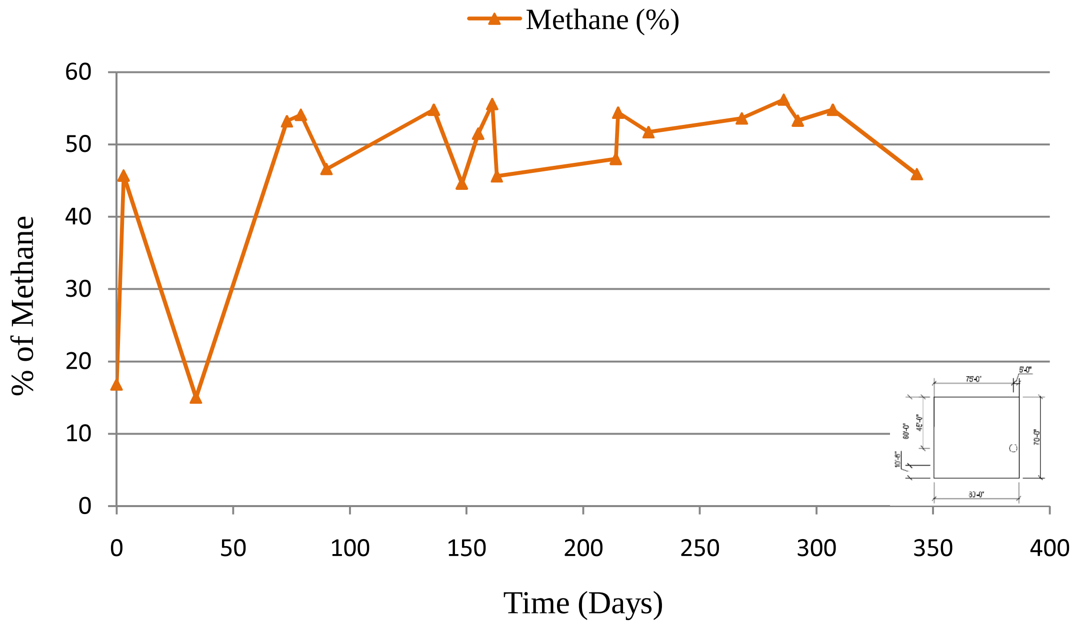


Figure 4.17: Methane concentration for pipe H6

## 4.5 Gas Flow Rate

The landfill gas flow rate is another important parameter. In general, the gas flow data can be obtained from the individual gas wells using the gas analyzer or from the landfill power generation station where landfill gas is converted into electricity. Gas flow rate data is directly linked to the level of decomposition of the solid waste in the landfill. In general, with the aid of leachate recirculation, the rate of solid waste decomposition increases, resulting in a higher gas flow rate.

### *4.5.1 Gas Flow Rate for Pipes with Leachate Recirculation*

Pipe H2 and H7 were the two pipes considered for the leachate recirculation studies. Pipes H2 and H7 were used for leachate injection starting early 2009. The leachate injection data and the gas flow rate data for pipe H2 and H7 are shown in Table 4.5 and Table 4.6, respectively.

Table 4.5: Gas flow rate and leachate recirculation data for pipe H2

| Date | Time (days) | Flow, SCFM[1] (ft$^3$/min) | Date | Time (days) | Leachate Injected (gallon) |
|---|---|---|---|---|---|
| 1/6/2009 | 0 | 9 | - | - | - |
| 1/9/2009 | 3 | 13 | - | - | - |
| 2/9/2009 | 34 | 12 | - | - | - |
| 3/20/2009 | 73 | 24 | - | - | - |
| 4/6/2009 | 90 | 38 | - | - | - |
| - | - | - | 5/8/2009[2] | 122 | 5008 |
| 5/12/2009 | 126 | 14 | - | - | - |
| - | - | - | 5/26/2009 | 140 | 2500 |
| 6/3/2009 | 148 | 16 | - | - | - |
| 6/5/2009 | 150 | 8 | - | - | - |
| 6/10/2009 | 155 | 8 | - | - | - |
| 6/16/2009 | 161 | 9 | - | - | - |
| 6/18/2009 | 163 | 8 | - | - | - |
| - | - | - | 7/9/2009 | 184 | 4010 |
| - | - | - | 7/20/2009 | 195 | 5045 |
| - | - | - | 7/28/2009 | 203 | 5006 |
| 8/6/2009 | 215 | 2 | - | - | - |
|  |  |  | 8/13/2009 | 219 | 5003 |
| 8/19/2009 | 228 | 8 | - | - | - |
| - | - | - | 8/25/2009 | 231 | 5151 |
| 9/4/2009 | 244 | 11 | - | - | - |
| 9/23/2009 | 263 | 11 | 9/15/2009 | 252 | 3633 |
| - | - | - | 9/17/2009 | 254 | 1439 |
| 9/23/2009 | 263 | 11 | - | - | - |
| - | - | - | 9/25/2009 | 262 | 5010 |
| - | - | - | 10/8/2009 | 275 | 10006 |
| - | - | - | 10/15/2009 | 282 | 10019 |
| 10/16/2009 | 286 | 17 | - | - | - |
| 10/22/2009 | 292 | 26 | - | - | - |
| - | - | - | 10/28/2009 | 295 | 10170 |

Table 4.5 – continued

| Date | Time (days) | Flow, SCFM[1] (ft$^3$/min) | Date | Time (days) | Leachate Injected (gallon) |
|---|---|---|---|---|---|
| - | - | - | 10/29/2009 | 296 | 6009 |
| 11/12/2009 | 307 | 15 | - | - | - |
| - | - | - | 11/18/2009 | 316 | 9681 |
| - | - | - | 11/19/2009 | 317 | 10353 |
| 12/3/2009 | 328 | 9 | - | - | - |
| - | - | - | 12/4/2009 | 332 | 11603 |
| 12/18/2009 | 343 | 15 | - | - | - |
| 12/21/2009 | 346 | 8 | - | - | - |
| - | - | - | 12/23/2009 | 351 | 6644 |

1. SCFM is ‘Standard Cubic Feet per Minute’, volumetric flow rate of a gas corrected to standardized condition of temperature, pressure & relative humidity.
2. 5/8/2009 is the first day of leachate recirculation for pipe H2.

Table 4.6: Gas flow rate and leachate recirculation data for Pipe H7

| Date | Time (days) | Flow, SCFM[1] (ft$^3$/min) | Date | Time (days) | Leachate Injected (gallon) |
|---|---|---|---|---|---|
| 1/6/2009 | 0 | 20 | - | - | - |
| 1/9/2009 | 3 | 18 | - | - | - |
| | | | 2/5/2009 | 30 | 10000 |
| 2/9/2009 | 34 | 17 | - | - | - |
| - | - | - | 2/27/2009 | 52 | 2065 |
| - | - | - | 3/18/2009 | 71 | 7895 |
| 3/20/2009 | 73 | 82 | - | - | - |
| 5/22/2009 | 136 | 21 | - | - | - |
| 6/3/2009 | 148 | 16 | - | - | - |
| 6/5/2009 | 150 | 18 | - | - | - |
| 6/10/2009 | 155 | 11 | - | - | - |
| 6/16/2009 | 161 | 18 | - | - | - |
| 6/18/2009 | 163 | 10 | - | - | - |
| - | - | - | 7/22/2009 | 197 | 5100 |
| - | - | - | 7/30/2009 | 205 | 1782 |
| 8/6/2009 | 215 | 11 | - | - | - |
| - | - | - | 8/13/2009 | 219 | 1069 |

Table 4.6 – continued

| Date | Time (days) | Flow, SCFM[1] (ft$^3$/min) | Date | Time (days) | Leachate Injected (gallon) |
|---|---|---|---|---|---|
| 8/19/2009 | 228 | 7 | - | - | - |
| - | - | - | 9/17/2009 | 254 | 1094 |
| 9/28/2009 | 268 | 33 | - | - | - |
| 10/22/2009 | 292 | 21 | - | - | - |
| 11/12/2009 | 307 | 13 | - | - | - |
| - | - | - | 11/19/2009 | 316 | 1314 |
| 12/18/2009 | 343 | 17 | - | - | - |

1. SCFM is 'Standard Cubic Feet per Minute', volumetric flow rate of a gas corrected to standardized condition of temperature, pressure & relative humidity.
2. 2/5/2009 is the first day of leachate recirculation for pipe H7.

### *4.5.2 Gas Flow Rate for Pipes without Leachate Recirculation*

Pipe H6 was the pipe considered for the non-leachate recirculation studies. The gas flow rate data for pipe H6 is shown in Table 4.7.

Table 4.7: Gas flow rate data for Pipe H6

| Date | Time (days) | Flow, SCFM[1] (ft$^3$/min) |
|---|---|---|
| 1/9/2009 | 3 | 13 |
| 2/9/2009 | 34 | 15 |
| 3/20/2009 | 73 | 6 |
| 3/26/2009 | 79 | 13 |
| 4/6/2009 | 90 | 22 |
| 5/22/2009 | 136 | 15 |
| 6/3/2009 | 148 | 16 |
| 6/10/2009 | 155 | 14 |
| 6/16/2009 | 161 | 17 |
| 6/18/2009 | 163 | 11 |
| 8/19/2009 | 228 | 11 |
| 9/28/2009 | 268 | 8 |

Table 4.7 – continued

| Date | Time (days) | Flow, SCFM[1] $(ft^3/min)$ |
|---|---|---|
| 10/16/2009 | 286 | 16 |
| 10/22/2009 | 292 | 10 |
| 11/12/2009 | 307 | 20 |
| 12/18/2009 | 343 | 12 |

1. SCFM is ‘Standard Cubic Feet per Minute’, volumetric flow rate of a gas corrected to standardized condition of temperature, pressure & relative humidity.

### *4.5.3 Change in Gas Flow Rate with Time*

For both, leachate recirculation pipes and non-leachate recirculation pipes, the changes in gas flow rate with respect to time are quite comprehensible. From the field test data for the gas flow rate, there is an understandable relationship of gas flow rate with leachate recirculation. The influence is quite evident from Figures 4.18 to4.20. Initially, before the recirculation the gas flow rate is low for both the pipes. But, the flow rate increases significantly due to the leachate recirculation. The gas flow rate increases significantly with time flowing by a lag phase of 25 to 30 days at the initial phase of recirculation. But, the flow rate also drops down with the additional leachate injection as occurred for pipe H7. The flow rate behaves similarly for both pipes, H2 and H7 as presented in Figures 4.18 and 4.19.

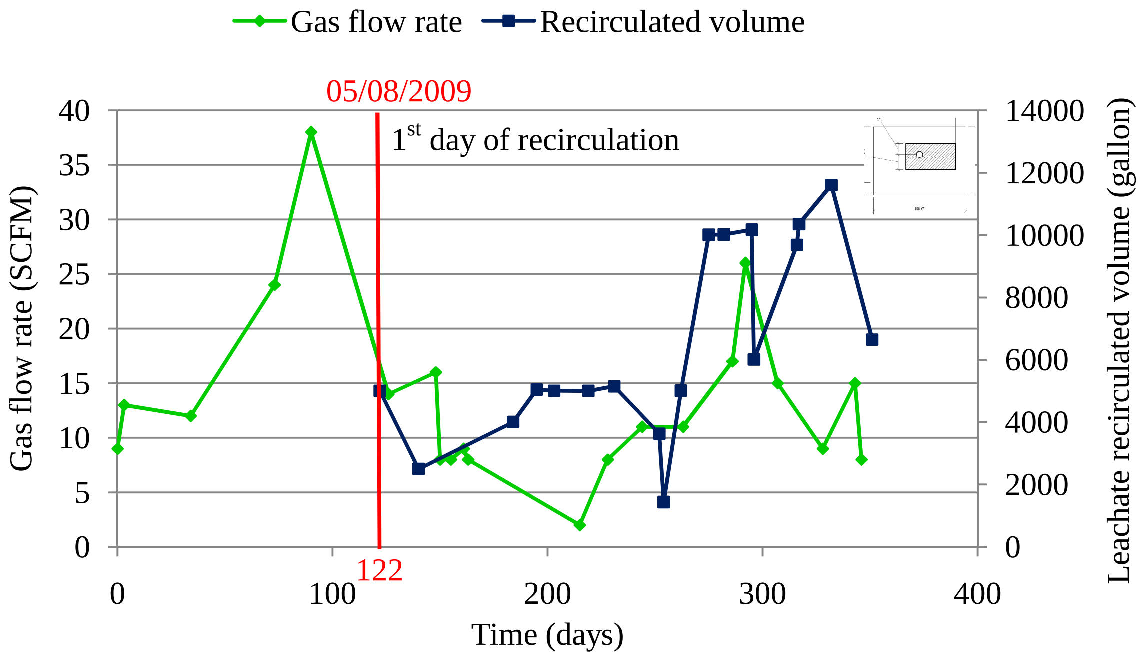


Figure 4.18: Change in gas flow rate with time for pipe H2

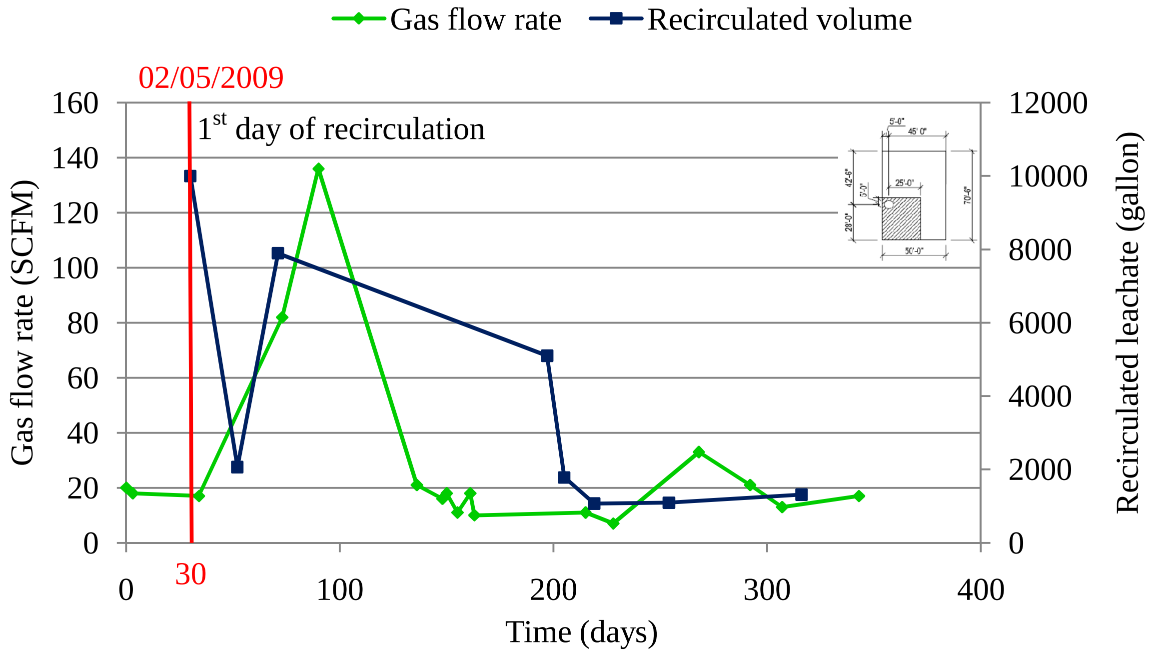


Figure 4.19: Change in gas flow rate with time for pipe H7

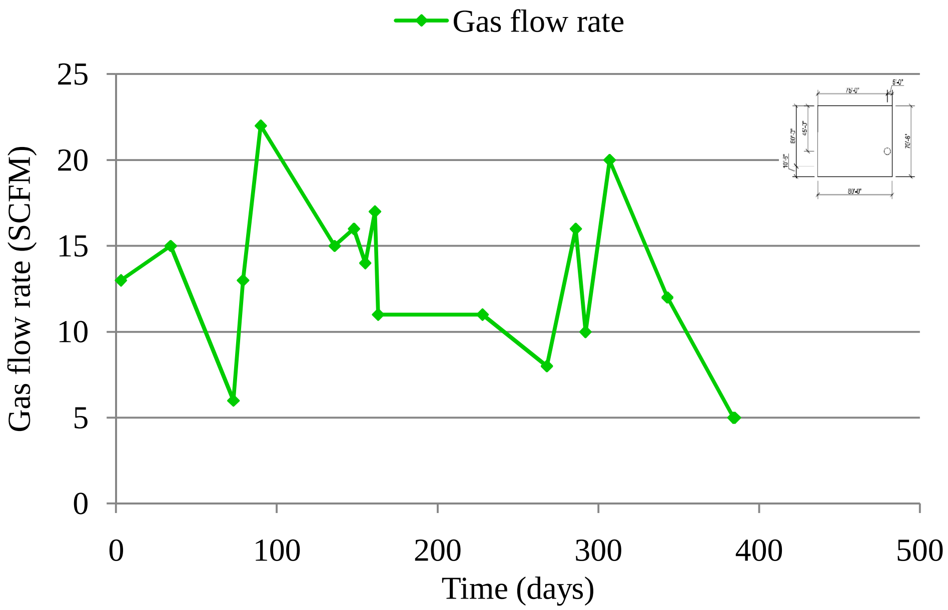


Figure 4.20: Change in gas flow rate with time for pipe H6

## 4.6 Modeled (Predicted) Gas Flow Rate

The City of Denton MSW landfill started accepting solid waste in 1984. At the beginning, solid waste was placed inside cell one. Cell two was started in January 1999 once cell one was closed. Cell two reached to desired height in September 2009, and cell two has been closed. Cell two was in an active phase for the entire ten years from 1999 to 2009. Initially this cell used conventional landfilling. Later on, bioreactor operation started in May 2009. This study was carried out with the information provided by City of Denton MSW authority.

The parameters assumed for the model to determine generated gas from pipe H2 are:

Methane generation potential, $L_o = 2.5\ ft^3/lb$ (recommended by CAA)

The first order reaction rate constant for dry cell, k = 0.05 $yr^{-1}$ (recommended by CAA)

The first order reaction rate constant for wet cell, k = 0.23 $yr^{-1}$ (recommended by CAA)

With the geometry specified earlier, the gas flow rate was modeled for pipe H2, H7 and H6. The predicted gas flow rate has been tabulated as shown:

Table 4.8: Predicted gas flow rate for Pipe H2

| Time | Year | $Q_t$ ($ft^3$/min) | | |
|---|---|---|---|---|
| | | Dry up to pipe | Wet up to pipe | Partially wet and rest of the part dry |
| June, 2009 | 10.5 | 21.765 | 32.735 | 22.420 |
| July, 2009 | 10.583 | 21.674 | 32.114 | 22.885 |
| August, 2009 | 10.667 | 21.584 | 31.504 | 23.312 |
| September, 2009 | 10.75 | 21.494 | 30.906 | 23.702 |
| October, 2009 | 10.833 | 21.405 | 30.319 | 24.057 |
| November, 2009 | 10.916 | 21.316 | 29.743 | 24.377 |
| December, 2009 | 11 | 21.227 | 29.179 | 24.664 |

The modeled flow rate has been shown in Figures 4.21 and 4.22 for pipe H2, Figures 4.23 for pipe H7 and Figure 4.24 for pipe H6. Waste upto the pipes was considered for the modeling of the gas flow rate. The movement of the methane is upward and the waste located top of the pipe would not be collected by the pipe. So, foe modeling purpose three conditions were considered as: waste is completely dry up to the pipe, waste is completely wet up to the pipe, partially wet and the remaining portion is dry. The modeled flow rate for pipe H2 is presented in Figures 4.21 and 4.22.

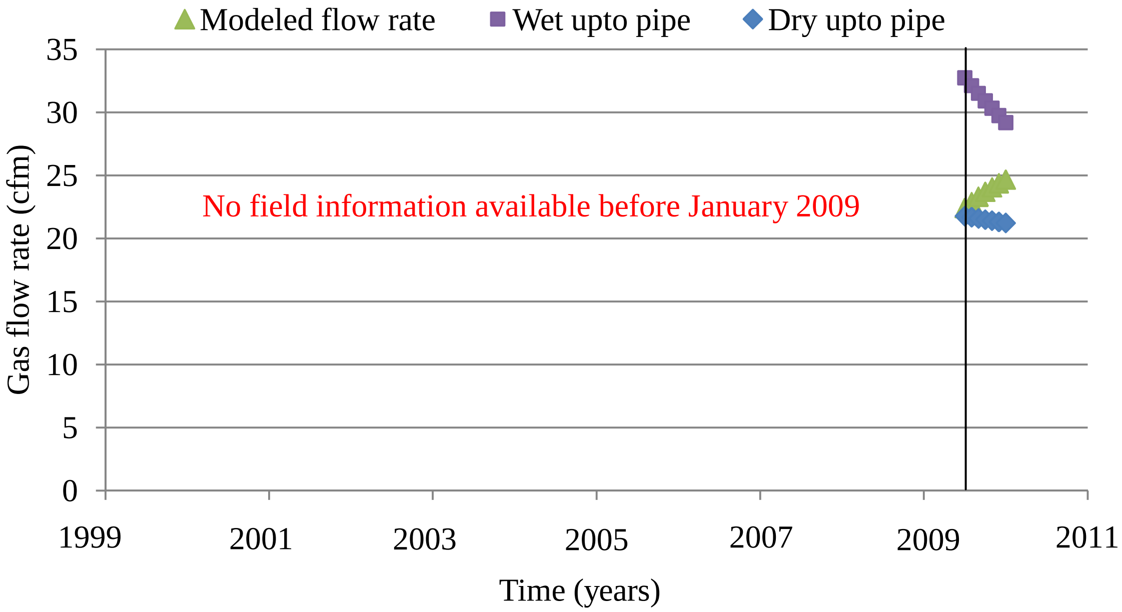


Figure 4.21: Modeled gas flow rate for pipe H2 (starting from 1999)

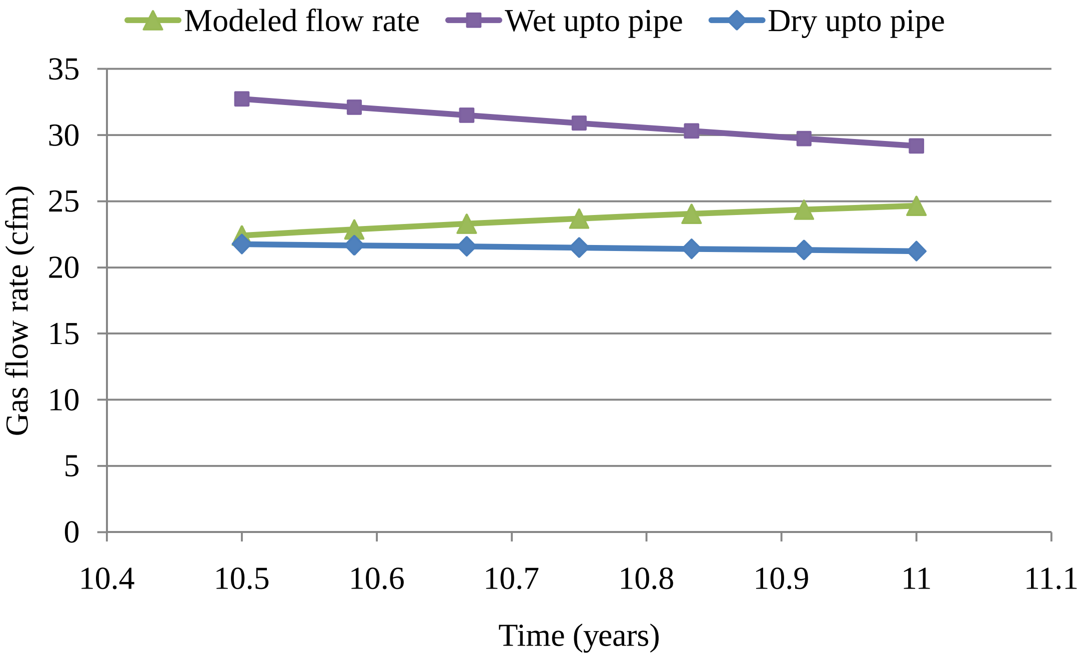


Figure 4.22: Modeled gas flow rate for pipe H2 (from June 2009 to December 2009)

Table: 4.9: Predicted gas flow rate for Pipe H7

| Time | Year | $Q_t$ (ft$^3$/min) | | |
|---|---|---|---|---|
| | | Dry up to pipe | Wet up to pipe | Partially wet and rest of the part dry |
| June, 2009 | 10.5 | 12.376 | 23.346 | 14.032 |
| July, 2009 | 10.583 | 12.285 | 22.725 | 14.496 |
| August, 2009 | 10.667 | 12.195 | 22.115 | 14.923 |
| September, 2009 | 10.75 | 12.105 | 21.930 | 15.313 |
| October, 2009 | 10.833 | 12.015 | 21.517 | 15.668 |
| November, 2009 | 10.916 | 11.927 | 21.355 | 15.988 |
| December, 2009 | 11 | 11.838 | 20.790 | 16.275 |

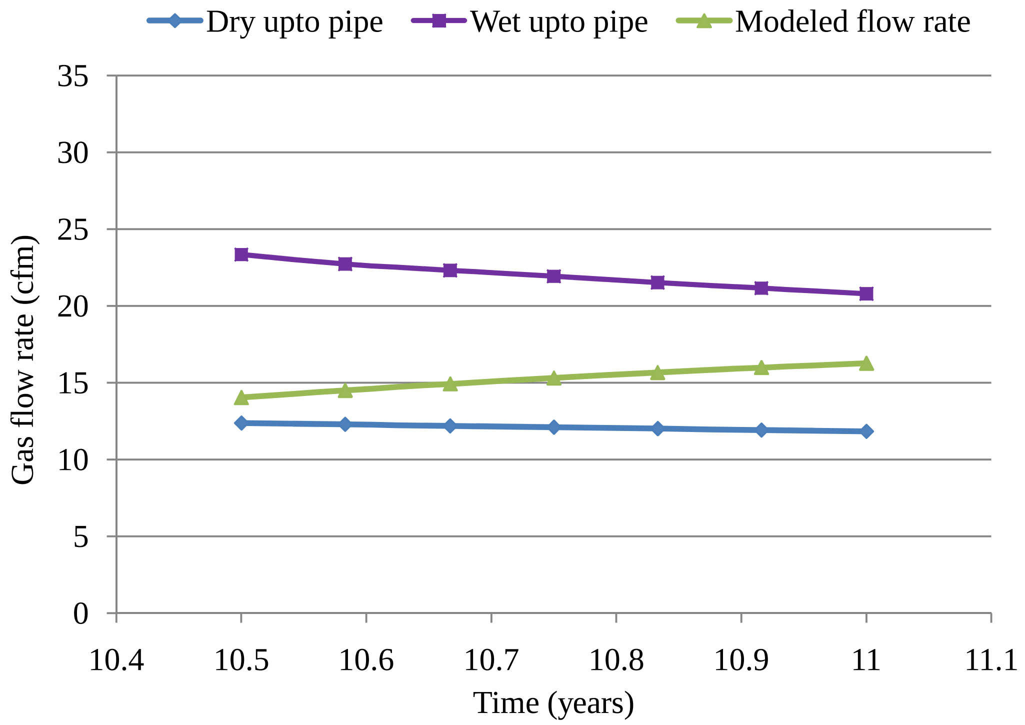


Figure 4.23: Modeled gas flow rate for pipe H7

Table 4.10: Predicted gas flow rate for Pipe H6

| Time | Year | $Q_t$ (ft$^3$/min) | | |
|---|---|---|---|---|
| | | Dry up to pipe | Wet up to pipe | Actual gas flow |
| June, 2009 | 10.5 | 13.139 | 20.200 | 13.139 |
| July, 2009 | 10.583 | 13.085 | 19.833 | 13.085 |
| August, 2009 | 10.667 | 13.030 | 19.473 | 13.030 |
| September, 2009 | 10.75 | 12.976 | 19.119 | 12.976 |
| October, 2009 | 10.833 | 12.922 | 18.772 | 12.922 |
| November, 2009 | 10.916 | 12.869 | 18.431 | 12.869 |
| December, 2009 | 11 | 12.815 | 18.096 | 12.815 |

The gas flow rate data are plotted for the dry, wet and model flow rate. The curves can be shown in Figure 4.24.

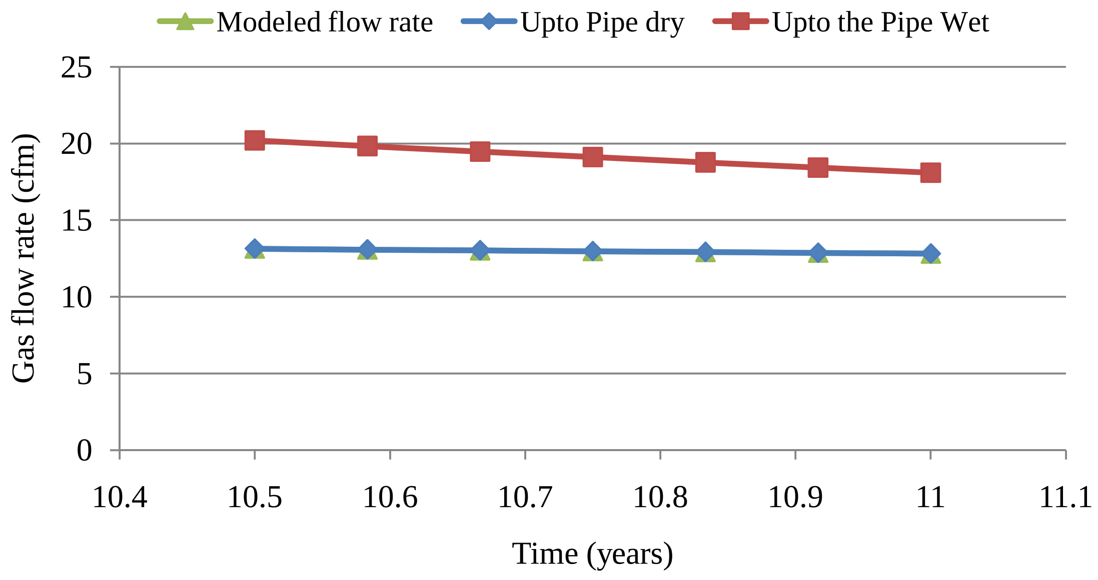


Figure 4.24: Gas flow rate for fully dry, fully wet and modeled flow rate for pipe H6

## 4.7 Comparison between Actual & Modeled (Predicted) Gas Flow Rate

The modeled gas flow rates are compared with the actual field flow rate to determine the efficiency of the gas collection system and the efficiency of the leachate recirculation system. In general, the field flow rate should be less than the predicted gas flow rate due to the collection efficiency being less than 100%.

### *4.7.1 Comparison of the Modeled (Predicted) Gas Flow Rate*

The predicted gas flow rate data have been compared and presented in Figure 4.25 for the study period starting from June 2010 to December 2010 for the pipes H2, H7 and H6.

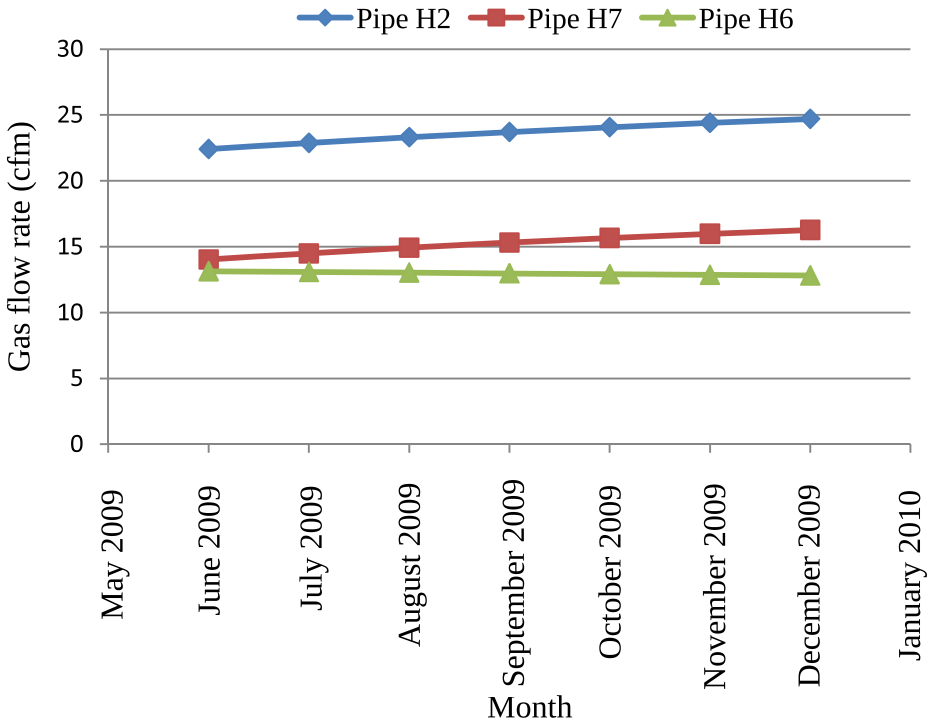


Figure 4.25: Comparison of modeled flow rates for pipe H2, H7 and H6

From the predicted gas flow rate data for pipes H2 and H7, it is evident that the flow rate increases with the addition of leachate into the waste mass. The gas flow rate from pipe H2 is higher compared to pipes H7 and H6. The quantity of solid waste covered by pipe H2 is more than the waste under pipes H7 and H6. Pipe H7 covered less amount of waste comparing to the pipe H6. Due to the intrusion of the additional moisture in pipe H7, the gas generation rate becomes higher comparing to pipe H6 whereas pipe H6 has always been a non-recirculating pipe. The movement of the lines for H2 and H7 are upward, providing increased gas generation potential whereas the line for pipe H7 moves downward with the progression of time.

*4.7.2 Comparison between Field and Predicted Gas Flow Rate*

a. Pipe H2: The modeled (predicted) gas flow data has been compared with the field flow rate data in Figure 4.26 to check the efficiency of the recirculation and gas collection system for pipe H2.

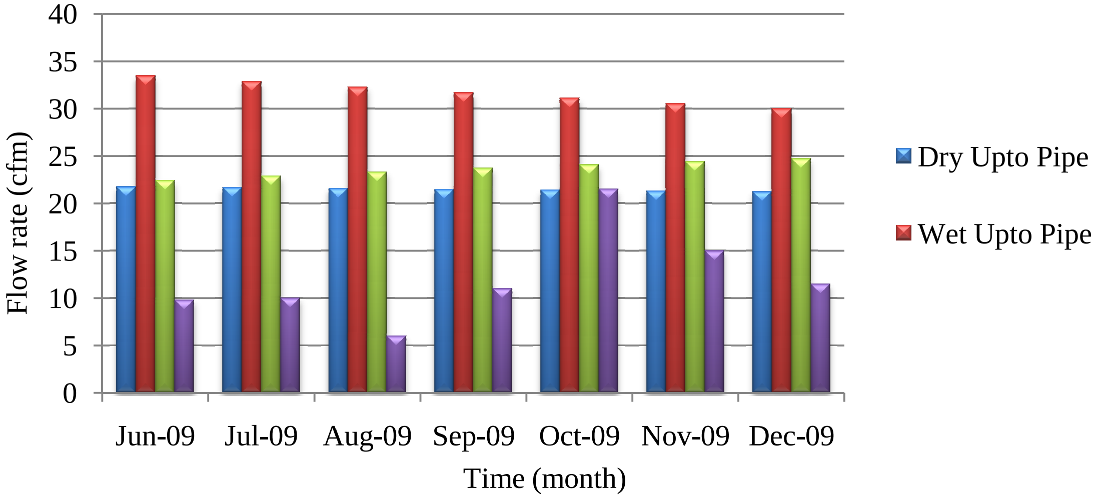


Figure 4.26: Comparison of gas flow rates for pipe H2

The field flow rate is presented in the tabular form in Table 4.6. The field flow rate has been considered with the average of the test results for every month during the study period. The field flow rate varies with respect to time depending upon the amount of leachate recirculated into the pipes. Initially the field flow rate was low (around 10 $ft^3$/min). But, with the presence of the additional moisture, the biodegradation became rapid that resulted higher gas generation rate. During October 2009, nearly 36,000 gallons of leachate was injected through the H2. As a result of the recirculation, the field flow rate eventually went up to 26 $ft^3$/min (average 22 $ft^3$/min for October 2009). The modeled flow rate and the field flow rate are presented into Figure 4.27.

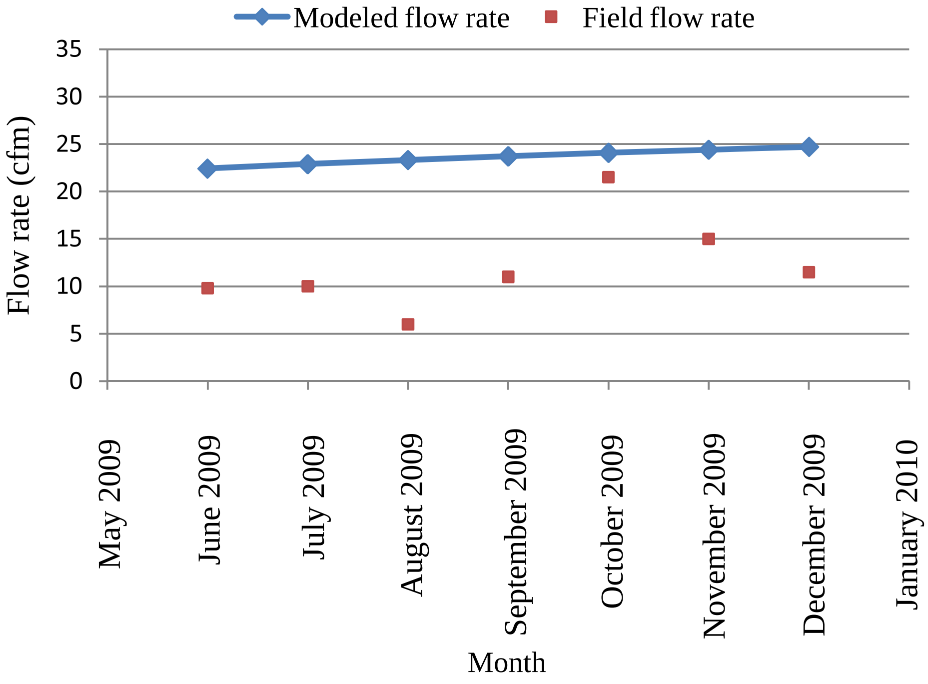


Figure 4.27: Comparison of modeled and field gas flow rates for pipe H2

From the comparison between the actual flow rate and the modeled flow rate, the efficiency of the gas collection systems can be determined for monthly basis. The comparison is presented in Figure 4.28 for pipe H2.

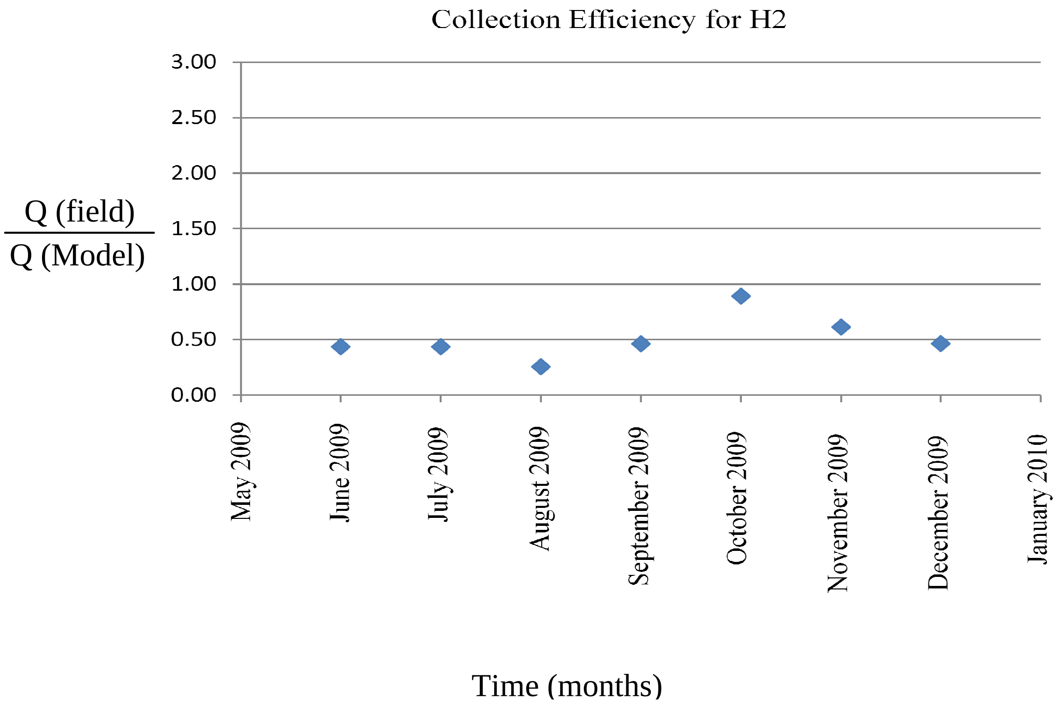


Figure 4.28: Comparison of field flow rate and predicted flow rate for pipe H2

b. Pipe H7: The modeled (predicted) gas flow data is compared with the field flow rate data to check the efficiency of the recirculation and gas collection system for pipe H7 in Figure 4.29.

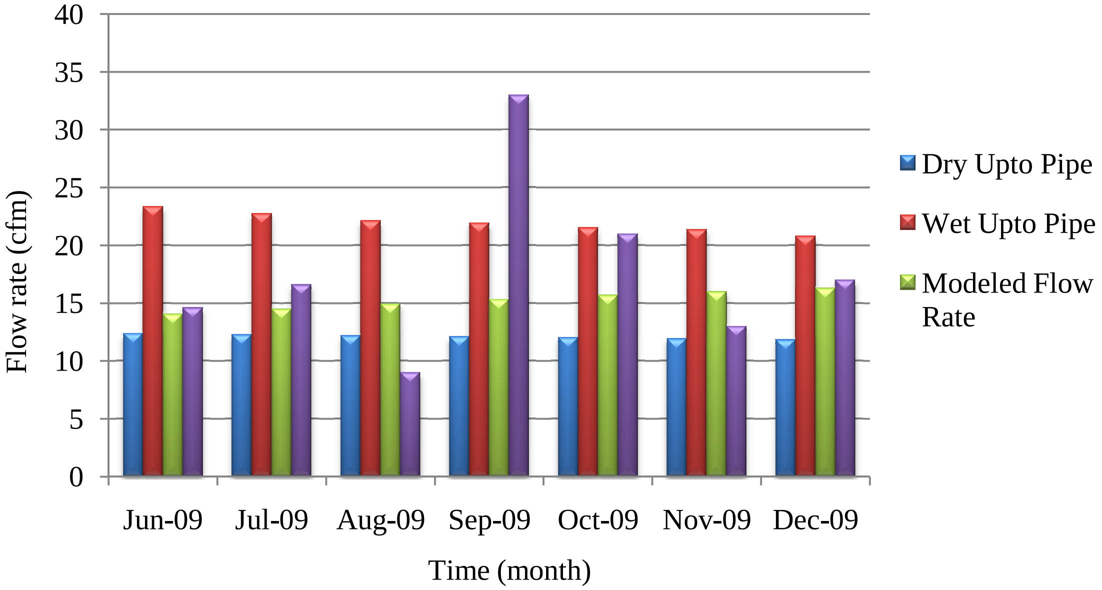


Figure 4.29: Comparison of gas flow rates for pipe H7

The trend of the modeled flow rate for pipe H7 also resembles with the trend for pipe H2. Leachate was first recirculated in pipe H7 in February 2010. Gas generation increased due to the presence of additional moisture inside the landfill. At the beginning the flow rate was low, but with the addition of leachate the flow rate increased significantly. There was no additional leachate injected from April 2009 to June 2009 into the pipe H7. As a result of that, the flow rate and percentage of methane dropped during June. Initially the flow rate was around 14 $ft^3$/min but, with the injection of additional leachate on July 2009 and August 2009, there was a rise in gas flow rate. Later, this pipe was kept resting from leachate recirculation and as a result, flow rate again dropped significantly. This pipe took good amount of leachate from the beginning of recirculation, but later, it refused to take high volume of leachate inside from August 2009. For this reason, this pipe has been kept resting for several months. The modeled flow rate and the field flow rate have been presented into Figure 4.30 for pipe H7 and the ratio has been presented in Figure 4.31.

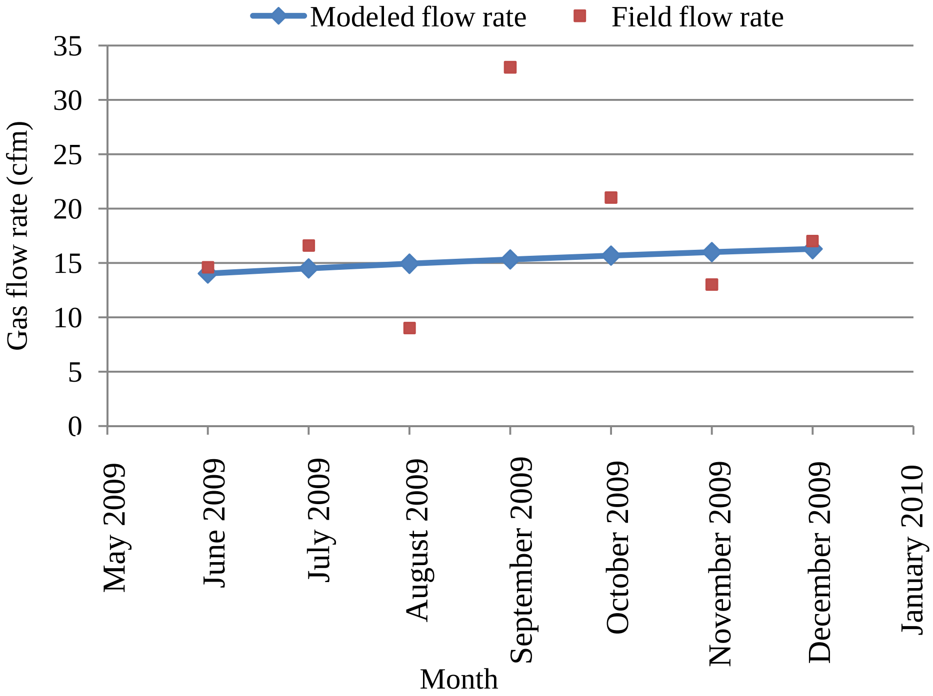


Figure 4.30: Comparison of modeled and field gas flow rates for pipe H7

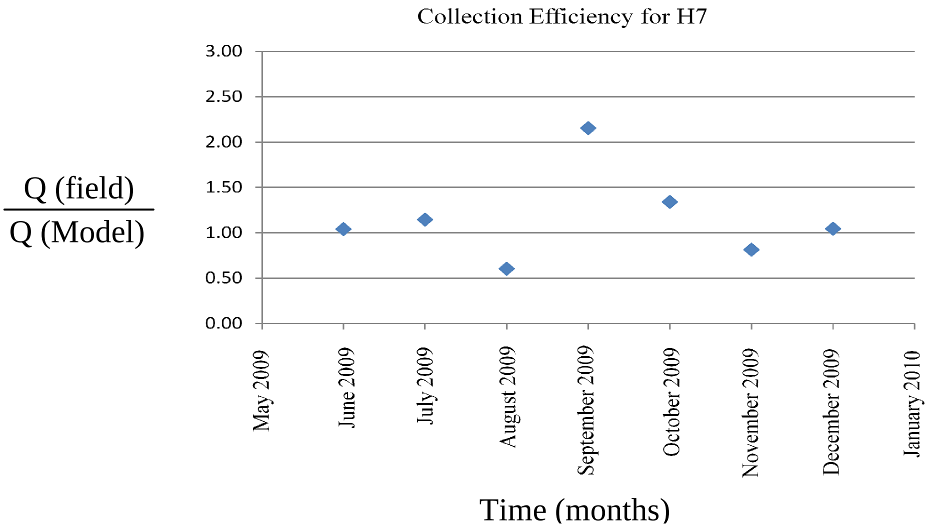


Figure 4.31: Comparison of field flow rate and predicted flow rate for pipe H7

c. Pipe H6: The field flow rate and the modeled flow rate for the non-recirculating pipe are compared presented in Figure 4.32.

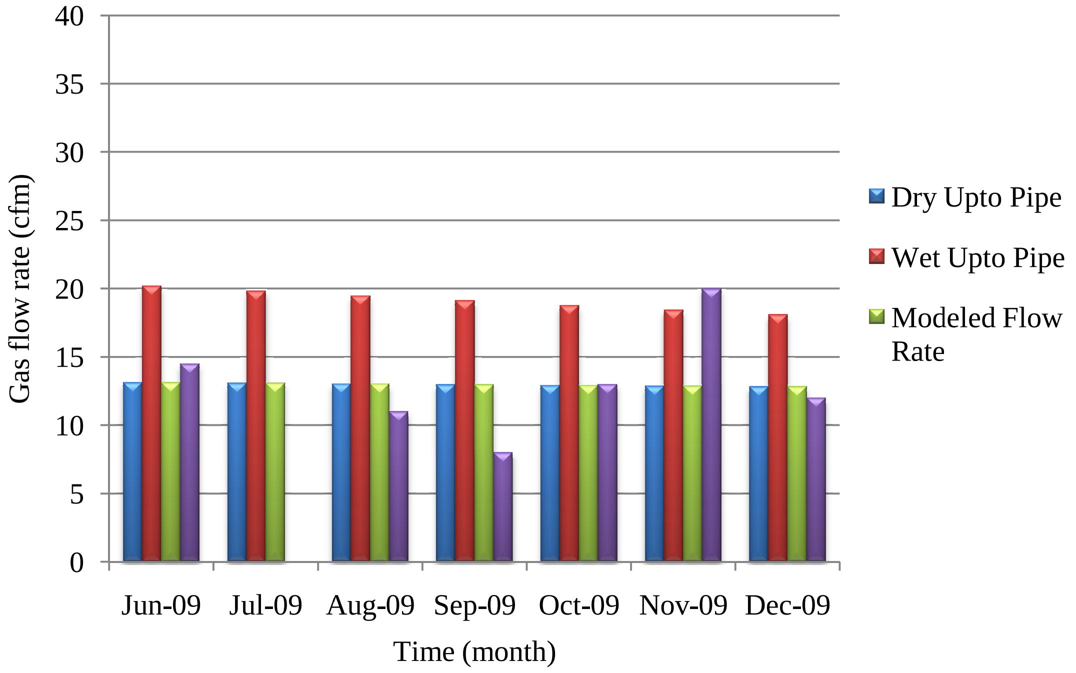


Figure 4.32: Comparison of gas flow rates for pipe H6

The field flow rate was considered with the average of the test results for every month during the study period. Leachate was never recirculated through this pipe. The elevation of pipe H6 is same as the elevation of pipe H7 and these two are just 10 feet apart from each other. During the initial stages, the field flow rate for pipe H6 was around 13 ft$^3$/min. As there was no additional moisture added into this pipe, the gas flow rate decreased eventually with respect to time, which is expected to happen for traditional landfilling operation. However, leachate was frequently recirculated through pipe H7, which is very close to pipe H6. From April 2009 to June 2009, there was no leachate recirculation carried out for pipe H7. So, the possibility of the lateral movement of leachate was almost zero. However, once leachate recirculation was started in July 2009, the change in field flow rate for pipe H6 is also quite clear. The field flow rate increased significantly for pipe H7 whereas leachate was recirculated in pipe H6. Later, during December 2009, once H6 was resting, the field flow rate again dropped down for pipe H7 as shown in Figure 4.33.

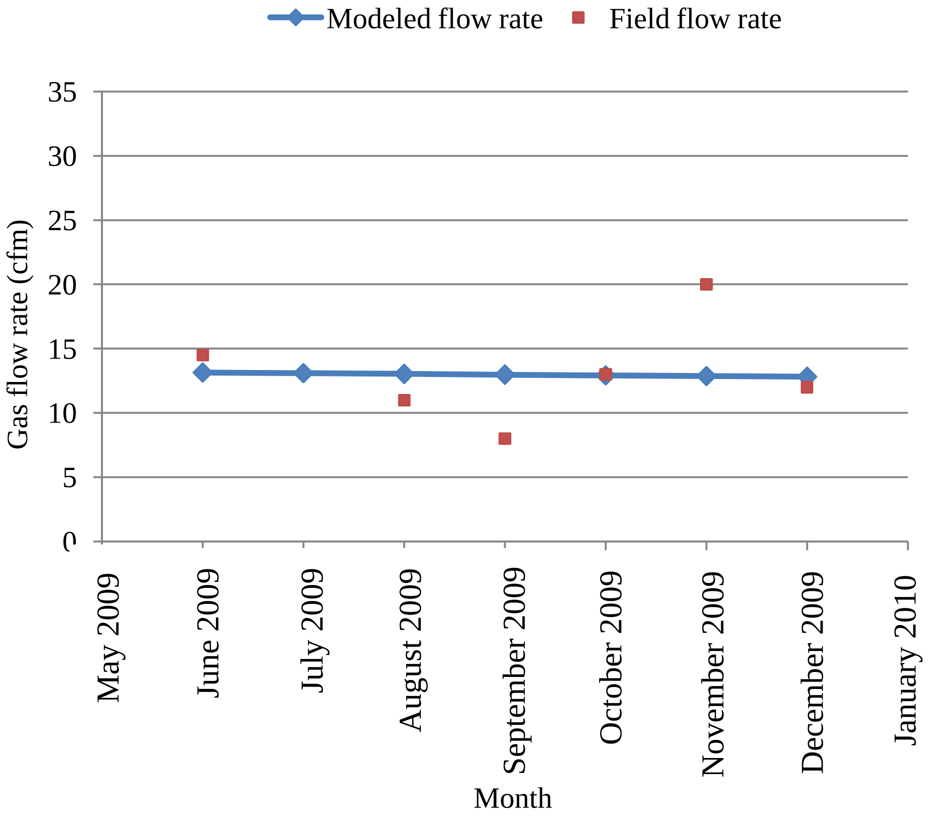


Figure 4.33: Comparison of modeled and field gas flow rates for pipe H6

The gas collection efficiency has been represented in the Figure 4.34 for pipe H6.

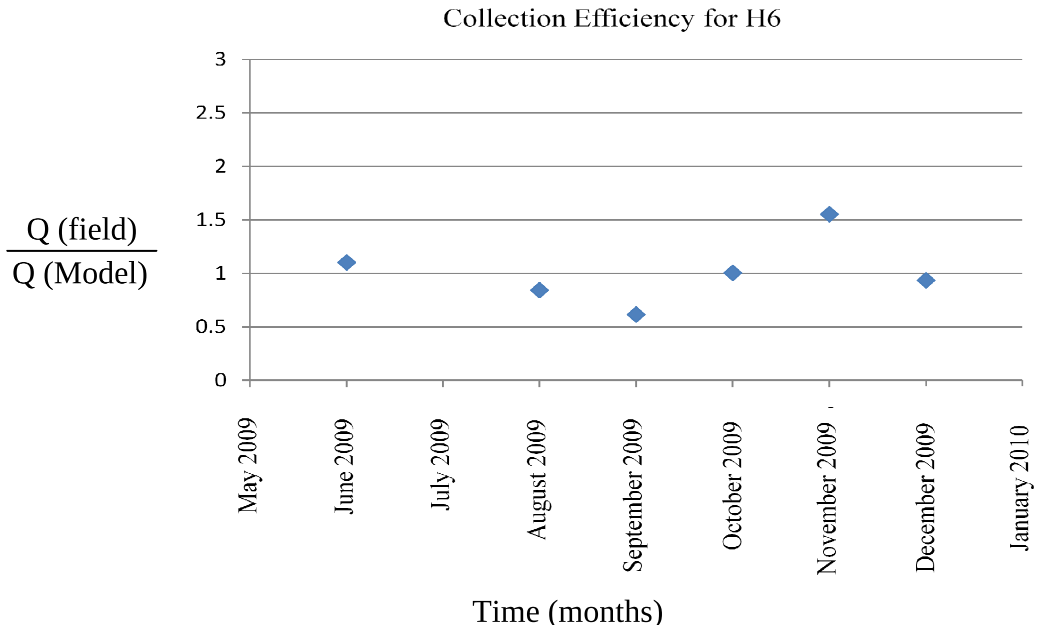


Figure 4.34: Comparison of field flow rate and predicted flow rate for pipe H6

The gas flow rate for the recirculating pipes H2 and H7 was very consistent throughout the study period. Initially the amount of the gas flow rate was lesser; however once recirculation took place, the gas generation rate started increasing significantly. With the progression of time, the moist area increased and the gas production also increased. The gas flow rate for pipe H7 was smaller than the pipe H2 because of the amount of solid waste present beneath the pipe. Pipe 7 was placed at a lower depth than pipe H2 and it covered almost half of the width of pipe H2. As a consequence, the flow rate from the pipe H2 was more than that of the pipe H7. The flow rate from the pipe H6 was less than the flow rate of pipe H7, although the amount of waste under the pipe H6 was more than the amount under pipe H7. The presence of the additional moisture inside pipe H7 results in higher gas production for this pipe.

# CHAPTER 5

# SUMMARY & CONCLUSIONS

## 5.1 Summary & Conclusions

Bioreactor landfills are operated to increase waste degradation, gas generation and waste stabilization. The main feature of bioreactor landfill operation processes is the injection of collected leachate back into the refuse mass to facilitate biodegradation. Due to the presence of moisture, the methane generation rate increases, with a higher gas generation yield over the period of time. The current study is a part of the performance evaluation project from City of Denton MSW landfill. Previously the effect of leachate recirculation has not been studied in a field scale landfill. RI tests have been effective in determining presence of moisture inside the landfill, and the results were evident from the test images. Using the geometry of the influence area from each individual pipe, landfill gas generation was modeled using the US EPA's 1st order gas generation equation with context for bioreactor landfills. The current research work compares the amount of gas generated (modeled flow rate) from landfill with the actual field gas generation rate (field flow rate). The results from the field tests and the modeled gas generation are summarized as follows:

- The quantity of gas generated from any individual pipe depends on the amount of waste beneath that specific pipe. The elevation of pipes H2, H7 and H6 are at 30 ft, 45 ft and 45 ft from the top of the landfill, respectively. The depth of MSW beneath the pipes H2, H7 and H6 were 43 ft, 28 ft and 28ft respectively. During the predicted gas generation, the MSW placed above the pipe was not considered because of the upward movement of methane which would not be collected by that individual pipe. The field gas flow rate data also converge with this consideration.
- The quantity of the waste for the gas production also depends on the total width covered by the individual pipe section. From the geometry, it was certain that the widths covered by pipe H2 and H6 were larger than the width covered by pipe H7. As a consequence, the average gas flow rate was higher for pipes H2 compared to H7.
- The leachate recirculation also played a significant role in the gas production rate for pipes H2 and H7. The average gas flow rates obtained from these pipes were near to 13-15 cfm, whereas for the non-recirculating pipe H6, the flow rate was close to 10 cfm.
- The leachate was pumped through the perforated pipes where the perforations started from 100 ft away from the both ends of the pipe to avoid leachate from coming out of the landfill. For convenience, the entire pipe was considered to be perforated, which may provide slightly over designed gas generation rate.

- The RI test section provided images of possible leachate flow path and moisture accumulation for before and after leachate recirculation. The leachate flow path and the accumulated moisture were considered to be uniform over the entire length of the pipe, which may not be the actual case. So, the predicted gas flow rate may not entirely reflect the actual field condition.
- From the predicted gas generation rate, the movement of the gas flow rate with time plot is remarkable. The gas flow rate after the leachate recirculation increases exponentially with time. With the intrusion of moisture, the amount of wet MSW increases, which leads to higher gas generation compared to the non-recirculation condition.
- The gas composition rate with respect to time is also very interesting. The gas composition line clearly denotes the effect of leachate recirculation, with the increase of percentage of methane content after leachate recirculation. The percentage of methane content decreased once the additional leachate percolates through the waste and the waste again become dry due to the endogenous bio-reactions.
- The results obtained from this study can be readily used by the City of Denton MSW landfill authority for the future (new) cells where the spacing, elevation and location of the pipes can be modified to accomplish a more efficient gas collection system.
- The accuracy and reliability of this study are limited to the data collected from the City of Denton MSW landfill authority and DTE Energy.

## 5.2 Future Works Recommendations

Leachate recirculation into the landfill is an up-to-date approach for MSW landfills to enhance biodegradation which leads to higher gas generation rates. The effects of leachate recirculation have been previously studied; however, the influence of leachate recirculation and the distribution of the moisture was missing. Following are the key approaches recommended for the further studies on bioreactor landfills:

- Recirculation pipes are placed within the MSW. The effect of placing recirculation pipes on permeable beds like shredded tire chips of crushed glass need to be studied. The moisture distribution by the aid of permeable bed should be more uniform around the pipes, which can transmit leachate into solid waste more uniformly and increase gas generation rate.
- The City of Denton is using horizontal recirculation systems for leachate recirculation systems. However, the efficiency of vertical recirculation system and their influence on gas production needs to be studied in future.

## REFERENCES

Batool, S. A., & Chuadhry, M. N. (2009). The impact of municipal solid waste treatment methods on greenhouse gas emissions in lahore, pakistan. *Waste Management, 29*(1), 63-69.

Bilgili, M. S., Demir, A., & Ozkaya, B. (2007). Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. *Journal of Hazardous Materials 143*, 177–183.

Calabrò, P. S. (2009). Greenhouse gases emission from municipal waste management: The role of separate collection. *Waste Management, 29*(7), 2178-2187.

Chan, G. Y. S., Chu, L. M., & Wong, M. H. (2002). Effects of leachate recirculation on biogas production from landfill co-disposal of municipal solid waste, sewage sludge and marine sediment. *Environmental Pollution, 118*(3), 393-399.

Dixon, N., & Jones, D. R. V. (2005). Engineering properties of municipal solid waste. *Geotextiles and Geomembranes, 23*(3), 205-233.

Faour, A. A., Reinhart, D. R., & You, H. (2007). First-order kinetic gas generation model parameters for wet landfills. *Waste Management, 27*(7), 946-953.

Filipkowska, U., & Agopsowics, M. H. (2004). Solid waste gas recovery under different water conditions. *Polish Journal of Environmental Studies, 13*(6), 663-669.

Gabr, M. A., Hossain, M. S., & Barlaz, M. A. (2007). Shear strength parameters of municipal solid waste with leachate recirculation. *Journal of Geotechnical and Geoenvironemental Engineering, 133*(4), 478-484.

García de Cortázar, A. L., & Tejero Monzón, I. (2007). Application of simulation models to the diagnosis of MSW landfills: An example. *Waste Management, 27*(5), 691-703.

Gawande, N. A., Reinhart, D. R., Thomas, P. A., McCreanor, P. T., & Townsend, T. G. (2003). Municipal solid waste in situ moisture content measurement using an electrical resistance sensor. *Waste Management, 23*(7), 667-674.

Haydar, M. M., & Khire, M. V. (2007). Leachate recirculation using permeable blankets in engineered landfills. *Journal of Geotechnical & Geoenvironmental Engineering, 133*(4), 360-371.

He, R., Shen, D., Wang, J., He, Y., & Zhu, Y. (2005). Biological degradation of MSW in a methanogenic reactor using treated leachate recirculation. *Process Biochemistry, 40*(12), 3660-3666.

Haque, M. A. (2007). Dynamic characteristics and stability analysis of municipal solid waste in bioreactor landfills, Ph. D Thesis, UT Arlington, Arlington, TX

Hossain, M. S., & Haque, M. A. (2009). The effects of daily cover soils on shear strength of municipal solid waste in bioreactor landfills. *Waste Management, 29*(5), 1568-1576.

Khire, M. V., & Haydar, M. M. (2007). Leachate recirculation in bioreactor landfills using geocomposite drainage material. *Journal of Geotechnical & Geoenvironmental Engineering, 133*(2), 166-174.

Khire, M. V., & Mukherjee, M. (2007). Leachate injection using vertical wells in bioreactor landfills. *Waste Management, 27*, 1233-1247.

Kumar, S., Gaikwad, S. A., Shekdar, A. V., Kshirsagar, P. S., & Singh, R. N. (2004). Estimation method for national methane emission from solid waste landfills. *Atmospheric Environment, 38*(21), 3481-3487.

Lou, X. F., & Nair, J. (2009). The impact of landfilling and composting on greenhouse gas emissions – A review. *Bioresource Technology, 100*(16), 3792-3798. doi:DOI: 10.1016/j.biortech.2008.12.006

Mehta, R., Barlaz, M. A., Yazdani, R., Augenstein, D., Bryars, M., & Sinderson, L. (2002). Refuse decomposition in the presence and absence of leachate recirculation. *Journal of Environmental Engineering, 128*(3), 228-236.

Miller, D. E., & Emge, S. M. (1997). Enhancing landfill leachate recirculation system performance. *Practice Periodical of Hazardous, Toxic and Radioactive Waste Management, 1*(3), 113-119.

Mor, S., Ravindra, K., De Visscher, A., Dahiya, R. P., & Chandra, A. (2006). Municipal solid waste characterization and its assessment for potential methane generation: A case study. *Science of the Total Environment, 371*(1-3), 1-10. doi:DOI: 10.1016/j.scitotenv.2006.04.014

Morris, J. W. F., Vasuki, N. C., Baker, J. A., & Pendleton, C. H. (2003). Findings from long-term monitoring studies at MSW landfill facilities with leachate recirculation. *Waste Management, 23*(7), 653-666.

Reddy, K. R., Hettiarachchi, H., Parakalla, N. S., Gangathulasi, J., & Bogner, J. E. (2009). Geotechnical properties of fresh municipal solid waste at orchard hills landfill, USA. *Waste Management, 29*(2), 952-959.

Talyan, V., Dahiya, R. P., Anand, S., & Sreekrishnan, T. R. (2007). Quantification of methane emission from municipal solid waste disposal in delhi. *Resources, Conservation and Recycling, 50*(3), 240-259.

Themelis, N. J., & Ulloa, P. A. (2007). Methane generation in landfills. *Renewable Energy, 32*(7), 1243-1257.

Tsai, W. T. (2007). Bioenergy from landfill gas (LFG) in taiwan. *Renewable and Sustainable Energy Reviews, 11*(2), 331-344.

Yedla, S., & Parikh, J. K. (2002). Development of a purpose built landfill system for the control of methane emissions from municipal solid waste. *Waste Management, 22*(5), 501-506.

Zekkos, D., Bray, J. D., Kavazanjian, E, Matasovic, N, Rathje, E. M., Fiemer, M. F., & Stoke, K. H. (2006). Unit weight of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering, 132*(10), 1250-1261.

Zhang, H., He, P., & Shao, L. (2008). Methane emissions from MSW landfill with sandy soil covers under leachate recirculation and subsurface irrigation. *Atmospheric Environment, 42*(22), 5579-5588.

# BIOGRAPHICAL INFORMATION

Shahed R Manzur was born in Dhaka, Bangladesh, on December 17, 1984. He completed his under-graduate degree (B. Sc. Civil Engineering) at the Bangladesh University of Enginering & Technology, BUET, Dhaka, in July 2007. Thereafter, for six months he worked in Pran Limited Construction Engineers., Dhaka, Bangladesh, as a Junior Design Engineer.

Shahed was admitted to the Master of Science program in Civil Engineering (MSCE) in August 2008 at the University of Texas at Arlington. During the period of study, he was appointed as a graduate research assistant with Dr. Md. Sahadat Hossain. During his study period, he was actively working on the performance monitoring of leachate recirculation systems in an Enhanced Leachate Recircualtion (ELR) landfill, funded by City of Denton, TX. His research interests focus into landfill design, gas production and collection systems for bioreactor landfills, foundations in expansive soils and slope stability analysis for expansive soils.