THE ESTIMATION OF LANDFILL GAS EMISSIONS IN THE DURBAN METROPOLITAN AREA (DMA) USING THE LANDGEM MODEL

By

LERATO E. LIPHOTO

Submitted in partial fulfilment for the degree of Master of Science (Environmental Sciences) in the School of Life and Environmental Sciences

UNIVERSITY OF NATAL – DURBAN

DECEMBER 2001

PREFACE

This work was carried out in the School of Life and Environmental Sciences, University of Natal, Durban, during the period March 2000 to December 2001, under the supervision of Professor R D Diab.

This study represents original work by the author and has not been submitted in any form for any degree to any University. Where use has been made of the work of other authors, it has been duly acknowledged in the text.

Lerato E. Liphoto (BSc, BSc-Hons)

ACKNOWLEDGEMENTS

I wish to thank all people and companies who made this study possible and successful. In particular, I would like to forward my gratitude to the following individuals:

Professor R D Diab, for the dedication and patience in supervising this valuable work. It was not an easy way, without her incredible experience this study would not be possible.

Dr. Christina Trois, at School of Civil Engineering, Surveying and Construction, for kindly providing most literature materials on landfill gas and waste management.

Lindsay Strachan, at Bisasar Road Landfill, Durban Solid Waste, Springfield, for supplying data and information about Metro Landfills. Without this data, this study would not be possible.

Lombard & Associates – Environment Protection and Waste Management Consultants, for providing background information on DMA (Durban Metropolitan Area) landfill sites.

Bob Couth, at EnvirosAspinwall Company, UK, for sending me some LFG published papers, which are unavailable in the country. I highly appreciate his kindness.

Frank Sokolic, at School of Life & Environmental Sciences, for his invaluable computer expertise to help in the construction of most diagrams used in this study.

All members of my Family who gave me a support in my studies. And all special friends who gave an emotional support during hard times in the course of these studies.

Above all, the Almighty, who gave me strength, hope and patience to pursue this work. Without Him, nothing is possible.

ABSTRACT

Landfill gas (LFG) contributes significantly to air pollution. Methane (CH_4) and carbon dioxide (CO_2) are the major constituents of LFG, and are significant greenhouse gases that play a vital role in causing global warming. Certain air pollutants from landfill sites are carcinogenic (e.g. benzene), while others are odorous (e.g. methyl mercaptan). Due to these potential negative impacts, there is need to forecast the yield and production rate of biogas generated.

Limited work has been done on the modelling of LFG emissions for landfill sites in Durban. This study focuses on the estimation of air pollutant emissions from three landfill sites, namely Bisasar Road, Shongweni and Buffelsdraai using the LANDGEM model and comparing the results against the findings of Hofstetter Gas Yield Model which has been utilized before by Durban Solid Waste (DSW) for Bisasar Road landfill.

The greenhouse gases of global concern, namely CH_4, CO_2 and halocarbons were investigated in this study. The LANDGEM model predicted CO_2 emissions to be higher than CH_4 and other greenhouse gases. The warm, moist climatic conditions suitable for CH_4 oxidation may be responsible for the increased generation rates of CO_2.

The main components of LFG which cause landfill odour problems are sulphur-containing compounds. Methyl mercaptan is the component causing persistent bad odours in the landfills, contrary to popular belief that hydrogen sulphide is the major contributor to odour pollution. Hydrogen sulphide has been predicted by LANDGEM to be the sulphur-containing gas that is produced in greatest quantities. Benzene and vinyl chloride are the most hazardous compounds emitted from landfills, since they are carcinogenic. The emission rates of benzene were found to be higher than those of vinyl chloride in the active landfill sites of Bisasar Road and Shongweni.

The LANDGEM model estimated total LFG emissions of 8.371×10^7 m^3y^{-1} at Bisasar Road landfill, compared with a lower emission rate of 3.285×10^7 m^3y^{-1} predicted by the

Hofstetter model. The LANDGEM model revealed LFG to peak during the closure of the landfill, and to decline thereafter for a long period of time. The Hofstetter model showed that LFG could reach its maximum within three years of waste deposition.

LANDGEM model is a widely used methodology for estimating LFG emissions. It is used in United States as regulatory model to quantify the potential LFG emissions produced from the landfill. This model can be used by landfill owners and operators to evaluate the performance of the landfill and to determine whether the landfill is still subject to regulatory requirements, especially in the countries where emission guidelines have been established. Therefore, in the developing country like South Africa, it is essential to quantify and evaluate the LFG emissions released from landfills despite the fact that no legal LFG emission guidelines are put in place yet.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

LIST OF PLATES

ABBREVIATIONS AND GLOSSARY OF TERMS

Abbreviations/Acronyms

AP-42 - Air Pollutant Emission Factors
BOD - Biochemical Oxygen Demand
C - Carbon
C_6H_6 - Benzene
CAA - Clean Air Act
CCl_2F_2 - Dichlorodifluoromethane
CCl_3F - Fluorotrichloromethane
CFC - Chlorinated fluorocarbons
CH_2CHCl - Vinyl chloride
CH_3CH_2S - Ethyl mercaptan
CH_3S - Methyl mercaptan
CH_4 - Methane
CO - Carbon dioxide
CO_2 - Carbon dioxide
COD - Chemical Oxygen Demand
DMA - Durban Metropolitan Area
DMC - Durban Metropolitan Council
DoE - Department of Environment
DSW - Durban Solid Waste
DWAF - Department of Water Affairs and Forestry
EEC - European Economic Community
GCL - Geosynthetic Clay Liner
GHG - Greenhouse Gas
H_2 - Hydrogen
H_2CO_3 - Carbonic acid
H_2O - Water/Water Vapour
H_2S - Hydrogen sulphide

HAP	- Hazardous Air Pollutants
HCl	- Hydrogen chloride
HDPE	- High Density Polyethylene
IC	- Internal Combustion
IPCC	- Intergovernmental Panel on Climate Change
IWM	- Institution of Waste Management
k	- Methane Generation Rate
L_0	- Potential Methane Generation Capacity
LANDGEM	- Landfill Gas Emission Model
LFG	- Landfill Gas
LFGTE	- Landfill Gas-To-Energy
MSW	- Municipal Solid Waste
N_2	- Nitrogen
NA	- Natural Attenuation
NH_3	- Ammonia
NH_4^+	- Ammonium ion
NMOC	- Non-Methane Organic Compounds
NSPS	- New Source Performance Standards
O_2	- Oxygen
OECD	- Organisation of Economic Cooperation and Development
PVC	- Polyvinyl Chlorinated Compounds
REH	- Rachel's Environment and Health
SWDS	- Solid Waste Disposal Sites
TLC	- Tradition Local Council
US EPA	- United States Environmental Protection Agency
VCC	- Volatile Chlorinated Hydrocarbons
VFA	- Volatile Fatty Acids
VOC	- Volatile Organic Compounds
WMP	- Waste Management Paper

Glossary of Terms

The definitions of terms used in this study:

Closure Year: The year in which the landfill stops, or is expected to stop, accepting waste.

Codisposal: Disposal of hazardous waste as well as other kinds of waste in a landfill.

Hazardous Air Pollutants (HAPs): Compounds found in landfill gas or emitted with landfill gas. A total of 47 HAPs in landfill gas are included in the model.

Landfill Capacity: The total amount of waste that can be disposed of in the landfill.

Landfill Gas: Landfill gas is product of biodegradation of waste in landfills and consists mainly of methane and carbon dioxide, with trace amounts of NMOCs, and other air pollutants.

Methane Generation Rate Constant (k): k is a constant that determines the rate of landfill gas generation. It is a function of moisture content in the landfilled waste, availability of nutrients for methanogenesis, temperature, and pH.

Nonmethane Organic Compounds (NMOCs): NMOCs are specified in this model as fraction of landfill gas containing nonmethane organic compounds. These include air pollutants and volatile organic compounds (VOCs).

Potential Methane Generation Capacity (L_0): L_0 is a constant that represents the landfill potential to generate methane, which is a primary constituent of landfill gas. L_0 depends on the amount of cellulose (carbon) in the waste body.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Most of the waste generated in South Africa is disposed of in engineered waste disposal sites known as landfill sites. This deposition of refuse in the earth is usually referred to as 'landfilling'. It is estimated that over 95% of waste generated in South Africa is deposited in landfills (DWAF, 1998a), the main reason being that landfilling is the most cost-effective method of waste disposal.

Once the solid waste is buried in the landfill, it undergoes decomposition (decaying), which is characterized by complex physical, chemical and biological processes (Ham, 1988). This biodegradation of waste leads to the release of contaminated water called leachate and polluted gas known as landfill gas (LFG). The focus of this study will be on LFG, which is one of the output streams of a landfill. LFG comprises predominantly CH_4 and CO_2, and includes large numbers of trace components. It contains approximately 60-65 % CH_4 and 35-40 % CO_2 (DoE, 1991; Young and Parker, 1983).

The release of gas to the atmosphere is influenced by characteristics of the local environment, which include temperature, pH, moisture content, waste type, soil type, permeability, and thickness of the soil cover. The influence of these factors is discussed in detail in this study.

It has been widely reported that air pollution from landfills can cause significant problems (REH, 1991; Campbell, 1996; Kerfoot, 1996; Neumann and Christensen, 1996). The uncontrolled release of the gaseous products of waste decomposition into the atmosphere contributes to global warming (Vieitez and Ghosh, 1999). Both CH_4 and CO_2 are greenhouse gases (Park and Shin, 2001), with CH_4 being 25-30 times more reactive than CO_2 in the atmosphere (Gardner *et al.*, 1993; Vieitez and Ghosh, 1999). CH_4 is estimated to contribute about 18 % towards global warming (Vieitez and Ghosh, 1999). Worldwide, CH_4 emissions are estimated to range from 20 to 70 Tg y^{-1} (Gardner *et al.*, 1993; Coops *et al.*, 1995; Boeckx *et al.*, 1996). It is estimated that 40 – 60 million tons of CH_4 are generated in landfills and old dumps on global scale (Humer and Lechner, 1999). These emissions are caused by insufficient LFG active recovery systems and uncontrolled emissions from old dumps, making landfills one of the most important global sources of the greenhouse gas CH_4.

Besides the contribution to global warming and climate change, LFG also causes many other environmental problems. The effects of LFG on plants are associated with the migration of gas into the root zone where it displaces oxygen (Neumann and Christensen, 1996). This is caused by CH_4 oxidation to CO_2 by microbial action which leads to increased CO_2 concentrations, and hence depletion of oxygen. These conditions severely inhibit the plant growth. CH_4 can also be produced in reduced aquifers such as leachate plumes, and the use of water from such sources requires aeration to remove the CH_4 gas (Kerfoot, 1996). CO_2 released from the degradation of waste can increase the corrosivity of groundwater as a result of carbonic acid formation when CO_2 is dissolved in water (Kerfoot, 1996).

Many components of LFG are considered dangerous to human health. Emissions of LFG with a high CH_4 content can be a source of risks for fire and explosions (Campbell, 1996; Borjesson, 2000). The subsurface lateral migration of gas beyond site boundaries can adversely impact on residents adjacent to a landfill. The trace gases in LFG, which form less than 1% of LFG, can cause odour nuisance and other health problems. Substances that pose the greatest concern are some mercaptans, benzene and vinyl chloride (Massacci, 1996). Mercaptans are usually associated with a bad egg odour at landfill sites (Young and Parker, 1983). Based on toxicity data, benzene and vinyl chloride represent the greatest threat of volatile organic compounds (VOCs) generated from landfills because both are known carcinogens (Kerfoot, 1996).

The evaluation of emission rates of landfill air emissions is a difficult problem. The estimation of LFG emissions can be determined by two common approaches (Cenuschi and Giugliano, 1996). The first is the calculation of the emissions based on the measurement of ambient pollutant concentration in the surroundings. The second option is the use of theoretical or empirical models of gas generation processes in the landfill.

Awareness of LFG problems is increasing in South Africa and has influenced Department of Water Affairs and Forestry (DWAF) to issue permits to operate landfill sites in terms of the Environment Conservation Act (Act of 73 of 1989). This act contains clauses that obligate the landfill operator to monitor and control LFG (Lombard *et al.*, 1998). Some studies have been done before in South Africa in an attempt to understand the aspects of LFG emissions. Morris *et al.* (1999) used stainless steel static accumulation chambers to measure LFG emissions from semi-arid landfills in Johannesburg. This was done to assist in identifying the degree to which degradation was proceeding and to assess the potential for establishing landfill gas-to-energy (LFGTE) projects at selected landfills. Lombard *et al.* (1998) utilized the Hofstetter Gas Yield Model to predict the production of LFG from Bisasar Road landfill in Durban. Therefore, based on LFG problems mentioned so far and limited studies done with respect LFG emissions, it was found necessary to conduct this study in Durban Metropolitan Area.

1.2 AIM OF THE STUDY

In the light of the increasing concern about landfill gas emissions, their potential effects on health, and the paucity of data available, there is a need to be able to evaluate the LFG generation rates and emissions released from landfill sites. The best and most widespread method of evaluating LFG generation and emissions is by theoretical models. The LFG emissions from the landfills are taken as the landfill gas generation rates at the landfills. The aim of this study is to estimate the LFG generation and air pollutant emissions from three landfill sites in the DMA using a Landfill Gas Emission Model (LANDGEM).

The specific objectives of this research are as follows:

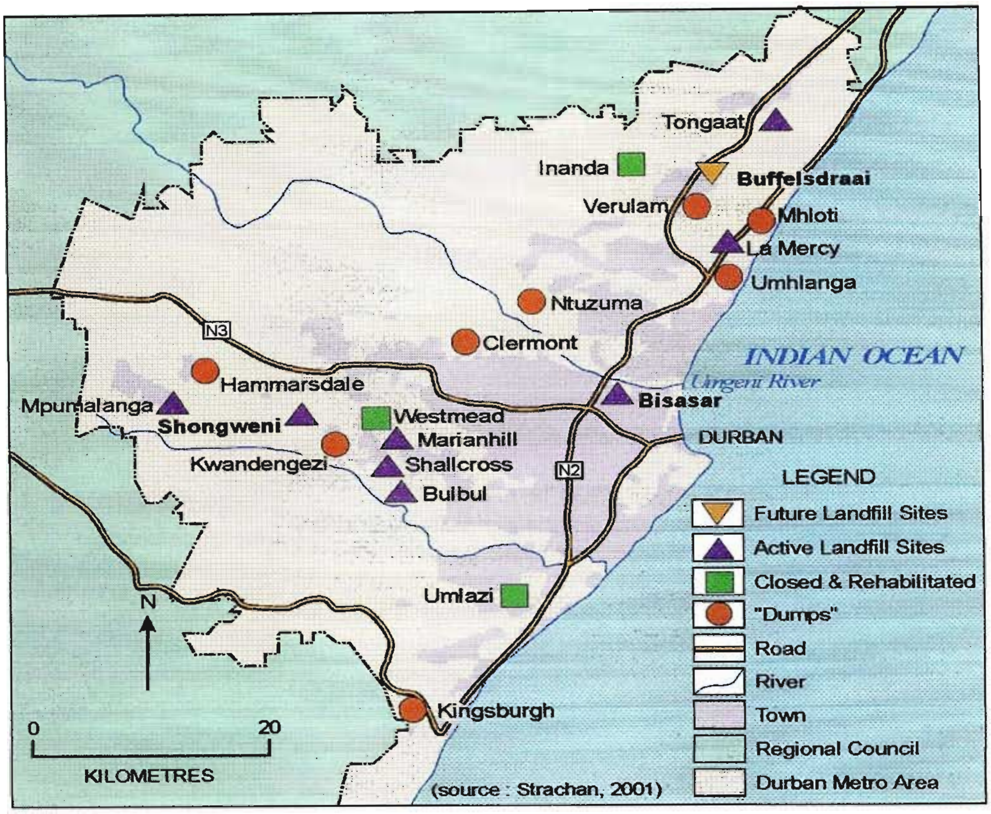
- To review the nature of pollutants emitted from a landfill
- To critically review the LANDGEM model and its applicability
- To determine LFG emissions from 3 selected landfill sites in the DMA using the LANDGEM model.
- To compare the results of the LANDGEM model with the methods currently utilized by Durban Solid Waste (DSW) to estimate LFG emissions.
- To undertake a sensitivity analysis of the LANDGEM model.

1.3 BACKGROUNDS AND LOCATION OF STUDY AREAS

The estimation of LFG emissions will be determined from three landfill sites located within the DMA. All closed, active and future landfill sites in the DMA are clearly shown in Figure 1.1. In this study two active landfill sites (Bisasar Road and Shongweni) and one proposed landfill (Buffelsdraai) have been selected for investigation. They are discussed in detail below.

1.3.1 Bisasar Road landfill

The Bisasar Road landfill was established in May 1980 prior to the establishment of the Minimum Requirements guidelines for landfills, and as such the base of the valley is not lined. The site is currently managed and operated by Durban Solid Waste (DSW). It is situated in Springfield, south of the Umgeni River in Durban. The landfill is bounded to the north by the flood plain of the Umgeni River on which are sited Clare Estate School, Clare Hills High School, and the Electricity, Solid Waste and Health Departments of the City of Durban (see Plate 1.1). To the east, south and west, the site is bounded by residential areas (Loudon and Partners, 1994; Lombard & Associates, 1994).



(source : Strachan, 2001)

Figure 1.1 Map showing closed, active and future DMA landfill sites.

In terms of the Minimum Requirements for Waste Disposal by Landfill (see Section 2.3.2), Bisasar Road is a class G:L:B+ landfill, which means the site is a large landfill that accepts general waste and has a potential to generate leachate. The site receives about 3000 tonnes of waste per day. The landfill design capacity of the landfill is approximately 21 x 10^6 m^3, and a volume of 10 x 10^6 m^3 has been filled (Strachan, 2001, pers.com). It is estimated that the site can continue to operate for another 12 years if no waste transfer station is commissioned (Strachan, 2000, pers.com). The duration of the landfill operation can be increased to 15 years if a transfer station is put in place.

Plate 1.1 Aerial views of Bisasar Road Landfill and adjacent land-use (Source: Strachan, 2001).

Bisasar Road has an active LFG management system to control LFG emissions from the site. Vertical wells have been retrospectively drilled into the waste. These wells are connected by suction pipework to a Hofstetter LFG extraction plant, which includes a 2,500 Nm^3/hr flare. LFG is extracted as it is generated, to control emissions to ground and to air. The LFG management system is being progressively developed with the landfill. Consequently, the LFG emissions quoted in this study from Bisasar Road landfill are controlled.

1.3.2 Shongweni landfill

The Shongweni landfill site is located in the Shongweni area, about 40 km west of Durban. The site was upgraded to a class H:h in August 1997, and is therefore permitted to receive low and moderate hazardous wastes (Lombard & Associates, 1997). It is one of only two landfills that accept hazardous waste in KwaZulu-Natal. Cells 1-3 of this landfill were commissioned in September 1997, following closure of Cell 0. The site is financed and operated by EnviroServ Holdings Limited, which is a private contracting organisation. The site is bounded to the north, east and south by sugar plantations and to the west by distinct roads P461 and P559. The airspace (total volume) of the site is approximately 1.6 x 10^6 m^3, with a volume of 337 015 m^3 occupied thus far (Kidd, 2000, pers.com). The landfill accepts about 9000 tonnes of waste per month. It is estimated that this site can operate for approximately 11 years based on the current rate of waste deposition (Kidd, 2000, pers.com).

1.3.3 Buffelsdraai landfill

The Durban Metropolitan Council (DMC), which is responsible for waste disposal in the DMA, has selected the Buffelsdraai site in the northern zone of the DMA for landfill development. The site is located about 6 km west of Verulam (Drennan *et al.*, 2000a), and occupies part of the farms Buffelsdraai 820 and Roodekran 828 (Plate 1.2) (Drennan, *et al.*, 2000b).

It is intended that the waste stream at this site will comprise domestic, commercial and certain types of industrial waste. The proposed site will initially receive waste at the rate of 400 tonnes/day, which is slightly more than the current refuse acceptance rate at La Mercy landfill (330 tonnes/day). It is expected that this volume will increase shortly after the new Bisasar Road Transfer Station is commissioned to 991 tonnes/day.(Drennan *et al.*, 2000c).

The site is classified as G:L:B+, since the anticipated daily deposition rate exceeds 500 tonnes/day. The total airspace of the landfill is estimated to range within 38 – 40 x 10^6 m^3 (Drennan, *et al.*, 2000a; 2000c) based on the preliminary design stated in the Minimum Requirements (Table 1.1). The site life span is projected to be more than 70 years.

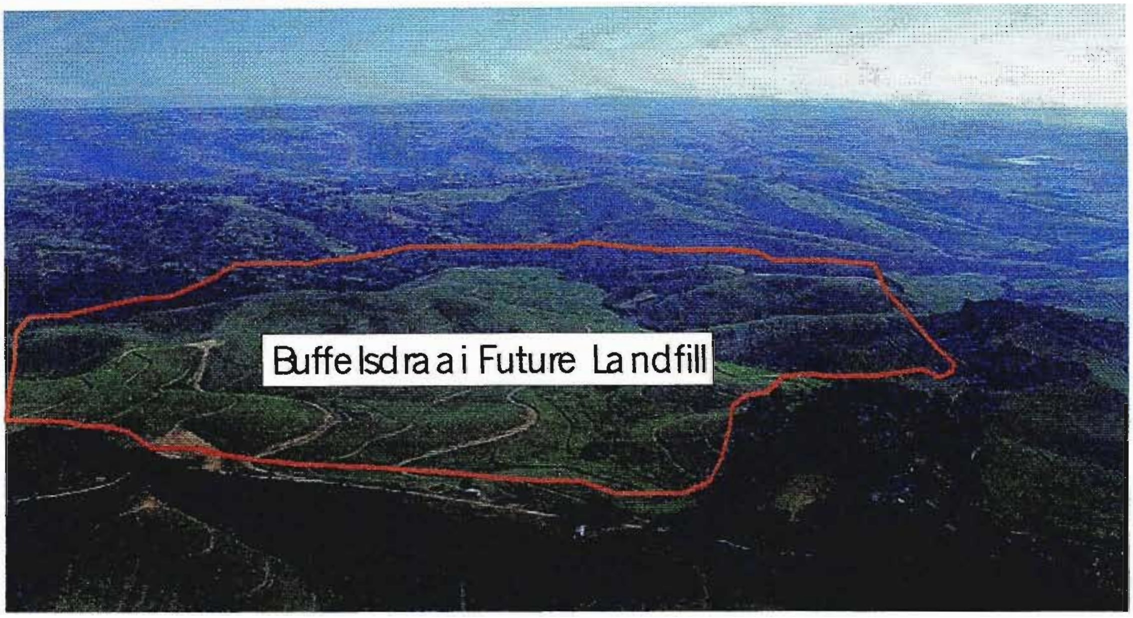


Plate 1.2 Aerial view of the proposed Buffelsdraai landfill site (Source: Strachan, 2001).

Table 1.1 The estimated capacity and life of Buffelsdraai landfill (Drennan, *et al.*, 2000c)

Cell No.	**Capacity (x 10^6 m^3)**	**Anticipated Life (Years)**
1	2855	7
2	1045	5
3	1600	3
4	7 700	17
5	10 776	20
6	5 840	8
7	8 484	12
TOTAL	**38 300**	**72**

The proposed site will be one of the large regional sites serving the DMA, in accordance with DMC policy to close down small landfills and develop regional sites. Initially this site will serve the northern part of DMA, yet after the closure of the existing Bisasar Road landfill will serve a far larger area. This site is anticipated to commence operating in 2003 (Strachan, 2001, pers.com).

CHAPTER 2

WASTE BIODEGRADATION AND LFG GENERATION

2.1 WASTE DEFINITION AND CLASSIFICATION

Waste is defined in EEC (European Economic Community) waste management and environmental protection legislation as unwanted discards (Lombard, 1992). The South African Minimum Requirements document (DWAF, 1998a) defines waste as an undesirable or superfluous by-product, emission, or residue of any process or activity, which has been discarded, accumulated or stored for the purpose of discarding or processing. It may be gaseous, liquid or solid or any combination thereof, which may originate from residential, commercial or industrial sources.

The classification of waste is a complex subject and there are many different classification systems in use internationally. For the purpose of this study only municipal solid waste (MSW) is discussed. Nuclear wastes, mining wastes, radioactive substances, power generation wastes and others, are not included as they are not of interest with respect to municipal solid waste (MSW) landfilling. Municipal solid wastes typically include household waste and bulky consumer wastes, as well as similar wastes from small commercial and industrial firms, institutions and markets, which are collected and disposed of by, or for local authorities (Novella *et al.*, 1999). There are, however, considerable variations in the exact definition of municipal waste between countries.

In general, waste can be classified based on its properties or characteristics. There are three basic groups of waste (Lombard, 1992):

(i) Inert Wastes

These wastes are not considered to be intrinsically harmful and pose no threat to humans and environment. Examples include builders' rubble and soil.

(ii) General Waste

General wastes comprise what is usually termed municipal solid waste. These wastes do not pose a significant threat to public health or the environment if properly managed (DWAF, 1998a). They may exert a negative impact on the environment when the products of their breakdown, including leachate and landfill gas, are allowed to pollute the environment. Other wastes such as commercial, garden and certain industrial wastes with similar properties to domestic refuse can also adversely impact the environment (Lombard, 1992).

(iii) Special Wastes (Hazardous wastes)

These wastes are defined in the EEC as a group of wastes, which because of their quantity, concentration, physical, chemical or infectious characteristics may cause ill health, increased mortality or adversely affect the environment or pose an immediate threat when improperly treated, stored, transported or disposed of. They exhibit the characteristics of toxicity, corrosivity, inflammability and carcinogenicity (Lombard, 1992). The following types of hazardous waste are mentioned in the Minimum Requirements (DWAF, 1998b): inorganic waste; oily waste; organic wastes; putrescible organic waste, low/high volume hazardous wastes, which contain small quantities of dispersed hazardous substances.

2.2 WASTE DISPOSAL BY LANDFILL

The landfill plays a most important role in the framework of solid waste disposal and will remain an integral part of the new strategies based on integrated solid waste management (Christensen *et al.*, 1996). The term 'landfilling' refers to the deposition of waste on land. The vast majority of landfills throughout the world are operated using the method of sanitary landfilling. The first sanitary landfill was established in the United Kingdom (UK) in 1912. In the United States (US), landfills as a preferred method of waste disposal became common in the 1930s (Hasan, 1996). Since then, thousands of sanitary landfills have been built worldwide.

The term sanitary landfill was first introduced in the US. The American Society of Civil Engineers (Chain and Dewalle, 1976) defines sanitary landfilling as 'an engineered method' of disposing of solid waste on land in a manner that protects the environment, by spreading the waste in thin layers, compacting it to the smallest volume and covering it with compacted soil by the end of each working day (Novella *et al.*, 1999). In the UK the term 'controlled tipping' is commonly used instead of sanitary landfill (Cope *et al*, 1983). In Scotland they are referred to as 'coups', whereas the term 'dumps' is widely used elsewhere in the world (Grawford and Smith, 1985).

Burial of MSW in controlled landfills continues to be the most common means of disposing of municipal waste within the Organisation of Economic Cooperation and Development (OECD). For example, France disposes of 45% of its annual production of municipal solid waste by landfilling (Marticorna *et al.*, 1993), and the percentage of municipal solid waste landfilled exceeds 75% in United Kingdom, Spain, Canada and United States. The MSW landfilled in Switzerland and Sweden is less than 40%, due to the increased importance of incineration in these countries (Little *et al.*, 1993). It is estimated that more than 95% of waste generated in South Africa is disposed of in landfills (DWAF, 1998a).

Most of the waste is disposed of in landfills because landfilling is the most cost-effective and most convenient method of waste disposal. Treatment of waste in a landfill bioreactor can lead to the formation of some by-products. The principal input and output streams to a landfill are shown below in Figure 2.1.

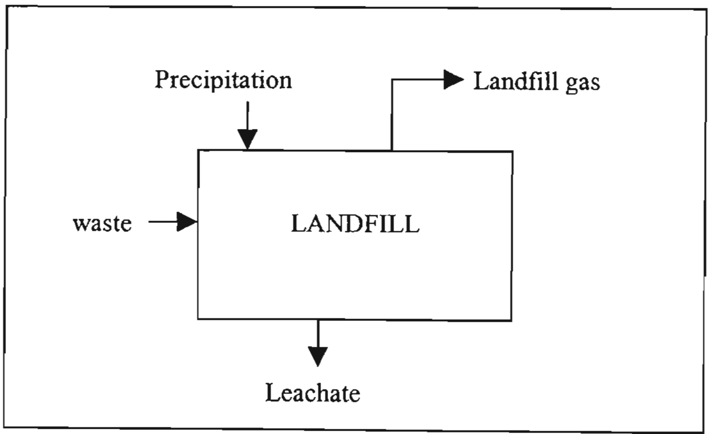


Figure 2.1 Principal input and output streams of a landfill (After Novella *et al.*, 1999)

2.3 LANDFILL CLASSIFICATION

The classification depends on various factors that can be considered by a local regulatory authority. This section focuses on two kinds of classification. The first classification is based on the geology of the site selected to be a landfill. The second type of classification is based on the type and quantity of waste disposed in a landfill, and the potential for landfill to produce leachate. Landfill classification differs from one country to another.

2.3.1 Classification based on local geology

Three categories of landfills may be established from hydrogeological considerations of an area. The classification of landfills depends very much on the geology (type of land) which is chosen for the proposed area (Grawford and Smith, 1985).

2.3.1.1 Class I or containment site

An impermeable or semi-permeable barrier, of natural or synthetic materials, surrounds this type of a landfill so that any leachate generated from the site is contained within the site (Novella *et al.*, 1999; Grawford and Smith, 1985). The design concept for a containment type landfill consists of restricting leachate seepage into the groundwater aquifer so as to minimize groundwater degradation. In order to satisfy these design criteria, landfills are lined with clay or a synthetic membrane or both and a leachate collection system is installed (Bagchi, 1990). In many countries class I sites are rare. All hazardous waste disposed to landfill in South Africa, must be disposed of in a containment site (Novella *et al*, 1999).

2.3.1.2 Class II or attenuation site

An attenuation site describes a landfill surrounded by a stratum of low permeability. The design concept for natural attenuation (NA) type landfills consists of allowing the leachate formed in the landfill to percolate slowly through the landfill base with an expectation that the leachate will be attenuated or diluted significantly by the unsaturated soil zone beneath the landfill, by the time it reaches the water table

(Grawford and Smith, 1985; Bagchi, 1990). Natural attenuation may be defined as a process by which the concentration of leachate parameters (pollutants) is reduced to an acceptable level by a natural process. The majority of landfill sites operating in the United States and the United Kingdom fall within this category (Senior, 1990).

In the past only NA type landfills were used for disposal of all types of waste. At that time it was thought that the soil in the unsaturated zone was capable of completely attenuating the leachate. This concept of attenuation by soil has changed significantly. Presently only non-hazardous wastes are disposed of in NA type landfills. Recent studies indicate that even small NA type landfills may impact on groundwater (Bagchi, 1990). Under current South African legislation, with the exception of the very small landfill sites, an attenuation site would be unacceptable (Novella *et al*, 1999).

2.3.1.3 Class III or rapid migration site

This kind of site describes a landfill surrounded by a stratum which has a high permeability such that leachate can rapidly migrate from the landfill to groundwater without sufficient attenuation (Grawford and Smith, 1985). Such a site allows little or no environmental protection to groundwater-courses.

2.3.2 Landfill classification in South Africa

The landfill classification system in South Africa is based on three parameters: the waste type, the size of operation and the potential of the site to generate leachate.

(a) Waste type

The class of waste that must be managed within the landfill operation is the most critical determinant. Waste before it is landfilled is sorted into two broad categories: general and hazardous. General waste comprises municipal solid waste and includes inert wastes. Hazardous waste covers a wide group of potentially harmful materials. A hazardous material is not a hazardous waste until it is no longer useful, or has been abandoned or discarded (Hasan, 1996). A toxic chemical (e.g. benzene) is not a hazardous waste until it becomes part of the waste stream.

(b) Size of operation

The quantity of waste handled defines the scale of the operation (Lombard, 1993). General landfills can be divided into four classes based on the magnitude of the waste stream and the size of the operation. It is noted however, that hazardous waste landfills are not classified according to size, but rather by the hazardous rating of the waste (DWAF, 1998b; Novella *et al.*, 1999).

(c) Leachate generation

The prevailing weather conditions, in particular, the rainfall and evaporation, are critical in the determination of the propensity for a landfill site to produce leachate. The potential for leachate generation is assessed by means of a simplified climatic water balance, i.e. the Site Water Balance. This is defined by DWAF (1998a) as:

$$B = R - E$$

Where

B = climatic water balance in mm of water

R = rainfall in mm of water

E = evaporation from the soil surface in mm of water

If the value of B were positive, the landfill would be classified as having the potential for leachate generation.

2.3.2.1 Sanitary (General Waste) landfills

General waste landfills are classified into four groups: communal; small; medium, and large. This system was adopted to meet the variations that exist in South Africa, and indeed in many developing countries (Novella *et al.*, 1999). These landfills can further be sub-divided into eight classes based on the magnitude of the waste stream, size of operation, and site water balance.

$G:C:B^-$ $G:C:B^+$ $G:S:B^-$ $G:S:B^+$

$G:M:B^-$ $G:M:B^+$ $G:L:B^-$ $G:L:B^+$

Where

G – General Waste

C, S, M, L – Communal (<25 tonnes/day), Small (25-150 tonnes/day), Medium (150-500 tonnes/day) or Large (>500/day).

B^- - No significant leachate generation

B^+ - Significant leachate generation

2.3.2.2 Hazardous waste landfill

Hazardous waste may only be disposed of at a landfill designed specifically for the disposal of hazardous waste. Hazardous waste in South Africa is classified in terms of hazard ratings. The hazard ratings allocated are (DWAF, 1998b):

Hazard Rating 1: Extreme Hazard
Hazard Rating 2: High Hazard
Hazard Rating 3: Moderate Hazard
Hazard Rating 4: Low Hazard

There are two categories of hazardous waste landfill sites, designated as "H:h" and "H:H". H:H landfills can accept all hazard ratings of wastes, while H:h landfills can receive only low, moderate hazardous waste and general waste. The co-disposal of significant quantities of hazardous waste with general waste may only be practised on a hazardous waste landfill.

2.4 BIODEGRADATION OF REFUSE

Landfill disposal of solid wastes is now widely understood as a dynamic process, treating the wastes instead of a static process simply disposing of the wastes (Ham, 1988). From a chemical engineering point of view, a sanitary landfill is a chemical and biological reactor utilising a heterogeneous mass of waste which varies according to the source. Like any other reactor one must consider the multiple reactions occurring within the reactor, such landfill stabilisation processes and particularly digestion in the case of the landfill bioreactor (Novella *et al.*, 1999). The decomposition of solid wastes in landfills is a complex process, which is not yet understood (Ham, 1988; DoE, 1991).

Once the solid waste is placed in a landfill, a complex sequence of physically, chemically, and biologically mediated events occur. These physical, chemical and biological processes all interact simultaneously in order to provide the overall decomposition patterns (Ham, 1988). Waste decomposition occurs, producing contaminated water or leachate and gases. Physical decomposition may be considered as the physical rising of material from the waste and changes in physical characteristics such as strength and settlement as a result of decomposition. Chemical decomposition includes the dissolution of materials from refuse by leachate. Biological decomposition, however, is the major mechanism by which refuse decomposes in a landfill and biological decomposition in practice controls chemical and physical decomposition because of its effect on variables such as pH and oxidation-reduction potential (Ham, 1988).

2.4.1 Major phases in decomposition of waste

The degradation of the organic fraction of waste materials within a landfill may be described as a five-stage process. Figure 2.2 illustrates the five stages of the process and the typical products generated at each stage. The first and fifth stages occur under aerobic conditions, whilst the remaining stages take place under predominately anaerobic conditions. Each stage of the process has an impact on the quality and rate of degradation of leachate and landfill gas (DoE, 1995).

Stage I: Hydrolysis/Aerobic degradation

Aerobic decomposition occurs when refuse is first placed in a landfill. The oxygen required for aerobic decomposition comes from air incorporated in the landfill during placement of the waste, from the direct access of air to refuse near the surface of a landfill, and from dissolved oxygen in precipitation entering the surface of a landfill (Ham, 1988). The organic fraction of waste is metabolised by aerobic micro-organisms (oxygen-consumers) present in the waste.

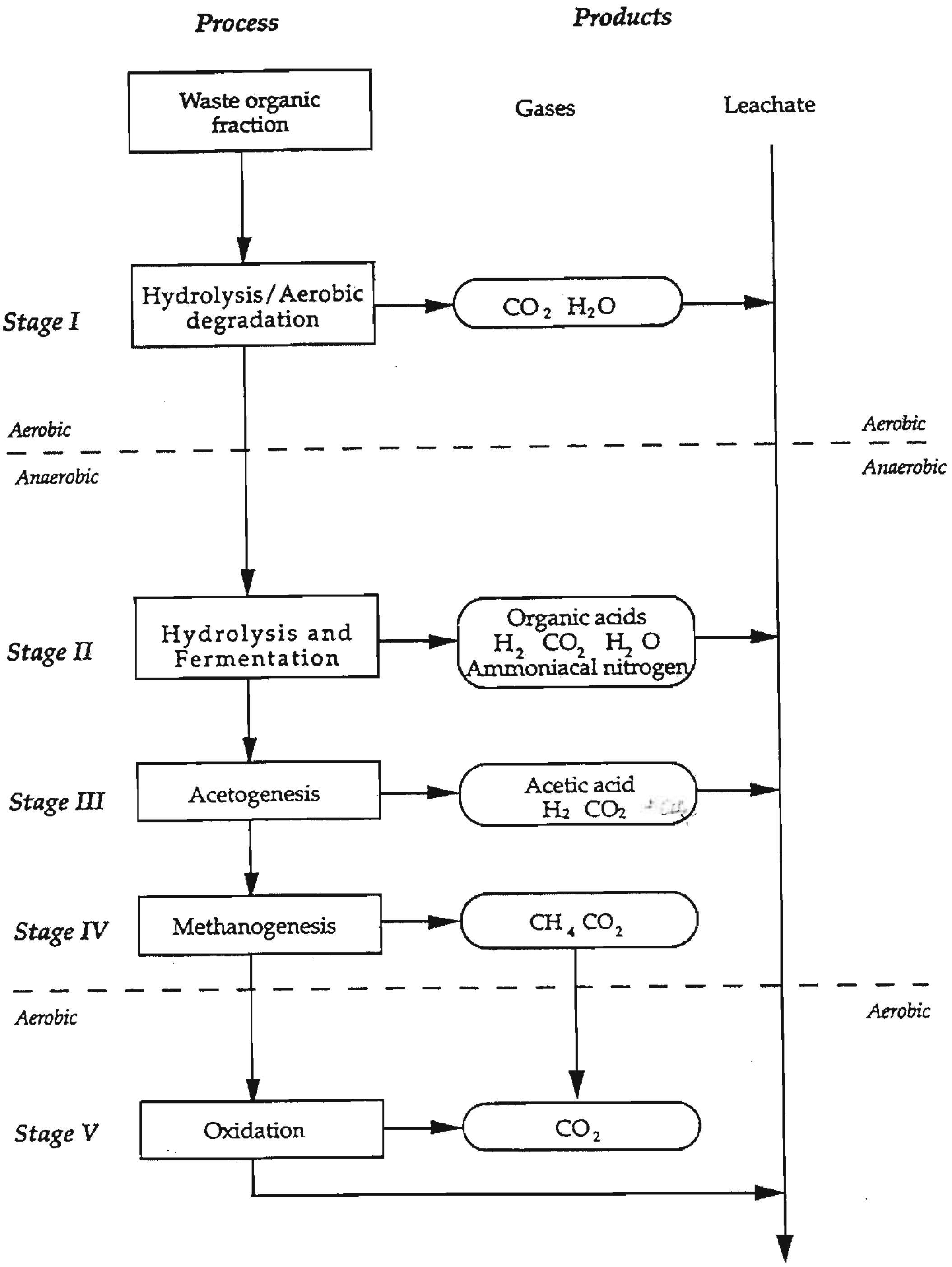


Figure 2.2 Major stages of waste degradation (DoE, 1995).

These micro-organisms convert readily degradable carbohydrates to simple sugars such as glucose, carbon dioxide and water. One of the characteristics of aerobic degradation is the production of heat (an exothermic reaction), which can cause the temperature of refuse to rise dramatically. According to DoE (1995) the temperature rises in the range of 80-90°C, while according to Ham (1988) the range is from 50-70°C. The process of aerobic decomposition uses oxygen, which is present within the waste. This stage of waste degradation is short and lasts for a few days or weeks (Robinson, 1989). However, in shallow landfills of less than 3m high, the aerobic stage may persists for long periods, producing significant amounts of CO_2 due to the availability of air which can readily enter the waste (Robinson, 1989).

The duration of this aerobic stage, which depends on the availability of oxygen, is influenced by management practices at the site, such as the degree of waste compaction, the depth of waste and the type of daily cover. The characteristic odour associated with this stage of the process is mainly due to the presence of organic esters (DoE, 1995). As oxygen becomes depleted further stages of degradation develop.

Stage II: Hydrolysis and Fermentation

Anaerobic and facultative organisms (bacteria) hydrolyse and ferment cellulose, carbohydrates, lipids and proteins producing simple, soluble compounds such as volatile fatty acids with high biochemical oxygen demand (BOD), acetate, carbon dioxide, hydrogen and inorganic salts, such as sulphate and ammonium. During this stage, nitrogen is displaced by carbon dioxide and hydrogen to form leachate with high ammoniacal nitrogen content. This leachate will characteristically have a low pH, and a high chemical oxygen demand (COD) reflecting the large amounts of partially degraded organic material (DoE, 1995; Ham, 1988). Characteristics of this stage of decomposition include a lower production of heat than was obtained during the aerobic process.

Stage II: Actogenesis

The bacteria (actogenic bacteria) convert the soluble acids formed by the activities of the fermentative bacteria of the previous stage to acetate, carbon dioxide and hydrogen. Other bacteria convert carbohydrates, hydrogen and carbon dioxide to acetic acid. The conversion of fermentation products such as butyrate, propionate and ethanol can only be achieved at low hydrogen concentrations. This stage of the overall process can only be maintained if hydrogen utilising organisms such as the sulphate-reducing bacteria and methane-generating bacteria are active. If the levels of hydrogen remain high, the intermediate products (e.g. propionate) cannot be further oxidised and therefore under these conditions, acid accumulates, forming acetogenesis. Gases generated from the waste mass during this stage are predominantly carbon dioxide, hydrogen and methane (DoE, 1995).

Stage IV: Methanogenesis

Under this phase of methanogenic anaerobic decomposition, the methane-generating bacteria (methanogens) which cannot tolerate aerobic conditions, metabolise degraded organics (acetate and formate) produced during the other degradation stages to form a mixture of carbon dioxide and methane (plus various trace constituents) which is released as landfill gas (Robinson, 1989; Ham, 1988; WMP2B, 1995). Some methanogens may also be able to generate methane by the direct conversion of hydrogen and carbon dioxide. Methanogens are most active in the pH range 6.8-7.4. As the soluble substrates are consumed, the production of methane from refuse becomes dependent upon the hydrolysis of cellulose. Cellulose contains the largest source of carbon in refuse which can be converted to methane. Characteristics of this phase of decomposition include the increase of pH to near neutrality. As a result of the increase in pH, the leachate produced during this stage is less chemically aggressive (Ham, 1988).

Stage V: Oxidation

In the final stage of the process as the degradable components become exhausted, progressive re-establishment of aerobic conditions can occur (DoE, 1995). Facultative and aerobic micro-organisms such as methane oxidising organisms start to recolonize the landfill and may then become established as prevailing conditions permit.

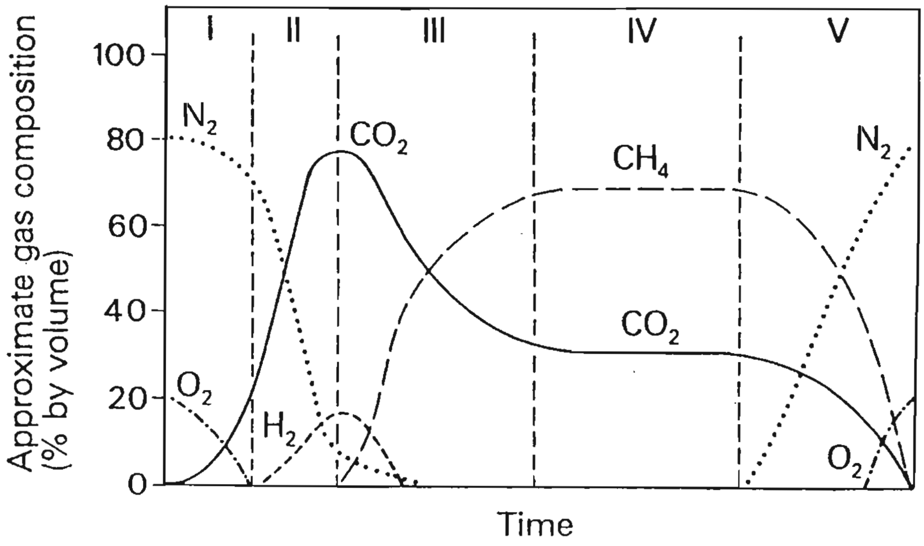
2.5 COMMON POLLUTANTS EMITTED FROM LANDFILL SITES

Data from landfill sites have demonstrated that the organic fraction of waste present in landfills generates pollutants known as leachate and landfill gas. This study focuses mainly on landfill gas emissions, which usually degrade air quality. Landfill gas (LFG) is principally a mixture of methane (CH_4) and carbon dioxide (CO_2), but it also includes a significant number of minor components.

2.5.1 Landfill Gas Generation

LFG is formed by the decomposition of waste through the processes of microbial degradation, chemical reactions and volatilisation in landfills (Couth, 2000a). The predominant part of the landfilled waste will become anaerobic soon after disposal, and microbial processes will degrade the organic waste, eventually converting the solid organic carbon to methane and carbon dioxide and other volatile organic compounds. However, in order to understand the overall process, attention must be paid to the microbial consortium or action on carbon conversion and the basic parameters influencing the process (Christensen *et al.*, 1996).

LFG in typical landfills is quoted as 60 to 65% CH_4, 35 to 40% CO_2, together with many other trace components (Young and Parker, 1983). Production rates are site dependent, varying according to a number of factors that will be discussed in Secton 2.6. The landfill may generate LFG for over 30 years. After the cessation of gas production, anaerobic activity has then ceased and the landfill is said to be stabilised. The landfill gas production process passes through several stages as illustrated by Figure 2.3, during which the composition of the gas changes significantly.



Phase I: Aerobic decomposition decomposition of biodegradable materials: entrained atmospheric oxygen is converted to carbon dioxide.

Phase II: Anaerobic decomposition commences as oxygen is used up: carbon dioxide concentration increases and some hydrogen is produced: no methane is produced at this stage.

Phase III: Anaerobic methane production begins and rises to a peak: concentration of carbon dioxide declines: hydrogen production ceases.

Phase IV: Steady methane and carbon dioxide generation in proportions of between 50-70% and 30-50% respectively.

Phase V: Steady decline in generation of methane and carbon dioxide: gradual return to aerobic conditions.

Figure 2.3 Change of LFG composition over different phases (Crowhurst and Manchester, 1993).

In the initial stages the biogas produced is a mixture of carbon dioxide and hydrogen. It is not until the third stage that methane production starts (methanogenesis). Subsequently, in the final stages, gas production declines although it can continue at a much lower rate, for many years (Crowhurst and Manchester, 1993). The waste decomposition process to form LFG, primarily CH_4 and CO_2 is shown in Figure 2.4 and this illustrates the decomposition process for proteins, carbohydrates and lipids in household waste.

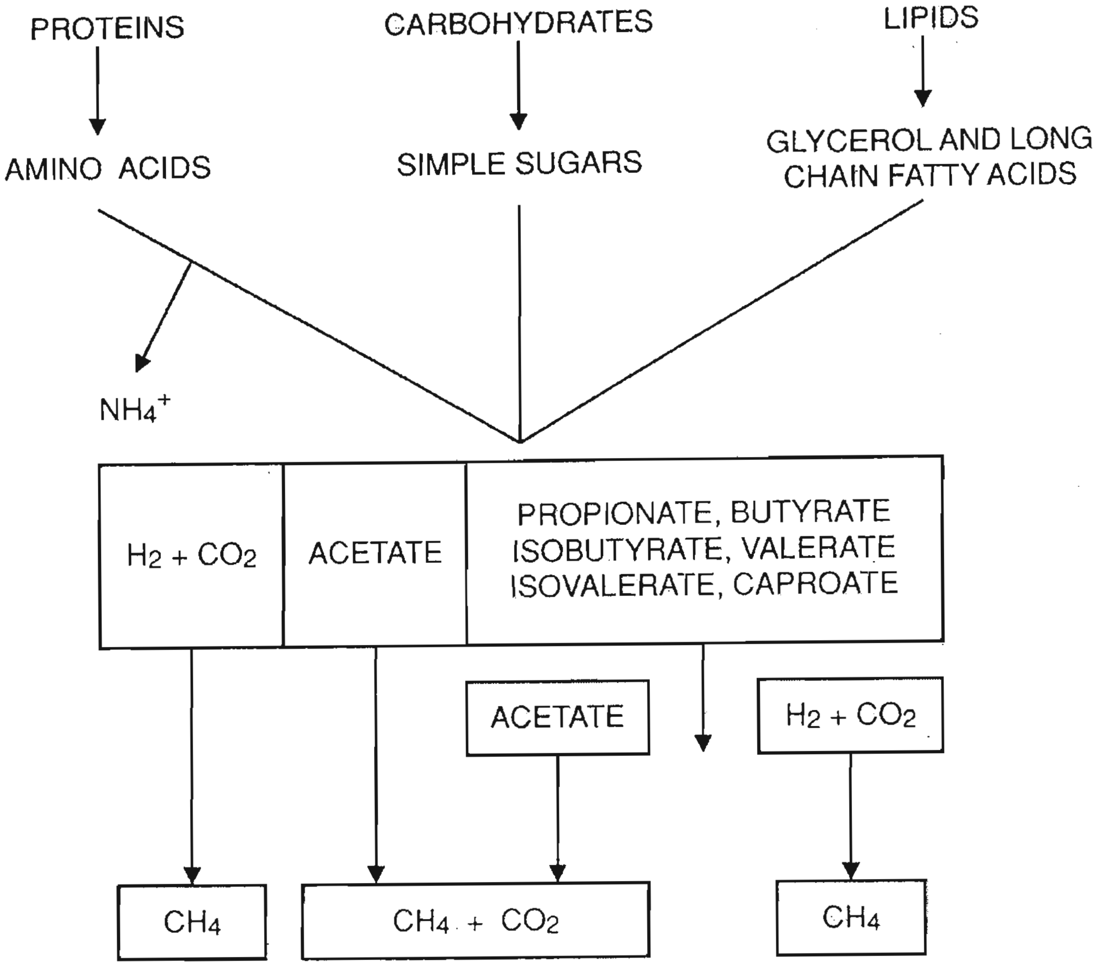


Figure 2.4 Production of LFG components as a result of decomposition of materials occurring in domestic waste (DoE, 1991).

Cellulose and other similar materials are the main source components of LFG. Organic matter such as paper, food, garden waste, wood (including shrubs and trees), sawdust, cotton, wool, etc. has the potential to undergo degradation and under anaerobic conditions, produce CH_4 and CO_2. Cellulose (organic matter) is more readily degradable by the anaerobic process than aerobic processes (Couth, 2000a; IWM LFG Monitoring Working Group, 1998).

2.5.2 Other constituents of LFG

In addition to the major components, landfill gas contains an extremely wide range of minor components, usually making up less than 1% of the gas volume (IWM LFG Monitoring Working Group, 1998). The type and concentration of these trace components depends on the composition of the landfilled waste (Rettenberger and Stegmann, 1996). The typical LFG, besides CH_4 and CO_2, comprises small amounts of hydrogen, oxygen and nitrogen and trace amounts of non-methane organic compounds (NMOCs). Hydrogen may be generated in the stages of waste decomposition through the action of fermentative and acetogenic bacteria. NMOCs include volatile organic compounds (VOCs), hazardous air pollutants (HAPs) and odorous compounds (US EPA, 2001a).

Owing to their generation, trace components can be differentiated into two types:

- trace components generated during anaerobic degradation in the landfill;
- anthropogenic trace components (i.e. generated by human activity) and deposited together with the waste.

2.5.2.1 Trace elements generated during biological degradation processes

The three main groups of biologically generated components are:

- Oxygen compounds;
- Sulphur compounds;
- Hydrocarbons.

Oxygen compounds. Compounds containing oxygen are generated mainly during the degradation of the organic waste components in the early phase of gas generation (Rettenberger and Stegmann, 1996). These oxygen-containing compounds include esters, furans and alcohols.

Sulphur components. Sulphur components in LFG may include gaseous compounds like hydrogen sulphide and mercaptans, which belong to more toxic LFG components. These are generated by a group of sulphate-reducing bacteria, which act on sulphate within the waste. At sites that receive large amounts of gypsum and plasterboard, concentrations up to 30% by volume (v/v) H_2S have been reported (DoE, 1995).

Hydrocarbons. These compounds may be naturally generated in the landfill as well as deposited with the landfilled waste. Table 2.1 below shows terpene hydrocarbons generally detected in the LFG.

Table 2.1. Concentration ranges of terpene hydrocarbons in landfill gas (Rettenberger and Stegmann, 1996).

Substance	Concentration (mg/m^3)
Limonene	3.3-269
Menthene	14
Camphor/fenchene	3-13
Others	5.5-503

Landfill gas is usually saturated with water vapour. A summary of compounds contained in landfill gas is shown in Table 2.2.

2.5.2.2 Anthropogenic trace components

The anthropogenic trace components in the LFG can be differentiated in two groups:

- Aromatic hydrocarbons
- Chlorinated hydrocarbons

Aromatic hydrocarbons. Aromatic hydrocarbons are widely detected in landfill gas. The environmental effects of aromatic hydrocarbons emitted from landfills are negligible as compared to those released from sources such as traffic and chemical industries. However, these components are of importance because of the possible effects they can pose on those who work on the landfill (Rettenberger and Stegmenn, 1996).

Table 2.2. Typical Landfill Gas Composition (Adapted from DoE, 1991)

Component	Typical value (% Volume)	Observed Maximum (% Volume)
Methane	63.8	88.0
Carbon dioxide	33.6	88.3
Oxygen	0.16	20.9
Nitrogen	2.4	87.0
Hydrogen	0.05	21.1
Carbon Monoxide	0.001	0.09
Ethane	0.005	0.0139
Ethene	0.018	-
Acetaldehyde	0.005	-
Propane	0.002	0.0171
Butanes	0.003	0.023
Helium	0.00005	-
Higher Alkanes	<0.05	0.07
Unsaturated Hydrocarbons	0.009	0.048
Halogenated Compounds	0.00002	0.032
Hydrogen Sulphide	0.00002	35.0
Organosulphur Compounds	0.00001	0.028
Alcohols	0.00001	0.127
Others	0.00005	0.023

In particular, the contents of benzene in landfill gas should be carefully monitored due to its proven carcinogenic effect (Rettenberger and Stegmenn, 1996).

Chlorinated hydrocarbons. The toxicity of the majority of these substances is rather low. However, with regard to the environmental impact owing to their persistence (i.e. chemical stability), these substances are the most significant trace components found in landfill gas (Rettenberger and Stegmenn, 1996).

2.6 FACTORS INFLUENCING THE GAS PRODUCTION

The degradation process as well as rates and amounts of biogas are influenced by a range of environmental factors, which include the ones briefly described below.

2.6.1 Moisture

The moisture content of the waste placed in a landfill is an important factor that affects landfill gas production. The incoming household waste has an average moisture content of about 25 %, with food and garden waste providing the highest moisture input (DoE, 1991). The moisture content of waste in a landfill can be increased by rainfall, surface and groundwater infiltration and products of waste breakdown. The recirculation of leachate practised on some sites will maintain high moisture contents and may provide a source of nutrients and bacteria, which will tend to accelerate gas generation rates. The distribution and flow of moisture is important in dispersing nutrients, and possibly diluting and removing inhibiting substances, and spreading micro-organisms through the landfill (Christensen *et al.*, 1996; IWM Landfill Gas Monitoring Working Group, 1998). In general, elevated moisture contents are known to increase gas production.

2.6.2 Waste type

The nature of the organic degradable matter present in the deposited waste, including the molecular structure of organic compounds, will affect both degradation rates and the proportions of gaseous components in landfill gas mixtures. The waste composition will also affect the rate and quantity of gas generated (DoE, 1991). Readily degradable materials (such as vegetable matter) support rapid initiation of microbial degradation processes, while less readily degradable matter, often with the highest degradable carbon content (e.g. newspapers), will support the longer term production of methane rich landfill gas mixtures from landfilled wastes (IWM LFG Monitoring Working Group, 1998). In general, the organics present in MSW can be divided into two types. The first class includes those materials that will biodegrade rapidly (within 3 months – 5 years), and the second one involves materials that will decompose slowly (up to 50 years or more) (Tchobanoglous *et al.*, 1993). Some of the rapidly and slowly decomposable components of organic constituents in solid wastes are listed in Table 2.3.

Table 2.3 The rate of organic constituents biodegradability in MSW (Tchobanoglous *et al.*, 1993).

Organic waste component	**Rapidly biodegradable**	**Slowly biodegradable**
Food wastes	✓	
Newspaper	✓	
Office paper	✓	
Cardboard	✓	
Yard wastes[1]	✓	✓
Plastics[2]		✓
Textiles		✓
Rubber		✓
Leather		✓
Wood		✓
Miscellaneous organics		✓

[1] Yard wastes consists mainly of typically 60 percent of rapidly biodegradable waste (e.g. leaves and grass trimmings). Woody portions of yard wastes are considered to biodegrade slowly.
[2] Plastics are generally considered non biodegradable.

Some waste components such as heavy metals may, at least locally, inhibit gas generated. The presence of some process wastes can lead to the formation of elevated concentrations of other gases (e.g. hydrogen sulphide from gypsum wastes) not commonly found in significant concentrations in landfill gas mixtures (IWM LFG Monitoring Working Group, 1998).

2.6.3 Waste density

The greater the waste density in a landfill the higher the theoretical yield of landfill gas per unit volume of void space. High waste densities will also serve to reduce permeability of the waste to gas and hence result in a build-up of gas pressure (WMP 27, 1991).

2.6.4 Waste input rates

High waste input rates will encourage more rapid development of the anaerobic process, during which most LFG is produced (DoE, 1991). The importance of waste quantity influencing the gas production potential of a landfill is also emphasized by Spillmann (2000). Figure 2.5 below depicts the gas production over time.

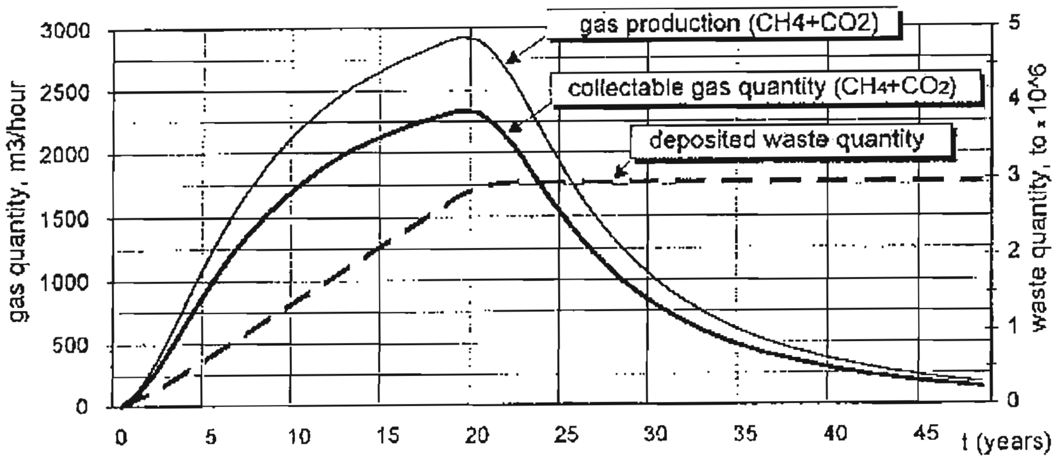


Figure 2.5 Profiles of gas generation over time in a landfill (Spillmann, 2000).

2.6.5 pH within landfill

Methanogenesis (methane generation) will proceed optimally between a pH range of 6.5-8.5 and is only inhibited when the pH value is outside this range (DoE, 1991). If the methanogens (methanogenic bacteria) are stressed by other factors, their conversion of hydrogen and acetic acids decreases, leading to an accumulation of volatile organic acids and a decrease in pH, which furthermore may inhibit the methane formation and lead to a further decrease in pH (Christensen *et al.*, 1996). Eventually, the methane generation may stop. In particular, household waste produces acidic leachate as a consequence of rapid degradation of easily biodegradable material. Unless other wastes buffer this, it may be responsible for inhibiting the onset of methane evolution.

2.6.6 Waste temperature

The optimum temperature for methane generation occurs between 35-45 °C, which is common in deep landfill sites (DoE, 1991; IWM LFG Monitoring Working Group, 1998). In shallow landfills, therefore, seasonal temperature variations may affect the output of methane. A significant reduction in gas evolution occurs below 10-15°C (DoE, 1991). At elevated temperatures, the methane production is more vigorous and produces more heat, and as such is self-enhancing (Christensen *et al.*, 1996).

2.6.7 Compaction and particle size

The higher surface area created by the reduction of particle size of the waste by pre-processing such as pulverisation, and compaction using thin layering techniques, will speed up the onset of anaerobic decomposition for the more readily degradable materials (DoE, 1991; IWM LFG Monitoring Working Group, 1998).

2.6.8 Oxygen ingress

The absence of free oxygen is essential for the anaerobic bacteria to grow and perform the conversion of the solid carbon to methane and carbon dioxide (Christensen *et al.*, 1996). Ingress of oxygen into anaerobically decomposing wastes can occur by excessive pumping rates in landfill gas extraction schemes or through digging of trenches into mature wastes for site operations. Such ingress will stop the anaerobic phase, thus inhibiting the methane formation in the influenced areas (DoE, 1991; Christensen *et al.*, 1996). In particular, the methanogenic bacteria are very sensitive, requiring very low redox potential, below –330 mV according to Christensen *et al.* 1996).

2.7 LANDFILL GAS CHARACTERISTICS AND HAZARDS

The major constituents of LFG are methane and carbon dioxide, both of which are colourless and odourless. Methane is an asphyxiant, flammable, non-toxic gas that is lighter than air with a vapour density of 0.6. CO_2 is a non-flammable, toxic gas that is heavier than air with a vapour density of 1.53 (Lombard, 1998). At concentrations above 1.5 % by volume CO_2 will become a hazard to health.

Many minor constituents are present in LFG at low concentrations. Organosulphur compounds (such as H_2S and mercaptans) and esters are present in gases derived from deposited waste and are usually responsible for LFG odour. H_2S, which is often thought to be responsible for odour, is generally of low concentration. Trace organics, such as the volatile chlorinated hydrocarbons (VCCs) and fluorinated hydrocarbons (CFCs) may pose a problem. Most VCCs are toxic, characterized by their lipophilic properties and relatively high volatility in steam (Deisper *et al.*, 1996).

2.7.1 Flammability

When CH_4 or H_2 is mixed with air, within certain concentration limits known as the 'flammable' or 'explosive' range, the resultant mixtures may ignite to produce fires and explosions. The term 'flammable' is used when the gas mixtures occur in the open atmosphere, whereas 'explosive' is used when the mixture is contained within a space such as an underground chamber or building (DoE, 1991). The flammable ranges of methane and hydrogen are 5-15 % and 4-74 % by volume respectively. The presence of CO_2 can affect these ranges. At low O_2 concentration levels, CH_4 cannot ignite, especially if it falls below 13 % by volume (DoE, 1991).

2.7.2 Asphyxiation

Asphyxiation is caused by a lack of sufficient oxygen in enclosed spaces. An asphyxiation risk from landfill gas is present whenever people have to enter any confined space in or near a landfill site. This may include manholes, sewers, or tunnels and even poorly ventilated spaces such as those built below landfill buildings (DoE, 1991). Asphyxiation in plants is caused by the lack of sufficient oxygen in the root zone as a result of physical displacement by LFG or by microbial oxidation of methane in the LFG, depleting the soil air of oxygen (Neumann and Christensen, 1996).

2.7.3 Toxicity

Some of the minor constituents of LFG could have toxic effects if present in sufficiently high concentrations. H_2S and the mercaptans, belong to the more toxic landfill gas components (Rettenberger and Stegmann, 1996). Hydrogen sulphide is toxic at low concentrations. It is a highly toxic flammable gas with a characteristic offensive rotten egg odour. At a level of 50 ppmv in air H_2S dulls the olfactory system and the gas is no longer detectable making it even more dangerous (Lombard, 1998). Aromatic hydrocarbons, such as benzene in landfill gas should be monitored carefully owing to its proven carcinogenic effect (Stegmann and Rettenberger, 1996). Most VCCs are toxic, and some are suspected of being carcinogenic (Deisper *et al.*, 1996).

2.7.4 Corrosive properties

There are some components of LFG, or derivatives, which have a corrosive potential. The CO_2 and volatile fatty acid (VFA) components of LFG are aggressive to concrete, brick mortar and mild steel (Lombard *et al.*, 1998). These materials must therefore be protected when used in a situation where LFG can be expected. The high rates of CH_4 oxidation in the landfill cover soil that lower overall pressure may cause downward migration of LFG may cause downward migration of LFG.. Methane and CO_2 have potential effects on groundwater (Kerfoot, 1996), especially if the landfill is not well lined beneath the waste. Methane has a relatively lower solubility in water than CO_2, and for this reason larger effects on groundwater can be due to CO_2 (Kerfoot, 1996). Owing to its higher solubility, CO_2 can readily be dissolved into water around waste (i.e. leachate), and can react with it to form carbonic acid (Young and Parker, 1983; Micales and Skog, 1997; Tchobanoglous *et al.*, 1993):

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad (2.1)$$

This reaction lowers the pH, which increases the hardness and mineral content of the groundwater through solubilization (Tchobanoglous *et al.*, 1993). Chlorinated hydrocarbons may generate hydrogen chloride (HCl), which may also cause corrosion problems (Rettenberger and Stegmann, 1996).

2.8 GAS MIGRATION

The movement of gas within the site and migration out of it are governed by a number of factors, which may be site specific. In general, gas will migrate in response to pressure, temperature or concentration gradients (diffusion), or density effects (IWM LFG Monitoring Group, 1998). The migration of gas requires both a motive force and a pathway.

2.8.1 Gas pressure and motive force

Within a landfill site and the surrounding rock, the principal motive for gas migration can be assumed to be the pressure of the gas itself, which is generated within the refuse. Gas pressure generated within the landfill is dependent on the microbial activity in the waste, and the permeability of cover and banding (compacted) material. Generally migration can be expected to be more rapid along a pressure rather than a concentration gradient. An increase in gas pressure will promote migration from the site, and this may be aided by (DoE, 1991):

- Changes in atmospheric pressure
- Changes in leachate levels in the waste
- Changes in the water table outside the site.

When rapid falls of barometric (atmospheric) pressure occur, large volumes of gas may move out of the site. However, if the barometric pressure rises rapidly, emissions of gas will be reduced. When barometric pressure is stable, gas from a landfill site will enter the atmosphere at a fairly constant rate (IWM LFG Monitoring Group, 1998).

The rising or falling of leachate levels in lined landfills is likely to affect the gas pressure. Rising leachate levels will increase gas pressure and falling levels will decrease pressure (DoE, 1991). It should be noted that leachate can carry gas out of a landfill site in dissolved form.

Natural rates of change in groundwater levels are usually seasonal and may also affect the soil gas pressure. The activities, which result in rapid falls in groundwater levels, would temporarily reduce the gas pressure in an unlined landfill site. Despite the fact that natural groundwater level fluctuations may not normally have major impacts within the landfill, they could affect the rates and directions of gas migration outside the landfill boundary (DoE, 1991).

2.8.2 Migration pathways

Gas will migrate along all possible pathways in proportion to their accessibility or permeability. However, gas may not move through even a very permeable system unless that system has an outlet point for gas release (IWM LFG Monitoring Group, 1998). The public safety and environmental concerns associated with LFG migration may be considered under three categories, namely subsurface migration, surface emissions (air pollution) and odour nuisance.

2.8.2.1 Sub-surface (underground) migration

Subsurface migration is the underground transmission of landfill gas to other areas within the landfill property and outside the landfill property (US EPA, 2001a). The potential for migration of gas through the ground surrounding the landfill will depend on the natural geological characteristics of the soil or rock. At sites with an unsaturated zone beneath the base of the site there is a possibility that gas will move down into this zone before lateral migration takes place. This is an important consideration for 'attenuate and disperse' sites (Section 2.3) that deposit biodegradation wastes above ground level (DoE, 1991). Since LFG is a potentially explosive gas, there is the risk that the gas will travel to underground voids such as underground cavities; basements; manholes; the space under site weighbridges, where it may accumulate and ignite resulting in destruction of property and injury or death (US EPA, 2001a ; DoE, 1991).

Migration of LFG displaces oxygen from the root zones (Section 2.7.3), and under certain conditions, CH_4 is oxidised to carbon dioxide and water, which further depletes the available O_2. This depletion of O_2 leads to inhibition of plant growth, thereby enhancing asphyxiation (Card, 1992; Christensen, 1996; Lombard *et al.*, 1998). Therefore due to microbial oxidation of CH_4 to CO_2, elevated levels of CO_2 in the near-surface zone can be indicative of the presence of landfill gas even if CH_4 is not detected.

Methane migration has high potential for groundwater contamination. Methane has a relatively low solubility in water. At 25 °C, 24.1 mg/l CH_4 is soluble (Kerfoot, 1996). Methane can also be produced in deep aquifers, and the use of groundwater from such sources typically requires aeration to remove the methane. Owing to the considerably higher solubility of carbon dioxide over that of methane, the effects on groundwater due to carbon dioxide are greater than those due to methane (Kerfoot, 1996). It has further been noted by Bishop (1967) that CO_2 from decomposition of refuse can increase the corrosivity of groundwater.

2.8.2.2 Surface emissions

Some gas will always find its way to the surface of the landfill, where it normally disperses into the atmosphere. Possibly the biggest health and environmental concerns are related to the surface emissions of LFG into the air. As previously mentioned in Section 2.5.2, LFG contains CO_2, CH_4, VOCs, HAPs and odorous compounds which can adversely affect public health and the environment. For instance, CO_2 is currently linked to global climate change. Furthermore, the contribution of CH_4 to the greenhouse effect is 21 times greater than that of CO_2. VOCs are known to contribute to ozone formation (Meadows *et al.*, 1997). The effects of landfill gas emissions on the atmosphere are discussed below.

Global warming is one of the most important current environmental issues. Increases in greenhouse gas concentration since pre-industrial times (approximately 1750) have led to a warming of the earth's atmosphere and produced other changes in climate (Meadows *et al.*, 1997). Increasing levels of greenhouse gases are likely to accelerate the rate of global temperature change. Scientists predict that the average global surface temperature could rise by 0.6 – 2.5 °C in the next fifty years, and 1.4 – 5.8°C in the next century, with significant regional variations (US EPA, 2001b). Figure 2.6 shows the increase of global temperature over the past century.

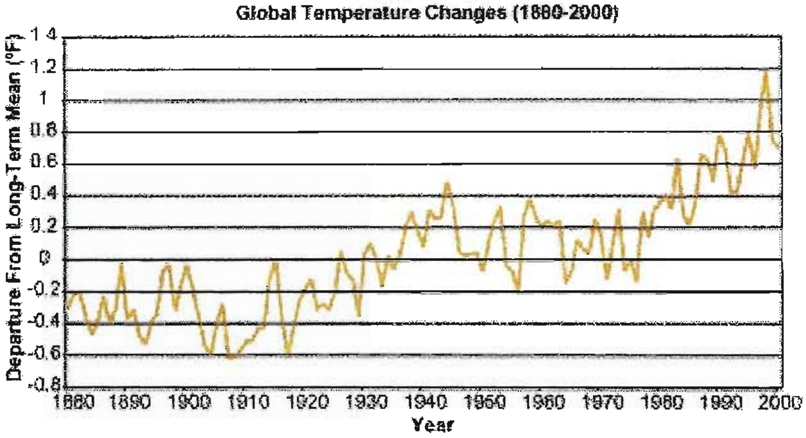


Figure 2.6 Variation of worldwide temperature over time (US EPA, 2001b).

The Intergovernmental Panel on Climate Change (IPCC) has concluded that there is considerable human influence on global climate and the global temperature has increased between 0.3-0.6 °C over the last 100 years (Thorneloe, 1996; Meadow *et al.*, 1997). Some gases, on a molecule per molecule basis have a greater estimated heat trapping ability ('Global Warming Potential' (GWP)) than others (Grantham *et al.*, 1997). Carbon dioxide is assigned a baseline GWP of 1; methane has a GWP of 26, and chlorinated hydrocarbons have GWPs ranging about 1500-7300. Thus one molecule of methane will contribute a heating effect 26 times than 1 molecule of carbon dioxide.

It is also known that VOCs contribute to ozone formation. Once formed, ozone is capable of reducing or damaging vegetation growth as well as causing respiratory problems in humans. Ozone in the troposphere is also a greenhouse gas.

Increasing concentration of methane in the atmosphere is of concern as methane is the second most important greenhouse gas and the second largest contributor to global warming after carbon dioxide (Johnston *et al.*, 2000; Meadows *et al.*, 1997).

Landfills among other sources of methane (such as agriculture, coal mining, fossil fuel production) have been estimated to represent the largest source of atmospheric methane in the UK (Grantham *et al.*, 1997). The mass of methane generated and emitted from solid waste disposal sites (SWDS) differs widely between countries. This is due different waste management strategies employed (e.g. unmanaged dumping, managed landfill, incineration), the nature of waste deposited and technologies used at SWDS.

Most developed countries rely on managed landfills as a major route for treatment and disposal of solid waste. Managed landfills tend to favour methane generation because they are deep and have low permeability liners and caps hence promote anaerobic degradation. Air especially O_2 can move into unmanaged sites relatively easily, and this inhibits anaerobic degradation of biodegradable wastes and hence methane generation (Meadow *et al.*, 1997).

2.8.2.3 Odorous emissions

The final concern related to landfill gas emissions is related to its odorous characteristics. A quantitative measure of odour is its concentration. There are two main sources of odour on a landfill site. There is odour associated with aerobic decomposition of fresh municipal waste and garden refuse, and odour generated in the long-term (months-years) from malodorous components of LFG during anaerobic decomposition within the waste mass.

LFG actually contains over a hundred trace compounds that can be malodorous. Organosulphur compounds such as hydrogen sulphide and mercaptans are among the LFG components mainly responsible for the odour of the gas. S-components such as mercaptans occur mainly during the operational phase of a landfill. Others, especially H_2S, are generated in all phases of LFG production (Rettenberger and Stegmann, 1996). Table 2.4 shows some of the sulphur components that have been detected in LFG.

Table 2.4. Concentration ranges of some sulphur components detected in landfill gases (After Rettenberger and Stegmann, 1996).

Substance	Concentration (mg/m^3)
Methyl mercaptan	0.1-430
Ethyl mercaptan	0-120
Dimethyl sulphide	1.6-24
Dimethyl disulphide	0.02-40
Carbon disulphide	<0.5-22
Carbon oxysulphide	<0.1-1.9

Typical malodorous compounds in addition to H_2S, include esters, terpenes and volatile fatty acids (VFA). These trace compounds are described as volatile organic compounds (VOC). The normal landfill gas odour is caused by VFA component, but the reduced sulphur containing compounds (e.g. H_2S and mercaptans) can also influence the odour of the gas depending on the types of waste landfilled (Lombard, 1998). An odour detection threshold of a substance is the concentration above which the odour of that substance can be detected (Laister and Stretch, 2000). Typical odour threshold levels of VOCs in mgm^{-3} are shown in Table 2.5.

Compounds found in LFG are associated with strong pungent odours, and these smells can be transmitted offsite to adjacent communities. This can lower the quality of life for individuals who live near landfills (US EPA, 2001a).

2.9 GAS CONTROL AND MANAGEMENT

The objective of any LFG control system must be to prevent uncontrolled LFG migration and to ensure that the landfill does not pose a risk to human health or cause pollution of the environment (DoE, 1991). Gas should not be allowed to escape from a landfill in an unplanned or uncontrolled manner. It should be contained and vented within the premises of the landfill except in special circumstances where it

Table 2.5 VOC odour threshold concentrations (Lombard, 1998).

VOC	Odour Threshold (mg/m^3)
Benzene	9000
Decane	1000
Dichlorodifluoromethane	-
Heptanes	100 000
Limonenes	57
Methylene chloride	750
Nonanes	2000
Octanes	1000
Propylbenzenes	-
Terpenes	1000
Toluene	700
Trichloroethylene	115 000
1,1,1 Trichloroethane	800 000
Undecane	800
Xylene	400
Ethylbenzene	200
1,2 Dichloroethane	250 000
Butylbenzenes	-

may be allowed to migrate off the site safely. The gas should be controlled using a gas management system designed for the purpose. Therefore it follows that most sites should be encouraged to have an adequate gas management system installed, maintained and operated. LFG management systems must be flexible and designed for changing gas quality and quantity throughout the life of the landfill (Couth, 2000b). The vital requirement of a gas control system is that it should have adequate protection against failure (DoE, 1991). Some of the main elements that form part of gas management systems are described below.

2.9.1 Gas barriers

Landfill liner systems which include clay, bentonite linings, geosynthetics (e.g. High Density Polyethylene (HDPE), Geosynthetic Clay Liner (GCL) and grout curtains are used to contain waste and its products such as leachate and also to prevent gas migration (Couth, 2000b; DoE, 1991). The effectiveness of liners in preventing gas migration is not yet fully understood and their permeabilities to gas have not yet been determined (DoE, 1991).

Natural clay or calcium bentonite linings are probably the most suitable commonly available materials for gas barriers. The material should be protected from chemical attack and physical damage or distortion which could increase its permeability. Ideally synthetic membranes must be durable, flexible, of very low gas permeability and have a high resistance to tearing or puncturing. They need to be inert to chemical or biological attack. Experts in this field should undertake the installation of these liner-systems. Grout curtains can also be formed to act as a gas barrier. These are usually constructed by drilling boreholes close together in a staggered pattern along a line (DoE, 1991). Injecting grouts are depth limited and therefore can be installed by retrodrilling.

Gas barriers can be installed at closed sites if there is a gas migration problem. Such barriers are: slurry trenches; membrane barriers and grout injection (Couth, 2000b). However, these are expensive to install and limited in depth.

2.9.2 Free/Passive venting

Free venting implies permeable cover soil with no structures or potentially hazardous gas accumulation points on the landfill (Ham, 1988). If surrounding soils are permeable to gas flow, uncontrolled migration will occur. Therefore, uncontrolled migration under these conditions implies potential flow over long distances to buildings and other possible hazardous gas accumulation points (Ham, 1988).

Vent trenches can provide a route through which gas can vent. The portion or side of the trench close to the site boundary should be sealed with a low-permeability barrier of natural or synthetic material (DoE, 1991). Trenches should be located between the waste fill and the gas barrier. Venting trenches at the surface of a landfill are not used much because of water ingress and attendant leachate flow considerations, and because of the inability to flare or burn the gas (Ham, 1988). On completion, trenches should be capped to prevent surface water ingress (DoE, 1991).

The purpose of passive venting is to (Card, 1992):

- Purge the ground and generally reduce concentrations and emission rates of landfill gas prior to development; and
- Encourage movement of gas to vent at specific locations of the site and thereby reduce any potential for uncontrolled migration across subsurface boundaries.

Lateral gas migration into surrounding soils can be minimized by use of either permeable vents or impermeable barriers at or beyond the waste boundary.

2.9.3 Gas wells

In situations where the depth of gassing material is in excess of 5m, gas wells may be more applicable than venting trenches mentioned above, and thus need to be constructed to the full depth of the gassing fill (Card, 1992). These are similar in design to boreholes. The effectiveness of the well will depend on the permeability of the surrounding wastes. The main advantage of wells is that all levels of waste are intercepted. In addition, they retain their integrity better than trenches constructed within the waste, which can become distorted as settlement occurs (DoE, 1991).

Gas wells for the collection and extraction of gas can be constructed at different stages of landfilling and depending on the type of landfill; they may be vertical or horizontal (DoE, 1991):

2.9.4 Encapsulation

This technique comprises the placement of a low permeability-capping layer over the site surface to control gas emission. On landfill sites, compacted clay capping layers are used to effectively seal in gas and prevent surface migration (Card, 1992). In order to avoid the build-up of gas beneath the capping layer, a granular blanket can be placed below the clay to allow controlled lateral migration.

2.9.5 Gas extraction system and flaring

As a technique to control landfill gas migration, active abstraction and flaring can be very effective if gas concentration and emission rates are relatively high (Card, 1992). The gas extraction system is typically a series of wells extending to or near the bottom of the landfill (Ham, 1988). This gas control by use of the designed gas well curtain is to prevent migration to specific high-risk areas. The wells are connected by a network of horizontal pipes or laterals, to which a vacuum pump, dewatering system, and any gas treatment devices are attached. The vacuum creates or develops a pressure gradient towards the pipes over most of the landfill to cause LFG to flow to the wells for collection. Too much of a vacuum (gas-extraction) will reduce gas quality and inhibit methanogenic bacteria activity as a consequence of the high volume of air drawn into the landfill (Ham, 1988).

The purpose of flaring landfill gas is to dispose of the flammable constituents safely and to remove odour to prevent nuisance (DoE, 1991). The odours associated with fresh waste can easily be controlled by immediate compaction and soil cover (Lombard, 1988). The typical odour of LFG is a result of trace constituents of volatile organosulphur compounds, esters, volatile fatty acids and amines, and the effective control of these components is flaring. Flaring also combusts CH_4 into CO_2 and water, hence reducing the greenhouse effect since CO_2 is 21 times less effective than CH_4.

Flaring and burning of LFG may lead to the problem of potential dioxin production during and after combustion (Stegmann, 1996). Dioxins are formed during the combustion process in the presence of specific organics and particulate matter. Some of the favourable conditions for dioxin formation include combustion of organic material in the presence of halogens (e.g. chlorine) or halogenated hydrocarbons and particulate matter under certain conducive thermodynamic conditions such as low temperatures (US EPA, 2001a). In conclusion, the potential production of dioxins may be minimized or avoided by using appropriate flares and burners. In addition, emission control monitoring should be obligatory on a routine basis (Stegmann, 1996). Respecting these measures, dioxin emissions are not a problem.

2.10 LANDFILL GAS UTILISATION

Due to the fact that landfill gas is made up of a substantial portion of methane (approximately 50 %), it may be recovered for its energy content and benefit (Wheeler Environment Management, 1998). Energy recovery from LFG is termed a renewable energy technology and is a significant resource. Since landfill gas (LFG) is an emission that has to be controlled at each landfill, its utilisation should be seriously considered. Owing to its high concentration of methane, it is both a major contributor to global warming and a valuable source of energy (Wetherill *et al.*, 1999).

Control and utilisation of LFG is recognised as being one of the most economically attractive greenhouse gas (GHG) mitigation options. LFG can be used for different purposes, such as burning to produce heat, supplying gas engines or turbines producing electricity, upgrading to natural gas quality by removing CO_2 and trace gases, as gas in boiler plants or, after purification, can be fed into the natural gas distribution network (Willumsen, 1996; Stegmann, 1996). The use of energy recovery for the control of MSW landfill air emissions has the potential to reduce secondary air impacts at coal-fired power plants and to decrease the use of fossil fuels (Thorneloe, 1996).

2.10.1 Utilisation options or approaches

There are basically three approaches for LFG utilization (Couth, 2000b; Wetherill *et al.*, 1999). These include:

i. Direct use

ii. Generation of electricity
iii. Gas processing and injection into gas pipelines

2.10.1.1 Direct use of LFG

The direct use of the LFG is often the simplest and most cost-effective approach. The options for direct-gas use include using it as a boiler fuel, for space heating and cooling, and industrial heating/co-firing applications or residential use (Thorneloe, 1996; Wetherill, 1999). These options require that the gas be transported, typically by a dedicated pipeline, from the point of collection to the point(s) of gas use. LFG has also been used as a direct end use replacement fuel in cement and brick kilns, bitumen production, lumber dying and leachate treatment. An advantage of many industrial applications is that fuel is required continuously, 24 hours per day (Thorneloe, 1996).

Using LFG as direct fuel leads to high efficiency rates, up to 90% (Stegmann, 1996). The LFG is cleaned by removing moisture and particulates prior to use. After this minimal level of cleaning, a gas quality of about 35% to 50% methane is typically produced (Wetherill, 1999). This level of methane concentration is generally acceptable for use in a variety of equipment, including boilers and engines. Lower concentrations are a result of overpumping the landfill, pulling air from outside into the landfill and diluting the LFG (Stegmann, 1996).

2.10.1.2 Electricity generation

If the direct use of LFG is not possible in a particular landfill site, the gas can be used to generate electricity. Production of electricity in internal combustion (IC) engines is practised all over the world in many plants. Internal combustion engines are the most commonly used conversion technology used in landfill-gas applications. Reprocating IC engines drive electrical generators to produce electrical power, which is typically sold to the local electric utility (Thorneloe, 1996). In the case of Pietermaritzburg Msuduzi TLC, South Africa, generation of power requires some 700 Nm^3h^{-1} of landfill gas at 50 % CH_4. Installation of a 900 kW capacity spark ignition engine, generator and switch gear is estimated to cost R3000 000 (Lombard *et al.*, 1998).

Landfill gas is very corrosive and water saturated. Consequently, the use of LFG in an IC engine can cause corrosion due to the impurities in LFG. As a result, the gas must be cleaned and filtered prior to use (Wetherill *et al.*, 1999). Corrosion can be avoided when specific oil developed for LFG engines is used (Stegmann, 1996).

Gas turbines can also be used to generate electricity in the landfills. Unlike IC engines, they require greater supply of gas (over 2500 m^3h^{-1}) to be economically attractive, and have therefore been used at larger landfills (Couth, 2000b; Wetherill *et al*, 1999). Turbines need greater clean up of the gas, and are consequently less flexible than reciprocating engines for LFG utilization. Turbines perform best when they operate at full load and difficulties can occur when they are operated at less than full load (Thorneloe, 1996).

2.10.1.3 Processing and injection of gas

In certain cases, the gas can be processed and injected into a gas distribution pipeline. There have been a number of projects worldwide to upgrade LFG to a similar energy value to natural gas. To do this, LFG needs to be dried, and have CO_2, sulphur and halogenated components removed (Couth, 2000b). However, these have not been significantly developed to date. Natural-gas pipelines typically transport high quality gas that contains over 95% methane and the LFG must be processed to remove carbon dioxide and other impurities (Wetherill *et al.*, 1999). Processing the LFG increases the cost of production, and is not usually economically viable unless costs for natural gas are high.

CHAPTER 3

METHODS USED TO ESTIMATE LFG EMISSIONS

3.1 INTRODUCTION

This chapter introduces general classifications and important information on which most models developed are based. There are several methods used for modelling landfill gas generation. The development of landfill gas models started in the 1970s. There is a high demand for LFG models that are able either to forecast the yield and generation rate of biogas produced, or to evaluate the potential gas migration and variety of related problems (Cossu *et al.*, 1996). The rationale to use LANDGEM model in this study as is indicated in other sections (Chapters 1, 5, 6 and 7) include its capacity to predict LFG generation for long periods of more than 200 years and ability to predict individual species (components) of LFG.

3.2 CLASSIFICATION OF MODELS

Depending on the approach, different classifications of models can be formulated. A general classification can be based on the availability of data and the state of knowledge of the system (Cossu *et al.*, 1996):

(i) **Statistical analysis** occurs when a large number of data are available, but knowledge of the system is inadequate. This kind of model presents general characteristics of data available and provides correlations.

(ii) **Stochastic model** is useful for describing the behaviour of black-box systems, which are characterized by input and output data. The describe the temporal trend of data without explaining it. Mathematical expression can be used to relate output to the input.

(iii) **Simplified deterministic model** requires knowledge of the mechanism governing the system. It describes the behaviour of the system with simplified mathematical equations. Most LFG models belong to this group.

(iv) **Complex deterministic model** operates in a similar manner to the above-mentioned model, but it uses more complex mathematical equations. This model can be used in the ecosystem to describe the relation between system components, and at this situation is referred to as ecological model.

Coops *et al.* (1995) state that, in general, LFG models are not based on microbiological or biochemical principles, but primarily on a practical description of LFG formation. There are numerous factors that influence either the amount of landfill gas eventually formed, or the speed at which it is produced. In general, these factors are all related to (Coops *et al.*, 1995):

- Waste composition, which determines the amount of degradable organic carbon in the waste, which is the raw material for landfill gas;
- Waste treatment, which involves mechanical pre-treatment, homogenisation, particle size reduction and baling, the extent of compaction, the dumping method, the addition of water all of which have significant effects on landfill gas formation;
- Site management, that includes site geometry, landfill gas recovery, and leachate water management;
- Local or regional climate conditions: temperature, precipitation, and evaporation.

All the above aspects differ from site to site. As a consequence, the amounts of LFG produced per tonne of waste and the speed at which the LFG is generated, differ from site to site.

As outlined in Section 2.5, LFG is formed as result of decomposition of organic carbon in the waste. It has been estimated that 1.87 m^3 of biogas is generated by degradation of 1 kg of organic carbon In general, LFG formation is calculated from waste amounts, composition and age using a model.

3.3 MODELLING LFG GENERATION

3.3.1 LFG generation rates

As outlined in the Section 2.5, LFG is formed as a result of decomposition of organic carbon in the waste. It is estimated that approximately 1.87 m^3 of LFG is produced per kg of organic carbon (Muntoni *et al.*, 1995; Coops *et al.*, 1995). The LFG formation on a waste body at a particular time, α_t, is proportional to the decay of organic waste at that time (Coops *et al.*, 1995):

$$\alpha_t = -1.87A\frac{dC}{dt} \tag{3.1}$$

Where, A is the amount of waste in place. Organic material degradation can be described as an nth order reaction equation (Coops *et al.*, 1995):

$$\frac{dC}{dt} = c \, . \, C^n \tag{3.2}$$

The substitution of solutions for equation (3.2) into equation (3.1) results in the formation of the models discussed below (Coops *et al.*, 1995):

Zero order model $\alpha_t = \zeta\, 1.87 k_0 A$

First order model $\alpha_t = \zeta\, 1.87\, A C_0 k_1 e^{-k_1 t}$

Second order model $\alpha_t = \zeta 1.87 A k_2 \left(\frac{C_0}{k_2 C_0 + 1}\right)^2$

Multi-phase model $\alpha_t = \zeta \sum_{j=1}^{3} 1.87 A C_{0,i} k_{1,i} e^{-k_{1,j} t}$

where:

α_t : LFG formation, m^3yr^{-1}

ζ : formation factor,

A : amount of waste in place, tonnes

C_0 : organic carbon content of the waste, kg/tonne

$C_{0\ i}$: amount of organic carbon of specific fraction, kg/tonne

k_0: model parameter for zero order model, kg $tonne^{-1}yr^{-1}$

k_1 : model parameter for first order model, yr^{-1}

k_2 : model parameter for second order model, m^3 $tonne^{-1}yr^{-1}$

$k_{1,i}$: model parameter for multi-phase order model, yr^{-1}

t : time elapsed since deposition, yr

These models mentioned above use simple and complex mathematical equations to describe the system (i.e. to estimate LFG formation), hence zero and first-order models may fall under type (iii) as they apply simple mathematical aspects, and second-order and multi-phase models belong to type (iv) since their mathematical considerations are advanced and complicated.

(a) Zero order model

In this model, landfill gas formation in a certain amount of waste is assumed constant with time. A zero-order model indicates that the rate of methane generation is not influenced by the amount of substrate remaining or the amount of biogas already produced (Cossu *et al.*, 1996).

(b) First order model

Landfill gas formation in a certain amount of waste is assumed to decay exponentially in time, hence it assumes waste to have a certain half-life of biodegradation. The majority of LFG models follow first order kinetics (Cossu *et al.*, 1996), which means that the limiting factor is the remaining amount of substrate or the amount of biogas generated. The USA EPA LANDGEM model that is used in this study to estimate LFG emissions from landfills uses first order equations (see Section 4.2).

(c) Second order model

This model describes the process, which consists of a large number of reactions with different reaction rates. Since LFG production is a complex system of different reactions, second-order kinetics might be suitable (Coops *et al.,* 1995).

(d) Multi-phase model

In this model, most fractions are differentiated, in order to describe LFG formation separately. Typical waste composition consists of slow, moderate and fast degradable fractions, and therefore the use of a multi-phase model is appropriate. This model uses first order equations for a range of waste including slow, moderate and fast degradable materials (Coops *et al.*, 1995).

3.3.2 Estimation of LFG yields

It is generally acknowledged in the literature that the maximum theoretical yield of LFG from MSW landfill is of order of 400 m^3/ton. A cumulative yield of 100 m^3/ton from household waste over the entire lifetime of the site is more likely (Gregory, 2000). According to Gregory (2000), LFG generation rates are typically only between 5 – 10 m^3 per tonne a year in first few years of active landfill operation, and decline thereafter.

Muntoni *et al.* (1995) proposed a biochemical model of biogas production. This model allows the forecast of gas emissions from the entire landfill. The total biogas formation is given by the equation below:

$$G_e = 1.868. C \qquad (3.3)$$

where, G_e is total gas production in m^3/t_{msw}, and C is organic fraction of MSW in kg/t_{msw}.

Since the organic fraction of MSW is not completely biodegradable, it is assumed that biodegradable organic carbon represents about 50% of total organic carbon (Lombard *et al.*, 1998). However, it is well known that different waste components have varying biodegradability (Table 3.1). It is noted that plastic and rubber materials, in particular, are the most non-biodegradable waste components. Some authors have estimated the total amount of organic carbon in municipal solid waste as 200 kg per ton MSW or 250 kg per ton MSW (Muntoni *et al.*, 1996).

Table 3.1: Organic carbon content (OC_i) and biodegradable organic fraction $(f_b)_i$ in different waste components (Andreottola and Cossu, 1988, in Cossu *et al.*, 1993).

Waste component	OC_i *(kg C/kg dry component)*	$(f_b)_i$ *(kg biodeg. C/kg C)*
Food waste	0.48	0.8
Yard waste	0.48	0.7
Paper and cardboard	0.44	0.5
Plastics and rubber	0.7	0.0
Textiles	0.55	0.2
Wood	0.5	0.5
Glass	0.0	0.0
Metals	0.0	0.0

However, biodegradability of organic waste may also depend largely on the lignin content of the waste (Tchobanoglous *et al.*, 1993). The biodegradable fractions of different waste components based on lignin content are presented in Table 3.2. It can be observed that these biodegradable fractions are very similar to those derived by Andreottola and Cossu (1988).

The generation of methane in landfills occurs during the methanogenic phace usually succeeding the acid phace of refuse degradation (Haarstad, 1997). The overall methane fermentation process in solid waste may be represented by the reaction equation below (Ham, 1988; Cossu *et al.*, 1996):

$$C_aH_bO_cN_d + nH_2O \Rightarrow xCH_4 + yCO_2 + wNH_3 + zC_5H_7O_2N + \text{energy} \tag{3.4}$$

Where $C_aH_bO_cN_d$ is the empirical chemical formulation for biodegradable organic material in solid waste, and $C_5H_7O_2N$ is the chemical formulation of bacterial cells.

Table 3.2: Biodegradability organic waste based on lignin content (Tchobanoglous *et al.*, 1993).

Organic waste component	Lignin content (% of VS)	Biodegradable fraction (% of VS[a])
Food waste	0.4	0.82
Newspaper	21.9	0.22
Office paper	0.4	0.82
Cardboard	12.9	0.47
Yard waste	4.1	0.72

[a] Represents Volatile Solids.

The energy content of the organics is split into the free energy content of CH_4, the energy for bacterial synthesis and the enthalpy of the reaction (Cossu *et al.*, 1996). For the practical evaluation of maximum theoretical LFG yield, cell conversion of organic matter can be neglected and equation (3.4) becomes

$$C_aH_bO_cN_d + \frac{4a-b-2c+3d}{4}.H_2O \Rightarrow \frac{4a+b-2c-3d}{8}.CH_4 + \frac{4a-b+2c+3d}{8}.CO_2 + dNH_3 \tag{3.5}$$

According to this equation the substrate material, $C_aH_bO_cN_d$, is decomposed anaerobically to methane, carbon dioxide and ammonia (Ham, 1988). Equation (3.5) allows the estimation of a maximum theoretical yield of landfill gas, starting from the general formula characterizing solid wastes ($C_aH_bO_cN_d$). The refuse can be analyzed to determine its elemental composition and its chemical formula calculated. This is followed by the use of equation (3.5) to compute the amount of gas that can be produced theoretically (Ham, 1988; Cossu *et al.*, 1996). Specific materials such as food waste or cellulose are known to be degraded into methane and the use of their chemical composition in equation (3.5) can assist in the calculation of the amount of gas generated. Application of equation (3.5) to specific materials found in MSW gives the results shown in Table 3.3, which report gas yield and gas composition derived from the degradation of a single compound or class of compounds (Ham, 1988; Cossu *et al.*, 1996).

Table 3.3: The Theoretical gas yields of LFG (CH_4+ CO_2) and methane for some typical classes of compounds (Ham, 1988; Cossu *et al.*, 1996).

A (Compound)	**Formula**	**Gas Yield** *(Nl/kgA)*[a]	**Gas composition** *(%CH_4)*
Cellulose	$(C_6H_{10}O_5)_x$	830	50
Protein	$(C_4H_6ON)_y$	1100	51.5
Lipids	$C_{55}H_{106}O_6$	1428	71.4
MSW	$C_{99}H_{149}O_{59}N$	966	54
Food Waste	$C_{16}H_{27}O_8N$	993	56

[a] unit represents volume of LFG produced per kilogram of waste A.

3.4 SUMMARY

Modelling and calculation of LFG generation rates and emissions is an important tool to evaluate and understand the nature of biogas released from landfill sites. Organic material of waste is the main source of LFG generation, and it is from this organic waste that LFG can be theoretically calculated. Quantity and rate of gas produced depend on type of waste deposited in a particular landfill. The rapidly decomposable components of organic waste generate great quantities of LFG with high content of CH_4.

CHAPTER 4

DATA AND METHODOLOGY

4.1 INTRODUCTION

This chapter provides a background on the LANDGEM model, which is the model selected to simulate landfill gas emissions in the DMA landfill sites. It also provides details of the input data utilized for the three landfill case studies. The existing Bisasar Road landfill, which is a large landfill classified as G:L:B$^+$ (See Section 1.3) accepts general waste, as will the proposed Buffelsdraai landfill. Shongweni landfill, however, is a large co-disposal site that accepts low hazardous wastes and hence is classified as H:h (See Section 1.3). The methods used to calculate gaseous emission rates are also included in this chapter.

4.2 LANDFILL GAS EMISSION MODEL (LANDGEM)

4.2.1 Background

The LANDGEM model was developed by the Control Technology Centre (CTC) of the United States Environmental Protection Agency (US EPA) (Pelt *et al.*, 1998). The model was released in September 1998 and can be accessed free of charge by downloading from the website http://www.epa.gov/ttn/catc/. The version of the model that will be used in this study is version 2.01 of LANDGEM, which has been upgraded from version 2.0. Full details concerning the model can be accessed in the EPA (1991a) document (Thorneloe *et al.*, 1999).

The LANDGEM model is classified as a simplified deterministic model according to the classification of Cossu *et al.* (1996) (See Section 3.2). It uses simplified mathematical equations to describe the decay of waste and since it is based on a first order decomposition rate reaction, it is also known as a first order model (Coops *et al.*, 1995).

4.2.2 Input data

The following input data are needed to estimate emissions from a landfill (Thorneloe *et al.*, 1998; 1999):

- The design capacity of the landfill, which indicates the total amount of waste that can be disposed of in the landfill;
- The amount of waste in place in the landfill, or the annual acceptance rate,
- The methane generation rate (k), which determines the rate of landfill gas generation;
- Potential methane generation capacity (L_o), which represents landfill potential to generate methane;
- The concentration of total and speciated NMOC;
- The years the landfill has been accepting waste (from open to closure year); and
- The nature of the landfill, i.e. whether it has been used for disposal of hazardous waste (co-disposal).

The input data for the three landfill sites in the study area are presented in Table 4.1. According to a permit application report by Drennan *et al.* (2000c), the Buffelsdraai landfill is estimated to accept refuse at a rate of 400 tons/day in the initial stages, and after closure of Bisasar Road landfill will increase to 991 tons/day (Section 1.3.3). This landfill is expected to operate for more than 70 years hence the closure is anticipated to be in 2073 (Table 4.1).

The values for other model input parameters are given in Table 4.2. In order to estimate landfill gas emissions, the model can be run using site-specific data, or in the absence of site-specific data, two different sets of defaults can be used. One set, the Clean Air Act (CAA) defaults, is used to estimate emissions in order to evaluate the applicability of the Clean Air Act regulations for MSW landfill emissions. This set determines whether the landfill is subject to the control requirements of the New Source Performance Standards

Table 4.1: Landfill input data for the three landfill case studies

Landfill Parameters	Bisasar Road	Shongweni	Buffelsdraai
Landfill Type	No Co-disposal	Co-disposal	No Co-disposal
Year Opened **Current Year** **Closure Year**	1980 2001 2012	1997 2001 2011	2003 2023[a] 2073
Landfill Capacity ($x10^6$ m^3)	21	1,6	40
Refuse Acceptance Rate (tons/day)	3000	400	400 991
Refuse in Place by year 2001 ($x10^6$tons)	10	0.445015	-

Source of data: Enviroserv Waste Mangement Pty(Ltd), 2000; Durban Solid Waste, 2000; Lombard *et al.*, 2000.

[a] The current year in which the emissions from Buffelsdraai landfill would be simulated is anticipated to be in 2023.

(NSPS) and emission guidelines, for new and existing MSW landfills in US (Pelt *et al.*, 1998).

Table 4.2: Model input parameters for all selected landfill sites

Parameters	Magnitude
L_o	100 m^3/Mg
k	0.04 l/yr
CH_4[a]	65 %
CO_2[b]	35 %
NMOC	595 ppmv (No Co-diposal) 2420 ppmv(Co-disposal)

Source of data: Pelt *et al.*, 1998.

[a] and [b] ratios estimated to represent typical LFG coming out of DMA landfill sites (Lombard, 2001, pers.com).

The other set of default values, the AP-42 defaults, is provided with the model to estimate emissions in the absence of site-specific data (Thorneloe *et al.*, 1999). The AP-42 default values are based on emission factors from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42*. They provide emission estimates that should reflect typical landfill emissions and are the values suggested for use in developing estimates for state inventories (Thorneloe *et al.*, 1999; Pelt *et al.*, 1998). This set of defaults is used in this study in all three landfill case studies.

CH_4 generation rate is estimated to be at its peak during closure of the landfill. CH_4 generation is approximated using two parameters: L_o, the methane generation potential of refuse, and k, the methane generation rate constant, which accounts for how rapidly the CH_4 generation decreases once it reaches the peak rate. L_o and k are constants. L_o for MSW varies from 0 to 400 m^3/Mg (Couth, 2000a), and k ranges from 0.02 to 0.05 1/yr (Pelt *et al.*, 1998). The theoretical AP-42 default values for L_o range from 6.2 to 270 m^3/Mg of refuse (Pelt *et al.*, 1998). Default values for 'k' and 'L_o' were used in this study (Table 4.2).

The ratio of CH_4 and CO_2 in LFG is site specific and is influenced by several factors (see Section 2.6). Studies in Durban have shown the average ratio to be roughly 65 % CH_4 and 35 % CO_2 (Letcher, 2001, pers.com; Lombard, 2001, per.com), mainly due to the climatic conditions of high temperature and high rainfall. This is the ratio used in this study as indicated in Table 4.2. The AP-42 default values for NMOC concentrations prevailing in no co-disposal and co-disposal landfills are also presented in Table 4.2. Other model and landfill input parameters are reported in Appendix 2.

4.2.3 Estimation of total landfill NMOC emission rate by LANDGEM

The equations below are used by LANDGEM to estimate the landfill NMOC emission rates, based on whether the refuse acceptance rate is known or unknown. Equation (4.1) is used in the case where the actual year-to-year solid waste acceptance rate is known (Thorneloe *et al.*, 1999):

$$M_{NMOC} \equiv 2\overset{n}{\underset{i=1}{k}} L_{\circ} M_i \left(e^{-kt_i}\right)\left(C_{NMOC}\right)\left(3.6 \times 10^{-9}\right) \qquad (4.1)$$

where,

M_{NMOC} = total landfill NMOC emission rate, Mg/yr

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

$L_{\circ}$ = methane generation potential, cubic meters per Mg of waste

M_i = mass of solid waste in the ith section, Mg

t_i = age of the ith section, years

C_{NMOC} = concentration of NMOC, parts per million by volume as hexane

If the actual year-to-year solid waste acceptance rate is unknown, the model applies equation (4.2):

$$M_{NMOC} \equiv 2L_{\circ}R\left(e^{-kc} - e^{-kt}\right)\left(C_{NMOC}\right)\left(3.6 \times 10^{-9}\right) \qquad (4.2)$$

where,

M_{NMOC} = mass emission rate of NMOC, Mg/yr

$L_{\circ}$ = methane generation potential, cubic meters per Mg of solid waste

R = average annual acceptace rate, Mg/yr

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

c = time since closure, years (for active landfill c = 0 and $e^{-kc} = 1$)

t = age of landfill, years

C_{NMOC} = concentration of NMOC, parts per million by volume as hexane

4.2.4 Output from model

The model supplies annual emission rate estimates of CH_4, CO_2, NMOC and other selected air pollutants from MSW landfills over the lifetime of the landfill and after its closure. LFG is assumed by the model to contain approximately 50% CH_4 and roughly 50% CO_2, with the inclusion of relatively low levels of 47 other air pollutants released from degradation of wastes. However, these default percentages can be changed, as was done in this study (see Section 4.2.2).

The primary pollutants that will be considered in this study involve gases that contribute significantly to the greenhouse effect and global warming, odour nuisance, and those that are mostly associated with problems in human health. The two main carcinogens of concern in the LFG are benzene and vinyl chloride. Furthermore, gases such as carbon monoxide that indicates danger (i.e. fire indicator) in the landfill site will also be included. The gases considered include:

- Benzene (C_6H_6)
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Dichlorodifluromethane ($CCl_2\ F_2$)
- Ethyl mercaptans (CH_3CH_2S)
- Fluorotrichloromethane (CCl_3F)
- Hydrogen sulphide (H_2S)
- Methane (CH_4)
- Methyl mercaptans (CH_3S)
- Non Methane Organic Compounds (NMOC)
- Vinyl chloride (CH_2CHCl)

4.3 SENSITIVITY ANALYSIS

A sensitivity analysis was performed in order to evaluate the sensitivity of the model to selected parameters. When using the model, many assumptions, the use of default values and the lack of data are common factors that are likely to lower the precision of the results. The sensitivity of this model to variations in certain parameters was considered. The parameters investigated included:

- CH_4 and CO_2 ratio
- Concentration of NMOC of landfill
- Landfill design capacity

- Magnitude of k and L_o values
- Refuse acceptance rate
- Refuse in place

CHAPTER 5

MODELLED RESULTS OF LANDGEM MODEL

This chapter presents results of predicted LFG emissions from landfills based on the LANDGEM model. The chapter ends by determining the sensitivity of the LANDGEM model. Simulations of a number of parameters were used to evaluate the sensitivity of the model.

5.1 LANDGEM MODEL RESULTS

5.1.1 Introduction

The Landfill Gas Emission Model estimates the gaseous emissions resulting from decaying refuse in the landfill. The anaerobic decomposition of waste in a landfill produces LFG, which is dominated by CH_4 and CO_2 constituents. Other landfill air pollutants present in LFG accompany these gases. This section will focus on emissions of targeted greenhouse gases (GHG), odorous emissions and volatile organic compounds, which include: methane, carbon dioxide, hydrogen sulphide, methyl and ethyl mercaptans, dichlorodifluoromethane, trichlorofluoromethane, vinyl chloride, carbon monoxide and benzene. Default input parameters for the CH_4 generation potential (L_o) and the CH_4 generation rate constant (k) are used for all three landfills.

5.1.2 Primary greenhouse gases (GHG) emitted from landfills

As mentioned earlier, the two greenhouse gases of CO_2 and CH_4 dominate LFG. Table 5.1 presents the maximum projected emissions of CH_4 and CO_2 according to the LANDGEM model in the three selected landfills in the DMA. Figures 5.1 and 5.2 illustrate the emissions of these greenhouse gases over time for the Bisasar Road landfill. Similar graphs for the other landfill sites are included in Appendix 1.

Table 5.1 Predicted maximum emissions of CH_4 and CO_2 in three DMA landfills, based on the LANDGEM model

Landfills	**Maximum levels of major landfill GHG (Mg/yr)**	
	CH_4	**CO_2**
Bisasar Road	3.630E+04	5.363E+04
Shongweni	3.389E+03	5.007E+03
Buffelsdraai	4.250E+04	6.279E+04

Carbon dioxide emissions are in all three cases higher than CH_4 emissions. This is contrary to expectations since during methanogenesis, LFG comprises approximately 60-65 % CH_4 (DoE, 1991; Micales & Skog, 1997). Possible reasons for this will be discussed later. The magnitude of the emissions from Bisasar Road and Buffelsdraai landfills are fairly similar (Table 5.1), which may be due to the fact that they are both No Co-disposal (sanitary) landfills.

The LANDGEM model shows LFG to increase with increasing waste deposition over time, and to peak during the year of closure (Figs. 5.1 and 5.2). CH_4 and CO_2 production rates are estimated to reach their peak during closure of the landfill (Thorneloe *et al.*, 1999). In the post-closure phase, the gas emissions decline over period of 200 years according to the LANDGEM model, and become negligible 100 to 150 years after closure. The emissions suddenly decline because little or no fresh, rapidly decomposable waste is available for biodegradation. The continuous release of gas after the cessation of waste disposal is due to biogasification of slow biodegradable wastes (see Section 2.6.2), such as textiles. From Figures 5.1 and 5.2, it is noted that CH_4 and CO_2 emitted by the Bisasar Road landfill are negligible after the year 2160.

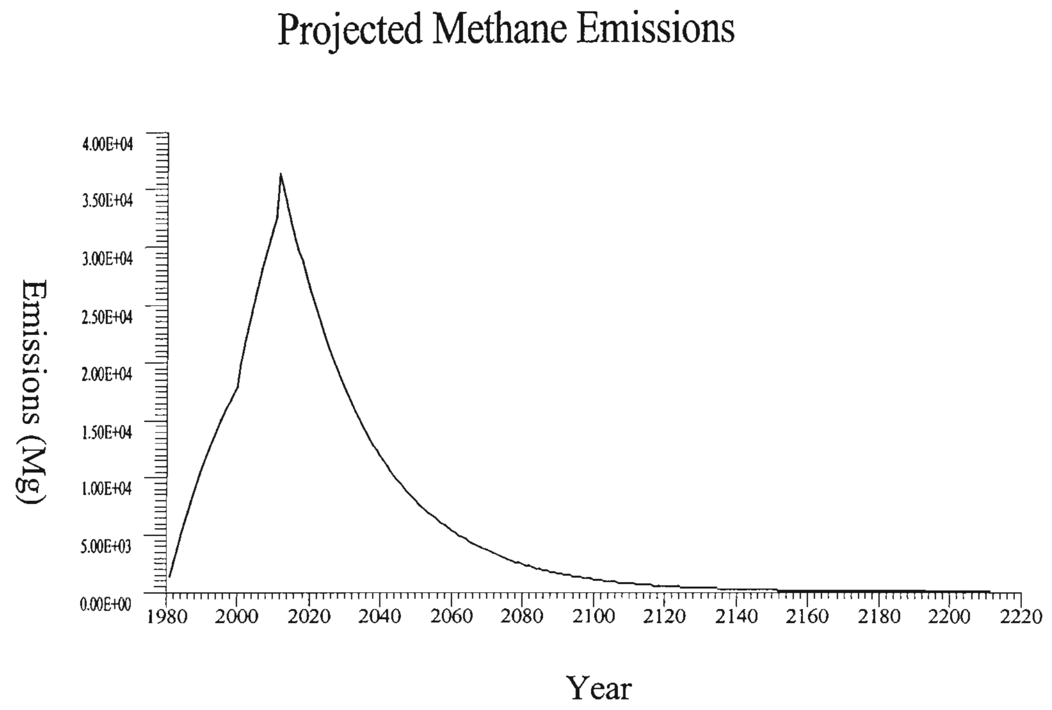


Figure 5.1 Estimated emissions of CH_4 at Bisasar Road landfill based on LANDGEM model

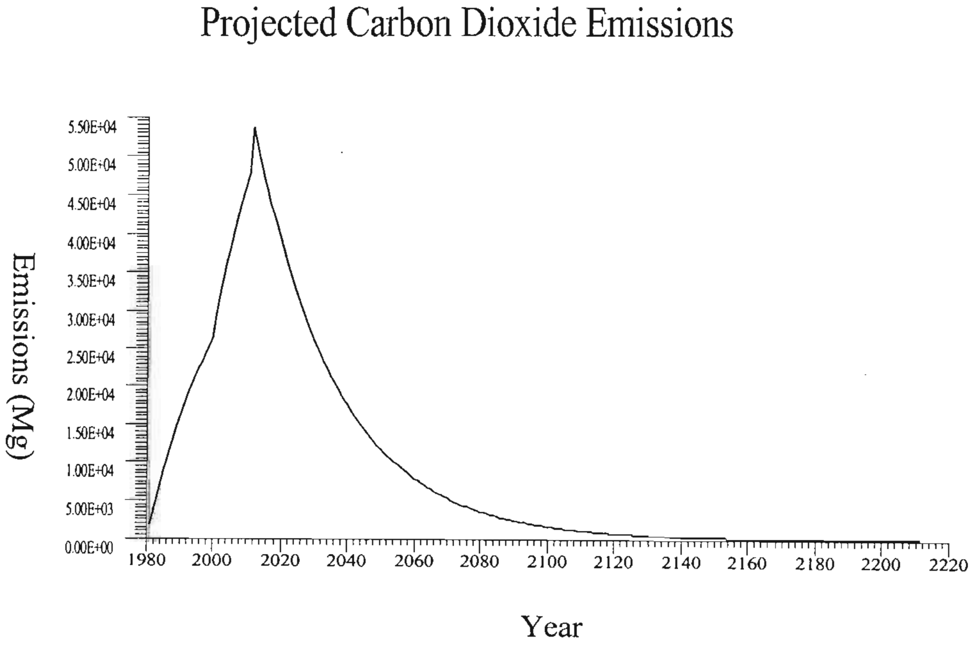


Figure 5.2 Estimated emissions of CO_2 at Bisasar Road landfill based on LANDGEM model

Emissions during the early stages of landfilling at the Buffelsdraai landfill are released at lower rates, but increases sharply after 2012 when the waste acceptance rate increases (Appendix 1).

The results of this model with respect to CO_2 and CH_4 levels reveal that surface emissions of CO_2 are always higher than CH_4 emissions. Gardner *et al.* (1993) reported that current total rate of CH_4 emissions in the UK is less than that of CO_2 emissions, however, it is increasing much more than the rate of CO_2. Therefore this situation supports the results of the LANDGEM model. It follows that large quantities of CH_4 are oxidised microbiologically to CO_2 within the landfill cover soil before reaching the atmospheric environment (Bogner *et al.*, 1997). There are many factors that contribute to the methane oxidation capacity of soil, including soil moisture content, soil temperature, microbial activity of methanotrophic bacteria that reside in the landfill cover soil, soil type and thickness of cover (Gardner *et al.*, 1993; Boeckx *et al.*, 1996; Bogner *et al.*, 1997; Micales and Skog, 1997; Visvanathan *et al.*, 1999; Borjesson *et al.*, 2000;).

Tropical climates with high soil temperatures and moisture content are most suited to methane oxidation (Visvanathan *et al.*, 1999). Methane oxidation is optimum at moisture contents of about 15-20 % and temperatures of 30-35°C (Haarstad, 1997; Visvanathan *et al.*, 1999). Since the DMA is a moist, subtropical region it is expected to have similar conditions. The Bisasar Road landfill is a wet landfill and thus has a high potential for CH_4 oxidation. Soil moisture is a critical factor affecting CH_4 oxidation because it influences both the movement of gases through the soil and microbial activity (Bogner *et al.*, 1997).

Water or an aqueous environment is one of the most important factors in anaerobic digestion, which is the process that leads to LFG formation (Gardner *et al.*, 1993). Most of the moisture available in a landfill originates from the waste itself (Micales and Skog, 1997). Therefore in co-disposal sites such as the Shongweni landfill, which accepts hazardous liquid wastes, faster degradation may be anticipated. The *in-situ* moisture content of the waste, although determined by factors such as the infilling method and original moisture content, is also influenced significantly by the site hydrogeology (Gardner *et al.*, 1993). Moisture levels may vary greatly within a single landfill, thereby causing highly variable rates of degradation at points within close proximity to each other (Micales and Skog, 1997). This implies that different stages of decomposition can occur within a single landfill.

Methanotrophs are a class of methylotrophs, which are capable of gaining energy from the oxidation of reduced carbon compounds containing one or more C-atoms (Bogner *et al.*, 1997). Portions of CH_4 diffusing into such landfill covers may be oxidised by methonotrophs which use the following reactions to gain energy and carbon for their growth (Borjesson *et al.*, 2000):

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO_2 \qquad (5.1)$$

Energy is yielded in all steps, except in the first. In cover soils that have been in place for several years methanotrophic CH_4 oxidation processes may become well established (Bogner *et al.*, 1997), and these require high concentrations of oxygen and aerated cover soil (Boeckx *et al.*, 1996; Visvanathan *et al.*, 1999). Oxidation is at an optimum in aerobic soil which is sufficiently permeable to allow oxygen to diffuse deep into the soil. Bisasar Road landfill has sandy soil which suits this process. The well-drained soil with a sandy, open structure, allows the free movement of gases, thus enhancing CH_4 oxidation. Shongweni landfill soil cover is generally very moist as a result of liquid wastes disposed at this site, as mentioned earlier. An increase in the moisture content at the top of the landfill would bring methanotrophs to the surface and may be an alternative means of attaining maximum oxidation rates (Visvanathan *et al.*, 1999).

Methane that escapes through cracks or macropores in the cover soil is not exposed to CH_4 oxidising methanotrophic bacteria hence will not be oxidesed (Micales and Skog, 1997). However, at the moment, landfill caps and cover soil are not designed with CH_4 oxidation in mind. In some developed and developing countries, landfills have little or no cover soil, and during the dry season cracks may form unless they are irrigated

(Bogner *et al.*, 1997). Therefore, it follows that landfill cover soil could be selected and engineered to optimise CH_4 oxidation. Manipulation of landfill cover soils to maximize their CH_4 oxidation potential may provide a complementary strategy for controlling GHG emissions, especially at older sites where CH_4 levels in the landfill are too low for flaring or energy recovery (Bogner *et al.*, 1997). This is particularly relevant for the Bisasar Road landfill, which has been operating for over 20 years.

A landfill can be a sink for atmospheric CH_4 in certain situations. If the rate of CH_4 oxidation exceeds the flux of CH_4 from the waste into the soil cover, and there is adequate O_2 diffusing into the soil, there may be net oxidation of atmospheric CH_4 (Bogner *et al.*, 1997). In such situations, the internal pressure (P_{int}) within the landfill tends to be less than atmospheric pressure (P_{atm}). It was reported recently that the Illinois landfill in US, served as a CH_4 sink due to very high levels of CH_4 oxidation in the cover soil and a CH_4 recovery system that lower the overall pressure of CH_4 in the landfill (Bogner *et al.*, 1997). The internal pressure in a landfill is mostly greater than atmospheric pressure causing the gas to be emitted. If it were less then the gas would not be emitted but held within the waste.

5.1.3 Production of odours from landfills

The compounds identified to be odorous in this study are mainly the organosulphur compounds produced during the biodegradation of waste. These are trace components of LFG (see Section 2.5.2.1 and 2.8.2.3), which involve hydrogen sulphide, methyl- and ethyl mercaptans. Table 5.2 indicates potential maximum levels of these odorous compounds predicted for each landfill.

Table 5.2 Predicted maximum emissions of H_2S, CH_3-SH and CH_3CH_2-SH in the DMA landfills according to LANDGEM model

Landfill	**Maximum emissions of landfill odorous emissions (Mg/yr)**		
	Hydrogen sulphide (H_2S)	**Methyl mercaptan (CH_3-SH)**	**Ethyl mercaptan (CH_3CH_2-SH)**
Bisasar Road	4.212E+00	4.171E-01	2.704E-01
Shongweni	3.933E-01	3.894E-02	2.525E-02
Buffelsdraai	4.931E+00	4.883E-01	3.166E-01

From Table 5.2 it is observed that the odorous pollutant with the highest emission rate is H_2S, followed by methyl mercaptan, with the least being the thiol compound (S-compound), ethyl mercaptan. These odorous emissions are much lower than those of the major constituents of LFG, namely CH_4 and CO_2 (see Section 5.1.2), and hence are referred to as trace components of LFG. They follow a similar trend to that of CH_4 and CO_2, in that their emissions also peak during landfill closure and decline thereafter (see Figs. 5.3 - 5.5 and Appendix 1). This may due to the fact that they are all the constituents of LFG, thus they follow the trend of the overall biogas.

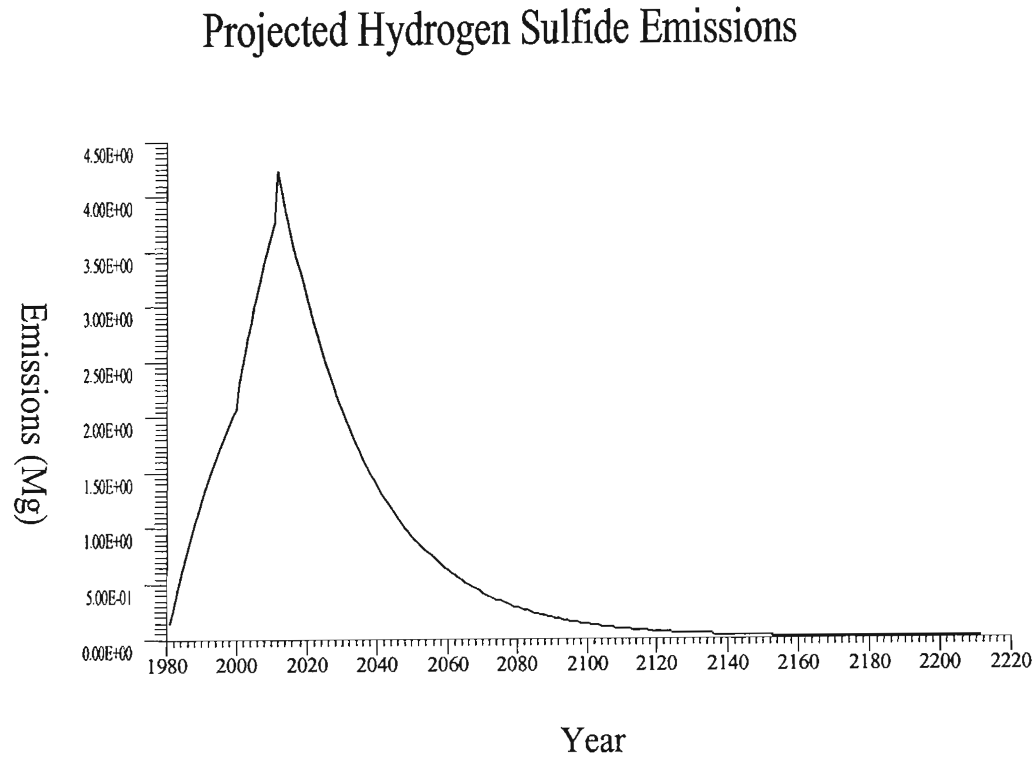


Figure 5.3 Estimated emissions of H_2S at Bisasar Road landfill based on LANDGEM

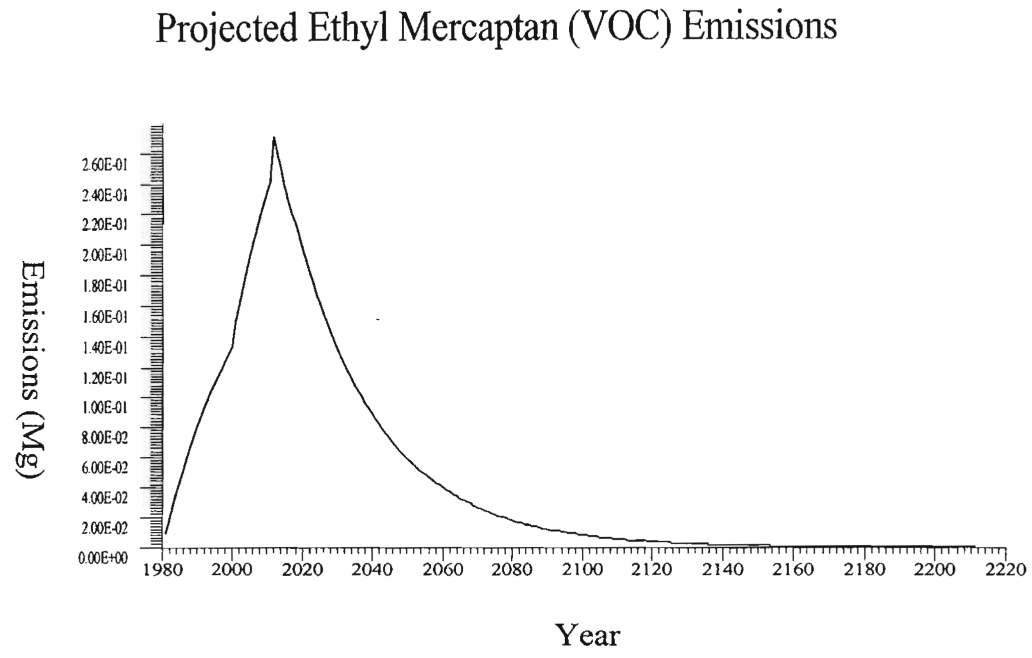


Figure 5.4 Estimated emissions of CH_3CH_2-SH at Bisasar Road landfill based on LANDGEM model

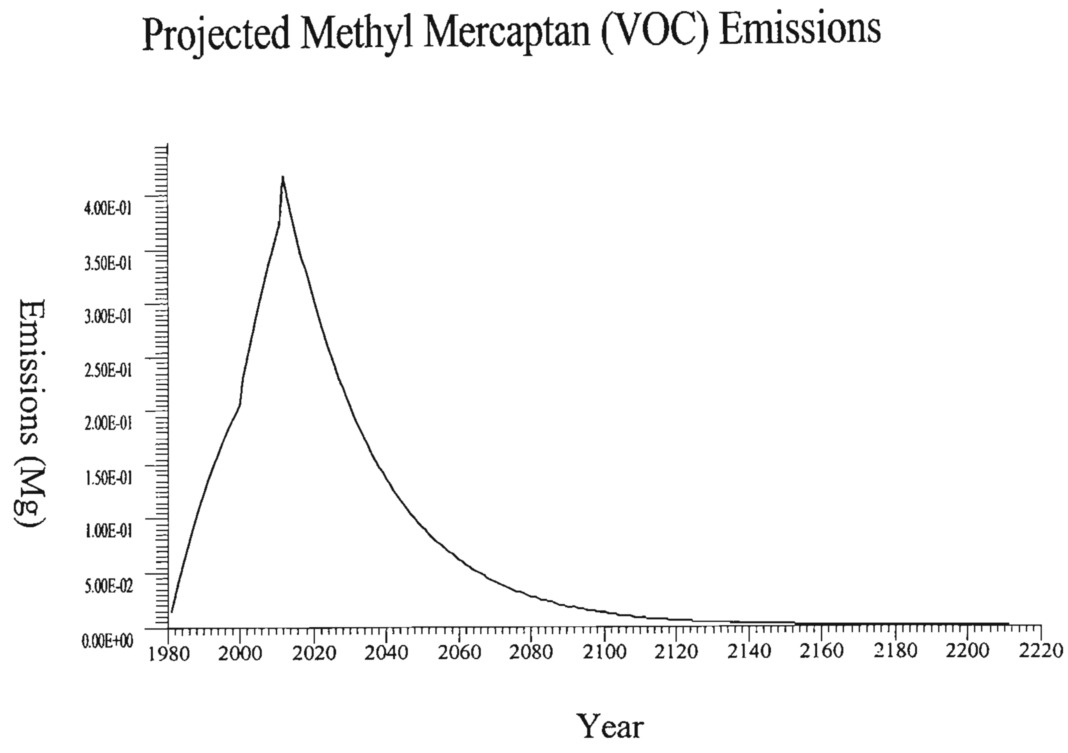


Figure 5.5 Estimated emissions of CH_3-SH at Bisasar Road landfill based on LANDGEM model

Hydrogen sulphide and other organosulphurs are expected to decline as degradation proceeds, however, the addition of large quantities of sulphate-bearing wastes may lead to very much higher levels (Young and Heasman, 1985). Sulphur components are mainly responsible for the odour of LFG and belong to the more toxic LFG components (Rettenberger and Stegmann, 1996). The sulphur-containing compounds are produced during anaerobic decomposition of SO_4 bearing refuse through the action of SO_4 reducing bacteria (see Section 2.8.2.3). They also arise from the degradation of S-containing proteins found in animal and vegetable matter (Young and Heasman, 1985; Letcher and Schutte, 1993). In the reducing (anaerobic) conditions, SO_4 can be reduced to sulphide (S^{2-}), which consequently combines with H_2 to form H_2S (Tchobanoglous *et al*, 1993):

$$\underset{\text{Lactate}}{2CH_3CHOHCOOH} + \underset{\text{Sulphate}}{SO_4^{2-}} \rightarrow \underset{\text{Acetate}}{2CH_3COOH} + \underset{\text{Sulphide ion}}{S^{2-}} + H_2O + CO_2 \qquad (5.2)$$

$4H_2 + SO_4^{2-} \rightarrow S^{2-} + 4H_2O$ (5.3)

$S^{2-} + 2H^+ \rightarrow H_2S$ (5.4)

The biochemical reduction of an organic compound containing sulphur radicals can lead to the formation of malodorous compounds such as methyl mercaptan (Tchobanoglous *et al.*, 1993). The reduction of an amino acid (protein), methionine, can be used as an example:

$$\underset{\text{Methionine}}{CH_3SCH_2CH(NH_2)COOH} \xrightarrow{+2H} \underset{\text{methyl mercaptan}}{CH_3SH} + \underset{\text{aminobutyric acid}}{CH_3CH_2CH_2(NH_2)COOH}$$

(5.5)

The methyl mercaptan can in turn be hydrolysed to hydrogen sulphide (Tchobanoglous *et al.*, 1993).

$$CH_3SH + H_2O \rightarrow CH_4OH + H_2S$$

(5.6)

Organosulphur compounds such as mercaptans occur especially during the operational phase of landfill (Rettenberger and Stegmann, 1996) and the presence of their strong odours may be indicative of young refuse present (Young and Heasman, 1985). H_2S is generally produced in all phases of LFG production (see Section 2.8.2.3), and this can account for its abundance as compared to methyl and ethyl mercaptans emission rates (see Table 5.2.). Hydrogen sulphide causes a distinct odour at concentrations of 0.3 mgl^{-1} (Al-Omar *et al.*, 1987). Through popular belief, this gas is often confused with methyl mercaptan, whereas it is not usually the source of odour pollution (Young and Parker, 1983; Letcher and Schutte, 1993). Methyl mercaptan is one of the more objectionable smells, typical of 'bad egg' organosulphur odours (Young and Parker, 1983). It is the most significant odorous compound. Hydrogen sulphide, which is often blamed for LFG odour, is seldom a major contributor to overall smell.

The organosulphurs, esters and terpenes are groups of compounds that contribute primarily to landfill odour (see Section 2.8.2.3). The odours of malodorous compounds such as esters and terpenes (e.g. limonene) are strong, but are not necessarily unpleasant (Young and Parker, 1983; 1984).

At concentrations above 21 mg/m^3, limonene produces a distinct smell of lemons, and the ester, ethyl butanoate gives a 'sweeter' odour, indicative of young, fresher refuse (Young and Parker, 1983; 1984). These additional odorous substances are not amongst the pollutants estimated by the LANDGEM model. However, taking account of the LANDGEM model results for other odorous emissions, it is anticipated that these odorous components would be at a maximum at the time of landfill closure and that emissions would continue for a long period thereafter. It should be noted that there are two types of odour associated with a landfill, the odour from the fresh waste disposal and the subsequent odour from the degradation of the waste. Covering the waste, controls odour from the fresh waste. Extracting and burning the LFG, control odour from the LFG.

5.1.4 Halocarbons and other NMOCs emitted from landfills

This section discusses the pollutants that contribute to the current environmental problems of global warming and ozone depletion, namely chlorinated hydrocarbons and chlorinated fluorocarbons (CFCs). The air pollutants that are of concern to public health and welfare such as vinyl chloride and benzene, which are believed to be carcinogens, are also included. Finally, the emission rates of NMOCs in general are highlighted.

In Table 5.3 peak emission rates of CFCs, benzene, carbon monoxide and NMOCs are reported. These pollutants, similar to the other landfill air pollutants discussed earlier, also reach maximum rates after cessation of waste deposition (Figs. 5.6 - 5.11 and Appendix 1).

In the class of halocarbons investigated in this study (i.e. CCl_2F_2, CCl_3F, CH_2CHCl), CCl_2F_2 (diclorodifluoromethane) is observed to be the chlorinated air pollutant produced most abundantly in all three case studies. The least emitted halocarbon is CCl_3F (fluorotrichloromethane) in all the three landfill sites. These compounds contribute significantly to O_3 depletion and global warming compared with CH_4 and CO_2, despite the fact that they are emitted in trace amounts (see Section 2.8.2.2).

Table 5.3 Predicted maximum emissions of NMOCs from DMA landfill sites according to the LANDGEM model

Pollutants (Mg/yr)	DMA Landfill Sites		
	Bisasar Road	Shongweni	Buffelsdraai
CCl_2F_2	6.609E+00	6.171E-01	7.738E+00
CCl_3F	3.635E-01	3.394E-02	4.256E-01
CH_2CHCl	1.597E+00	1.491E-01	1.870E+00
C_6H_6	5.195E-01	2.819E-01	6.082E-01
CO	1.375E+01	1.284E+00	1.610E+01
NMOC	1.785E+02	1.667E+01	2.090E+02

However, there is a greater impact from CFC's from fridges and LFG does not have a significant impact on the O_3 layer. The concern from LFG is the impact as a greenhouse gas. It follows that the emission of these volatile CFCs from landfills poses a special problem, since they are the most persistent compounds (Letcher and Schutte, 1993; Deipser *et al.*, 1996; Rettenberger and Stegmann, 1996). Halocarbons are also sources of corrosion problems in LFG engines (motors), since acidic hydrogen chloride (HCl) may be formed from combustion of these chlorinated hydrocarbons (Young and Heaseman, 1985; Rettenberger and Stegmann, 1996).

However, CFCs are reported to be substances of low toxicity or are non-toxic and are non-flammable (Deipser *et al.*, 1996; Rettenberger and Stegmann, 1996). CCl_2F_2 and

CCl_3F are among the CFCs occurring most commonly in waste, and before 1990, these compounds were the most often used CFCs (Deipser *et al.*, 1996). Hence they are investigated in this study to represent the behaviour of most halocarbons.

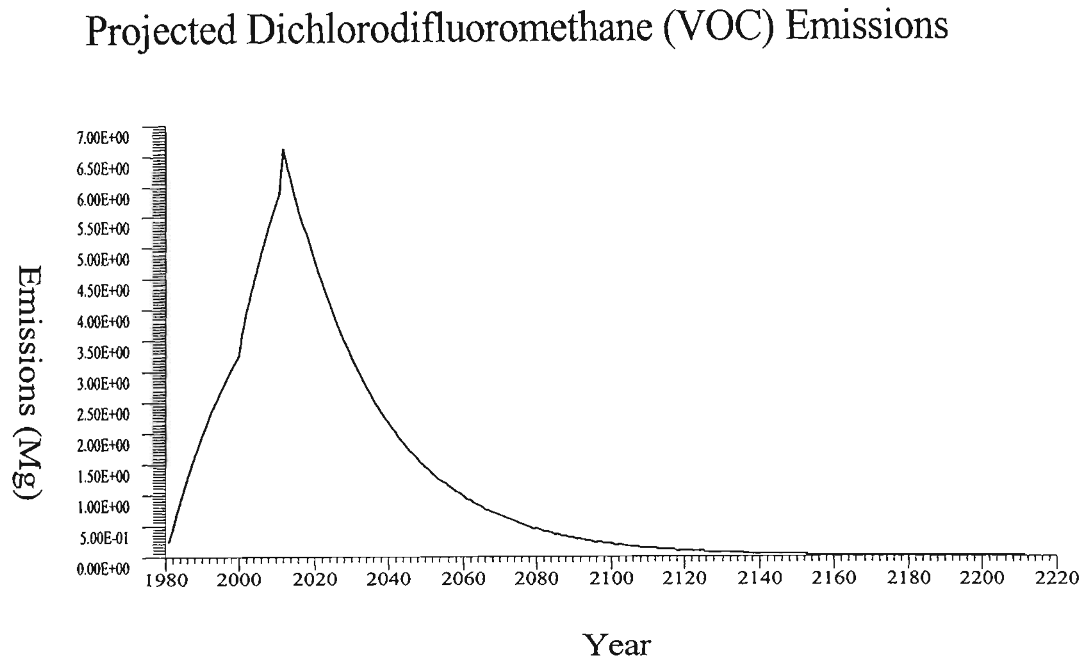


Figure 5.6 Estimated emissions of Cl_2CF_2 at Bisasar Road landfill based on LANDGEM model

Chlorinated and fluorinated hydrocarbons can be transformed to more toxic compounds, thus CCl_2F_2 can be converted to more toxic chlorodifluoromethane, and biodegradation of CCl_3F generates carcinogenic dichlorofluoromethane (Rettenberger and Stegmann, 1996). CFCs reach landfills mainly through corrosion of spray cans and old refrigeration equipment in a landfill and from domestic refuses containing these compounds (Young and Heasman, 1985; Deipser *et al.*, 1996). Biochemical degradation of chlorinated hydrocarbons under anaerobic conditions generates volatile substances, which are present in LFG.

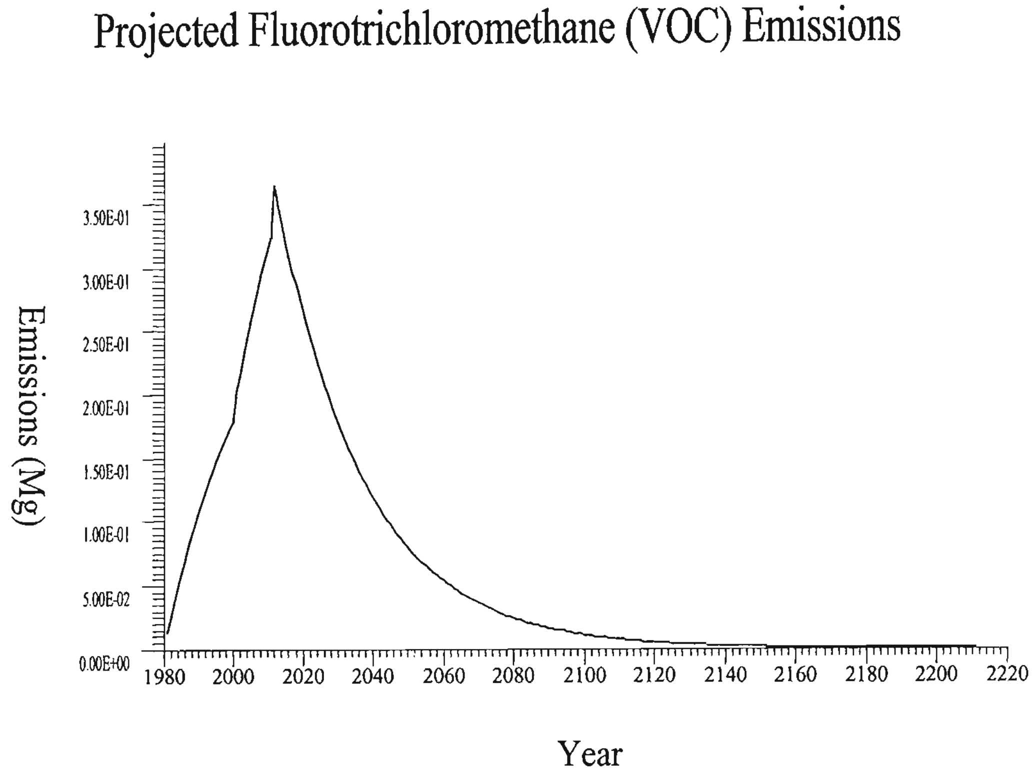


Figure 5.7 Estimated emissions of $CFCl_3$ at Bisasar Road landfill based on LANDGEM model

Benzene (C_6H_6) is a VOC that has been proven to be carcinogenic and occurs with a maximum in the range of 5.2 – 6.1 x 10^{-1} Mg/yr in the general landfill sites of Bisasar Road and Buffelsdraai respectively (Table 5.3; Fig. 5.8 and Appendix 1). A maximum emission of about 2.8 x 10^{-1} Mg/yr was observed at the Shongweni co-disposal site (Table 5.3 and Appendix 1). The emissions of aromatic hydrocarbons from landfills are negligible compared with the generation of these compounds from other sources such as traffic and chemical industries. However, these components may be of great importance because of the potential effects they pose on landfill workers. In particular, the contents of C_6H_6 in LFG must be carefully monitored due to its proven carcinogenic effect (Rettenberger and Stegmann, 1996). Benzene is a recognised carcinogen and exposure to 1 mg/m^3 produces a lifetime risk of approximately 4 x 10^{-6} for leukaemia (WHO, 1987).

Besides benzene and methylmercaptan, vinyl chloride (CH_2CHCl) is the most hazardous compound emitted from landfills, and is a known carcinogen found in significant quantities (Young and Parker, 1983; Rettenberger and Stegmann, 1996). This carcinogenic substance occurs at lower emission rates than C_6H_6 with magnitudes of 1.6 – 1.9 Mg/yr at Bisasar Road and Buffelsdraai sites respectively (Table 5.3; Fig. 5.9 and Appendix 1), and roughly 0.15 Mg/yr at the co-disposal site of Shongweni (Table 5.3 and Appendix 1). Table 5.4 reports the predicted current emissions of these carcinogens at the existing Shongweni and Bisasar Road landfills. These levels can be used to estimate the present health risks posed to workers at these sites.

Table 5.4 Predicted current (2001) emissions of CH_2CHCl and C_6H_6 at active landfills based on the LANDGEM model.

Landfills	**Current emissions of landfill carcinogens (Mg/yr)**	
	Vinyl Chloride (CH_2CHCl)	**Benzene (C_6H_6)**
Bisasar Road	8.830E-01	2.872E-01
Shongweni	4.888E-02	9.239E-02

Benzene and vinyl chloride are frequently prevalent at industrial (co-disposal) sites and their origin may be linked to higher levels of halocarbon solvents in landfills (Young and Parker, 1983). Vinyl chloride can be formed from the biodegradation of chlorinated hydrocarbons, and may also result from disposed polyvinyl chlorinated (PVC) materials (Ham, 1988). The degradation products are usually more toxic than original wastes, for instance, 1,1,1-trichloroethane; trichloroethane and tetrachloroethane are all transformed microbially to vinyl chloride (James and Stack, 1997). In general, vinyl chloride and benzene are believed to be the most critical compounds found in LFG (Eikmann, 1996).

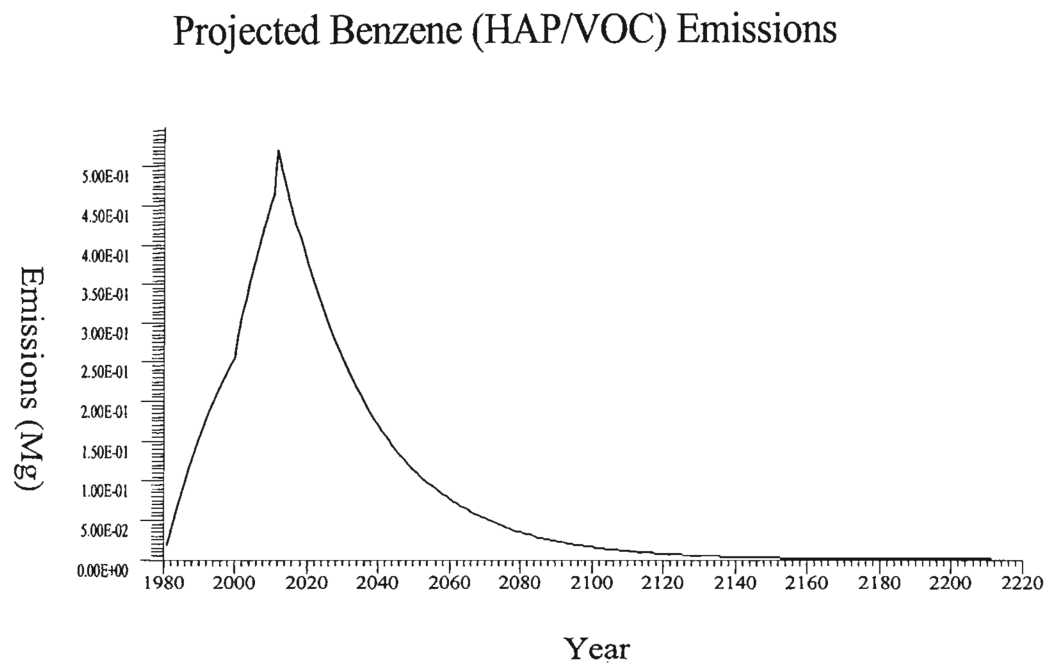


Figure 5.8 Estimated emissions of C_6H_6 at Bisasar Road landfill based on LANDGEM model

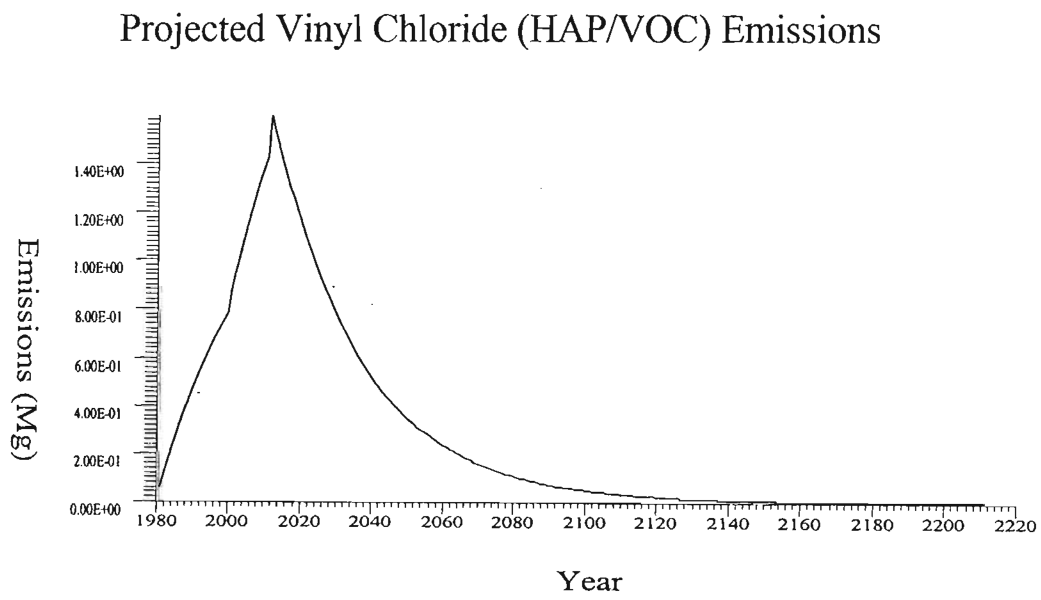


Figure 5.9 Estimated emissions of CH_2=CHCl at Bisasar Road landfill based on LANDGEM

Carbon monoxide is a known by-product of anaerobic decomposition of waste (Al-Omar *et al.*, 1987) that can also be predicted by the LANDGEM model. Unlike CO_2, which is another carbon oxide produced from refuse biodegradation, CO occurs as trace component of LFG even though its levels seem to be fairly considerable with respect to the three case studies (Table 5.3; Fig. 5.10 and Appendix 1). The importance of this gas in the landfill industry is that its sudden increase may indicate danger such as fire in the site. It is therefore imperative to predict emissions of such a gas in order to optimise safety in the landfill. Crowhurst and Manchester (1993) reported that CO could be produced by subterranean fires within combustible wastes such as landfill material with a high organic content.

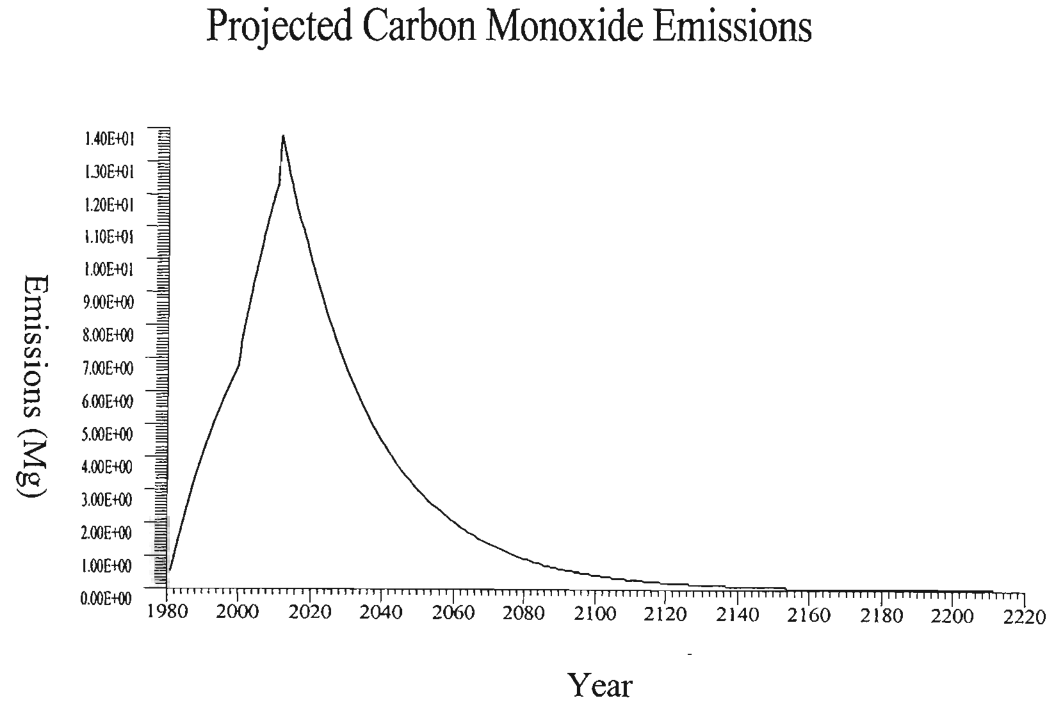


Figure 5.10 Estimated emissions of CO at Bisasar Road landfill based on the LANDGEM model.

NMOC is a class of compounds that represents all hazardous and volatile organic compounds generated from a landfill except CH_4. There are more than 100 different volatile species identified in LFG (Young and Parker, 1984), and some of the volatile compounds are present in the waste as it is deposited (Young and Parker, 1983).

Household products such as oils and cleaning agents may contain hazardous organic compounds that contribute to the VOC levels in landfills (James and Stack, 1997). It is observed from Table 5.5 that their emission rates are lower than those of CH_4 and CO_2.

Table 5.5 Predicted peak emissions of primary LFG components based on the LANDGEM model

Landfill	**Emissions of LFG Major Constituents (Mg/yr)**		
	CH_4	**CO_2**	**NMOC**
Bisasar Road	3.630E+04	5.363E+04	1.785E+02
Shongweni	3.389E+03	5.007E+03	1.667E+04
Buffelsdraai	3.063E+04	4.525E+04	2.090E+02

NMOCs are dominantly trace components of LFG, and these vapours make up less than 1% of total LFG (Young and Parker, 1984). Although more than 100 of these compounds are generated by a landfill, the LANDGEM model can only predict 47 landfill air pollutants (Pelt *et al.*, 1998:pp 4.13). The emissions of these components projected in DMA sites from the birth to closure of respective landfills, are presented in Figure 5.11 for Bisasar Road and Appendix 1 for the other two landfills. The US has developed regulatory exceedance limits to control NMOCs from landfills. The LANDGEM model is used as a regulatory model to determine whether a landfill is subject to regulatory requirements for landfills (Thorneloe *et al.,* 1999). Accordingly, NMOC emissions from large landfill sites may not exceed the regulatory limit of 50 Mg/yr (Bogner *et al.*, 1997). It is noted that this limit is exceeded at all three landfill sites for the greater part of their life span. In the case of Bisasar Road, this would be for approximately 50 years between 1990 and 2040 (Fig. 5.11).

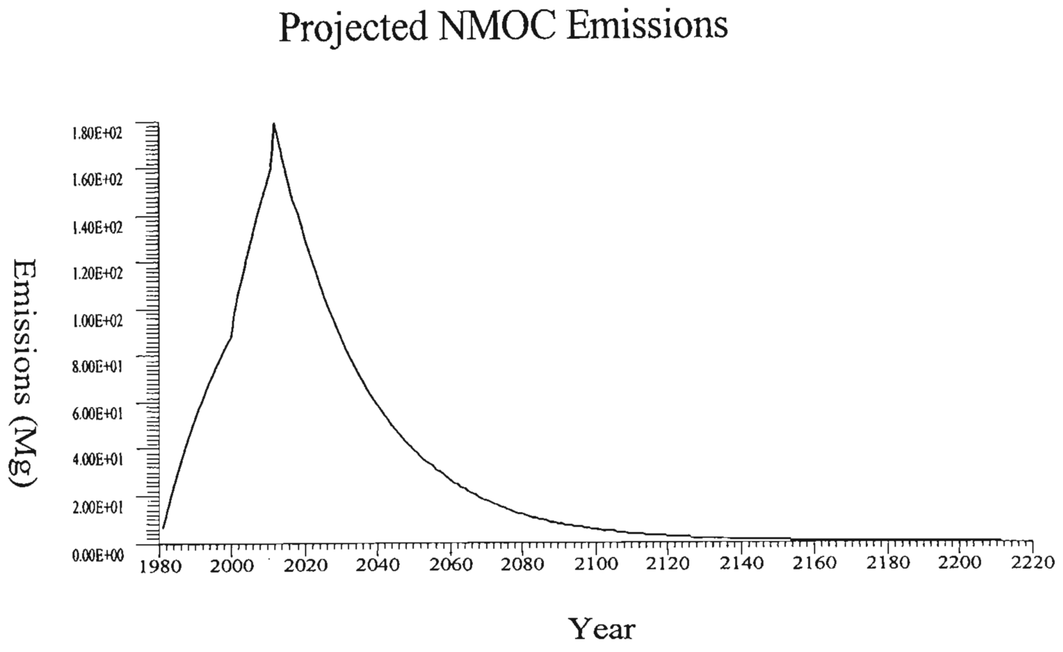


Figure 5.11 Estimated emissions of NMOC at Bisasar Road landfill based on LANDGEM model

5.2 MODEL SENSITIVITY ANALYSIS

Changes to a number of model parameters were investigated in order to determine the sensitivity of the LANDGEM model to these changes. The initial model and landfill parameters used to test the sensitivity of the model are indicated in Appendix 2. When one parameter was varied, the other parameters were kept constant as reported in Appendix 2. Simulations of CH_4, CO_2 and NMOC emissions were used to evaluate the sensitivity of the model.

5.2.1 Ratio of CH_4 to CO_2

The LANDGEM model assumes landfill gas emissions to constitute 50% CH_4 and 50% CO_2. These default percentages can be changed easily. In this study the ratio of 65:35 was utilized due to the high temperatures and high rainfall experienced in Durban.

Additional model simulations were performed for CH_4:CO_2 ratios of 50:50, 65:35 and 70:30. Predicted maximum emissions for these model simulations are shown in Table 5.6. It is evident that there is no marked change in CH_4 emissions when the ratio is increased, however, the emissions of CO_2 and NMOC decrease with an increased CH_4:CO_2 ratio (Table 5.8).

Table 5.6 Maximum emissions (Mg/yr) predicted based on CH_4 to CO_2 ratio

CH_4:CO_2 Ratio	CH_4	CO_2	NMOC
50:50	5.639E+03	1.547E+04	1.466E+02
65:35	5.639E+03	8.332E+03	1.128E+02
70:30	5.639E+03	6.631E+03	1.047E+02

5.2.2 Magnitude of k and L_o

The model accepts user specified k and L_o values, however, in their absence, defaults are provided by the model. As mentioned earlier in Section 4.2.2, AP-42 default values were used in this study because they provide emission estimates that reflect typical landfill emissions (Thorneloe *et al.*, 1999).

A second set of default values namely CAA defaults, are available to evaluate the applicability of the Clean Air Act (CAA) regulations for MSW landfill emissions. This is primarily meant to control LFG emissions in US. The values used are k (0.05 l/yr) and L_o (170 m^3/Mg). The predicted maximum values of key gases are shown in Table 5.7. Use of the CAA defaults produces higher emission estimates, almost twice as much as those predicted by the AP-42 default values. Hence this model is very sensitive to changes in these parameters.

Table 5.7 Maximum predicted emissions (Mg/yr) based on the magnitude of k and L_o

Default Values	CH_4	CO_2	NMOC
AP-42 defaults k 0.04 l/yr L_o 100 m^3/Mg	5.639 E+03	1.547E+04	1.466E+02
CAA defaults k 0.05 l/yr L_o 170 m^3/Mg	1.111E+04	3.089E+04	4.776E+02
CAA arid area parameters k 0.02 l/yr L_o 170 m^3/Mg	5.654E+03	1.551E+04	1.470E+02
AP-42 arid parameters k 0.02 l/yr L_o 100 m^3/Mg	3.326E+03	9.125E+03	8.477E+01

The k value is a function of refuse moisture content and temperature (Section 2.6), hence the higher the k value the greater the methane generation rate. It is possible that the CAA defaults are more suited to Durban in view of its climate and that the use of the AP-42 defaults is underestimating emissions. From Table 5.7, it is observed that the emissions based on the CAA arid area parameters are similar to those of the default AP-42 parameters, further indicating that the use of the AP-42 defaults may be underestimating emissions.

The L_o value depends primarily on the amount of carbon content present in the landfill. The higher the cellulose content of the refuse, the higher the value of L_o. With respect to Bisasar Road landfill, the application of the CAA L_o default would be more appropriate because of high carbon waste deposited in this landfill (Appendix 3), and again this would lead to higher emissions.

5.2.3 NMOC concentration in a landfill

The amount of NMOC concentration in the landfill gas depends on the types of wastes deposited in the landfill. The model suggests 3 default NMOC concentrations, one for the CAA regulations, and two for the AP-42 default option (see Section 4.2.2). They are as follows:

CAA default
- 4000 ppmv

AP-42 defaults
- 2420 ppmv (Codisposal of hazardous waste)
- 595 ppmv (No Codisposal)

From these values it is noted that relatively higher NMOC emissions are expected from hazardous waste landfills due to the wide variety of wastes disposed in such landfills. The CAA default assumes the NMOC emissions to be the same irrespective of type of the landfill, which may not be fully representative. The use of the AP-42 NMOC defaults is therefore taken as appropriate. However, model simulations have been performed using the CAA and the AP-42 defaults, and the results are presented in Table 5.8. The results show that a change in the NMOC concentration, only affects the NMOC emissions.

Table 5.8 Maximum predicted emissions (Mg/yr) based on NMOC concentrations

NMOC conc.	CH_4	CO_2	NMOC
AP-42 defaults			
595 ppmv	5.639E+03	1.547E+04	3.464E+01
2420 ppmv	5.639E+03	1.547E+04	1.466E+02
CAA default			
4000 ppmv	5.639E+03	1.547E+04	2.424E+02

5.2.4 Landfill design capacity

The initial landfill design capacity of 3 x 10^6 Mg (Appendix 2) was increased by margin of 100 000 Mg in one scenario and reduced by same margin in another. The changes in LFG emissions are reported in Table 5.9. Higher emissions are anticipated from large landfills. In this study, the largest landfill site is Buffelsdraai, and the LANDGEM model has predicted highest emissions to be released from this landfill as compared to the two. A 3.33 % increase in landfill capacity produces a 4.73 % increase in CH_4, 4.78 % increase in CO_2 and 4.77 % increase in NMOC (Table 5.9).

Table 5.9 Maximum predicted emissions (Mg/yr) based on a change in landfill design Capacity

Landfill Capacity (Mg)	CH_4 (Mg/yr)	CO_2 (Mg/yr)	NMOC (Mg/yr)
2 900 000	5.422E+03	1.488E+04	1.410E+02
3 000 000 (Initial)	5.639E+03	1.547E+04	1.466E+02
3 100 000	5.906E+03	1.621E+04	1.536E+02

5.2.5 Refuse acceptance rate and refuse in place

These two parameters are closely related. An increase in the refuse acceptance rate leads to a rise in the amount of refuse already in place in a landfill. When LANDGEM model simulations were performed, it was noted that the entry of an increased acceptance rate in a particular year resulted in an increase of refuse in place for successive years. Increased waste input rates cause the generation of higher LFG emissions, as expected and are not shown here.

5.3 SUMMARY

The LANDGEM model has been used to estimate selected LFG emission from three landfill sites. The Buffelsdraai landfill is estimated to have the highest emissions, most likely due to its bigger design capacity than either Bisasar Road or Shongweni landfills. CO_2 emissions occur most abundantly in all three case studies.

CHAPTER 6

LIMITATIONS OF LANDGEM MODEL AND COMPARISON WITH HOFSTETTER MODEL RESULTS

This chapter describes the limitations of LANDGEM model encountered. It was found very important to look at the model's limitations after the results of three case studies were comprehensively set out in the previous chapter. The chapter concludes by comparing the results of LANDGEM against Hofstetter model results used by DSW.

6.1 CRITIQUE OF THE LANDGEM MODEL

The LANDGEM model is based on a number of assumptions, which limit its ability to predict LFG emissions. These limitations are as follows.

- The model does not take into account gas that has been recovered, through LFG extraction or flaring.
- The model uses only first order kinetic equations to predict LFG emissions.
- Only 47 of the estimated 300 LFG components are included in the model (Young and Parker, 1983).
- The model does not allow the percentage (%) by volume of NMOC to be specified in the model. Only CH_4 and CO_2 percentage volumes can be specified.
- The model does not take account of the type of waste in order to estimate emissions. Waste type is important since not all waste is biodegradable.
- The factors that influence the composition and generation rates of LFG such as CH_4 oxidation by bacteria, moisture content and temperature are not considered in this model.
- The natural processes of decay and attenuation (e.g. degradation; sorption) are not taken into account, and therefore the estimates should not be equated to measured fluxes at soil – atmosphere interface.

- The seasonal variation of LFG is not considered in the model. The fluxes of LFG emissions generally decrease from summer through to winter. LFG and CO_2 emissions are highest in summer (Maurice and Lagerkvist, 1997; Park and Shin, 2001). CH_4 emissions vary less as a function of season. In winter they can be low because snow covers the landfill surface inhibiting gas emissions, and during summer the high activity of CH_4 oxidising bacteria also produces low emissions of CH_4 (Maurice and Lagerkvist, 1997).
- The model does not estimate LFG emissions of typical hazardous landfills such as H:H class in South African context. It only predicts emissions from co-disposal and sanitary landfilling.

Despite these limitations, LANDGEM model is widely used. It is selected as a regulatory model to monitor the LFG emission exceedances in the US (Bogner *et al.,* 1997; Thorneloe *et al.,* 1999). The US promulgated the Clean Air Act (CAA) regulations for MSW landfill in 1995. This law was set to reduce CH_4 emissions by 5 to 7 Tg/yr by year 2000 (Doorn and Barlaz, 1995). Under this act (CAA) EPA was authorised to establish regulations that govern the sources, which significantly contribute to air pollution (Bogner *et al.,* 1997).

Therefore on March 1996, New Source Performance Standards (NSPS) were issued for landfills to reduce emissions of NMOCs, HAPs and odorous gases (Roe *et al.,* 1995; Bogner *et al.,* 1997; Thorneloe *et al.,* 1999). Solid waste landfills are required under NSPS to install LFG collection and control systems if their estimated emissions of NMOCs exceed 50 Mg/yr (Thorneloe *et al.,* 1999). In order to quantify the potential LFG emissions from the landfill, EPA developed the LANDGEM model as a methodology for estimating LFG emissions. Landfill operators use this model to determine whether the site is subject to requirements of NSPS.

LANDGEM provides useful estimates that gives an indication for planning and gives an idea for LFG measurements. It has a capability to predict several individual chemical species instead of only giving total LFG. LANDGEM supplies quick runs to display and interpret the emission results. The model assists in the design of LFG recovery systems, since the idea about the trend and quantity of potential biogas generation can be easily predicted. This automated tool can be used in the decision making of landfill construction and harnessing. This implies to the installation of odour control stations or LFG control if air pollutant emissions are anticipated to be beyond certain limit.

6.2 HOFSTETTER GAS YIELD MODEL RESULTS FOR BISASAR ROAD LANDFILL

6.2.1 Introduction

The Hofstetter Gas Yield Model was used to simulate LFG generation at the Bisasar Road landfill in 1994 by Lombard *et al.* (1998). The input parameters used to estimate LFG generation and the expected gas yield per tonne of waste in landfill are presented in Appendix 4. The gas yield was predicted for a period of 50 years, commencing in 1979 when the site was opened. The Hofstetter model has been validated at many landfill sites around the world, although in this study there are no field results to date to validate modelled results.

6.2.2 Predicted LFG yield

Figure 6.1 illustrates the expected landfill gas production per tonne of putrescible waste at Bisasar Road landfill. The Hofstetter Gas Yield Model, which is based on European experience, indicates that total gas generation from the waste body reaches a peak within three years of waste deposition. This is different from the LANDGEM model which predicts LFG emissions to peak at closure. A yield of more than 30 m^3 of gas can be produced in a year from one tonne of waste at the peak. This dramatic rise of gas within a short time may be caused by rapid completion of the methanogenesis phase (see Section 2.4.1). If methanogenesis does become established, methane production can last for 8-40 years (Micales and Skog, 1997). At this stage, anaerobic decomposition of decaying material produces CH_4, which rises to a peak, and CO_2 starts to decline, and become steady (see Fig. 2.3).

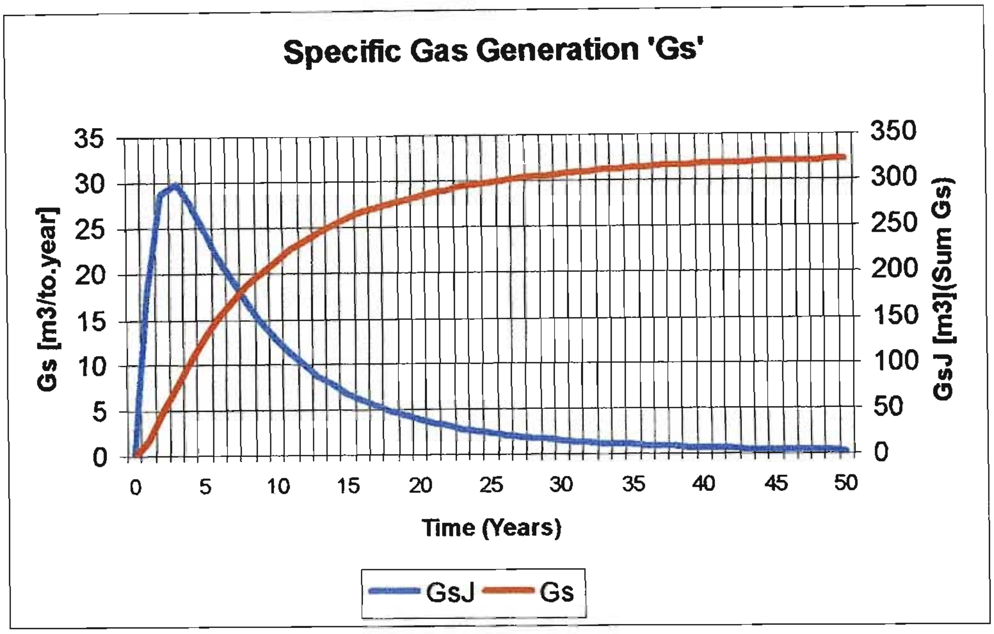


Figure 6.1 Predicted gas generation (Gs) and accumulation (GsJ) at Bisasar Road landfill based on the Hofstetter model (Source: Lombard *et al.*, 1998).

From Figure 6.1 it is observed that the gas declines for a period of 50 years after the peak. This may depict the final stages of biodegradation, in which gas production declines even though it can continue to be generated at a much lower rate for many years (Growhurst and Manchester, 1993). This continuous generation of gas leads to the accumulation of gas within the landfill, denoted as GsJ in Figure 6.1. This continuously produced gas builds up pressure within the waste mass, causing gas to escape through the landfill surface into the atmosphere. This occurs especially when the gas pressure within the waste body is greater than atmospheric pressure (Micales and Skog, 1997). The sum of accumulated gas becomes almost constant after approximately thirty years, at which time production rates are very low. Ultimately, methane production decreases and the landfill becomes an inert soil-like mass (Micales and Skog, 1997). Studies have shown that the landfill may generate LFG for over 30 years (see Section 2.5.1) and after the cessation of gas production, anaerobic processes stop, and the landfill is said to be stabilized. This is significantly less than 200 years predicted by the LANDGEM model.

Landfills in the US, which are designed using the LANDGEM model, are entombed dry waste sites with slow waste degradation rates i.e. 100's of years (Couth, 2001, pers.com). Landfills in Europe have traditionally been wetter sites, many uncontained, and similar to the landfill sites in South Africa. In these sites waste degradation is over a period of 30 to 50 years. Indeed, there have been studies in Sweeden and England to seek to get landfills to stabilise in 2 to 5 years, and such sites are known as flushing bioreactors (Couth, 2001,pers.com). Consequently, the Hofstetter model should produce more accurate results for South African landfill sites.

6.2.3 Waste quantity and gas production

Waste input rates and quantities play an important role in influencing the LFG production rate. High input rates are found to encourage the establishment of anaerobic processes, which lead to increased LFG generation (see Section 2.6.4). Figure 6.2 illustrates the direct proportionality of gas production to waste quantity. The behaviour or trend of biogas shown in this figure is very similar to Figure 2.5. Both figures show that the closure of landfill or cessation of waste deposition, results in the decline of gas produced. The consequence of this may be due to the fact that there would be no more organics available for biogasification. The anaerobic decomposition of organic materials in a landfill can be described by Tchobanoglous *et al.* (1993) with the following chemical reaction:

$$\underset{\text{matter}}{\text{Organic}} + H_2O \xrightarrow{bacteria} \underset{\text{matter}}{\text{Biodegraded organic}} + CH_4 + CO_2 + \text{Other gases} \tag{6.1}$$

The only available material would be the slowly biodegradable material (see Section 2.6.2), which accounts for the continuous low generation rate of gas after the closure of the site. Eventually, the biogas production potential of a landfill site is determined by the quantity and quality of the waste (Gardner *et al.*, 1993). These two figures indicate that approximately 80% of native gas generated can be extracted from the landfill (see Appendix 4). The Hofstetter model assumes that 50% of the deposited putrescible or decaying waste will biogasify to generate gas (see Appendix 4).

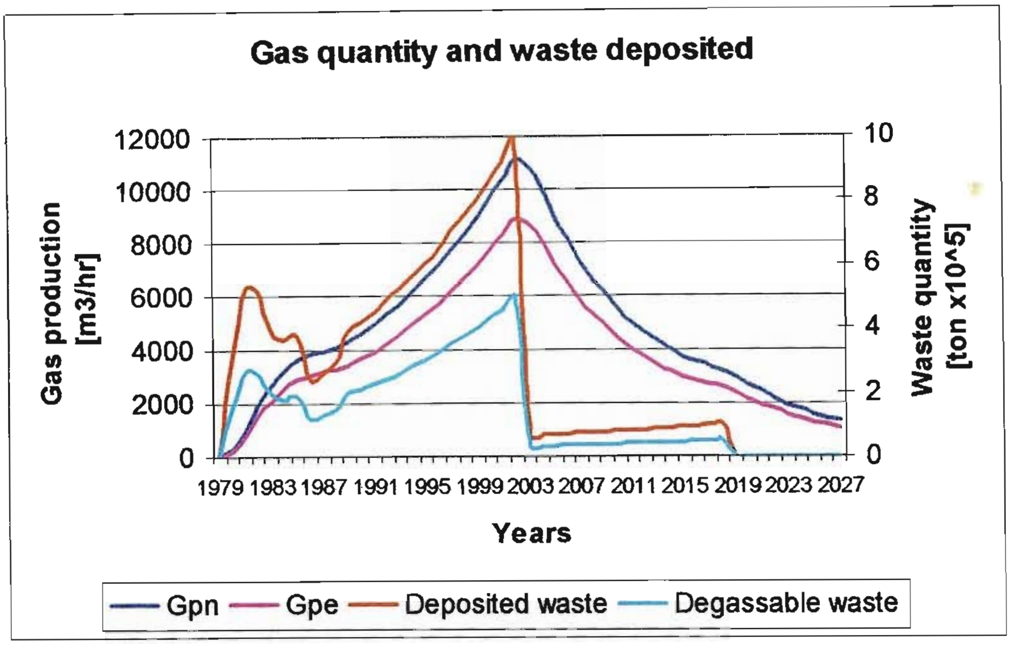


Figure 6.2 Quantities of native gas production (Gpn), recoverable gas (Gpe) and waste deposited at Bisasar Road landfill (Lombard *et al.*, 1998).

6.3 COMPARISON OF LANDGEM AND HOFSTETTER MODEL RESULTS

The Hofstetter model estimates total LFG and assume methane to be the dominant constituent, with a content of 50 % by volume (Appendix 4). The LANDGEM model has the capacity to estimate about 47 air pollutants found in LFG, with CH_4 and CO_2 as major components of the gas. The ratio of these two primary constituents of LFG has to be specified in the model before the estimation of LFG emissions. The ratio of 65:35 % by volume CH_4 to CO_2 was used in this particular study (see Section 4.2.2).

Figure 6.1 indicates that the Hofstetter model estimates a maximum of 30 m^3 of gas per tonne of waste in a year. Considering the current annual refuse acceptance rate at Bisasar Road landfill (Table 4.1) the peak emission rate is estimated to be 3.285×10^7 m^3y^{-1}. The LANDGEM model, however, does not estimate gas production per tonne of waste but as a mass emission rate per year (i.e. Mg/yr and m^3y^{-1}). Assuming CH_4 and CO_2 to represent the typical LFG emitted from Bisasar Road landfill, a maximum emission rate of 8.371×10^7 m^3y^{-1} (8.993×10^4 Mg/yr) (Table 5.5) was predicted by LANDGEM. Based on these results it is evident that the LANDGEM model predicts higher LFG emissions at the Bisasar Road landfill than the Hofstetter model.

Since there are no regulatory emission limits in place in South Africa now, the above-anticipated emissions cannot be compared against any legal guidelines. Other studies, such as Willumsen (1996), have indicated typical CH_4 production rates to be around 2.5 m^3 CH_4 per tonne of waste per year. According to Gregory (2000), landfill gas production rates typically range between 5-10 m^3 per tonne per year in the first decade of a landfill's active life, and decline thereafter. A cumulative yield of 100m^3 per tonne per year MSW can be predicted over the entire lifetime of the site (Gregory, 2000).

6.4 COMPARISON BETWEEN LFG EMISSIONS FROM HAZARDOUS AND SANITARY (MSW) LANDFILLS

Bisasar Road and Shongweni landfills are two different waste disposal sites. The Bisasar Road is a sanitary landfill, which receives general wastes (MSW), while Shongweni is a co-disposal site receiving low hazardous, industrial refuse. The LANDGEM results presented in section 5.1 reveal that LFG emissions are higher in the MSW landfill than in the co-disposal site, which is contrary to expectations. A possible reason for this is sought in the age difference between the two landfills.

The occurrence of significant levels of VOCs in LFG is associated more with older landfills that receive industrial and commercial waste containing VOCs (Tchobanoglous *et al.*, 1993). The Bisasar Road landfill is a large, old (~20 years) landfill which does accept commercial waste and limited industrial refuse (see Appendix 3). In newer landfills in which disposal of hazardous waste is not permitted, the concentration of VOCs in LFG have been found to be very low (Tchobanoglous *et al.*, 1993). However, Shongweni is a young (~3years) hazardous landfill and therefore it is unlikely that the age difference is responsible for the difference in emissions.

The presence of liquid waste at the hazardous (industrial) sites is confirmed by high levels of halocarbons (Young and Parker, 1983). The Shongweni landfill practises co-disposal landfilling in which MSW is used to soak up the hazardous liquid waste. Therefore considerable levels of CFCs and VOCs (see Section 5.1.4) can be anticipated at this site due to disposal of liquid wastes, which always contain CFCs and VOCs. Benzene and vinyl chloride are particularly present at elevated levels in industrial landfill that accept liquid wastes such as solvents and petrol wastes (Young and Parker, 1983). The gas may not be found more toxic and more odorous by presence of the industrial waste (Young and Heasman, 1985). Therefore toxicity and odoriferous effect of gas may not be dependent on type of refuse deposited, the concentration of LFG constituents matters most. Young landfill gas is usually more odorous, even though the frequency of odour is more related to the rate of gas generation (Young and Heasman, 1985). Young and Parker (1983) reported that there is strong evidence to suggest that odour is worst a year after deposition, in which esters and organosulphurs play a major role (see Section 5.1.3).

6.5 SUMMARY

A comparison of the LANDGEM model results with the Hofstetter model reveals that higher LFG emissions are predicted in the former. Waste quantity and type play an important role in the rate of LFG production. The LFG emissions are found to be higher in sanitary landfills than in hazardous sites, and this is contrary to the theoretical expectation.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY

Landfill gas emissions from three landfills in the Durban area were estimated using the LANDGEM model and compared with results obtained from the Hofstetter model for one of the landfill sites. All landfill sites have shown the potential to produce considerable quantities of LFG emissions. The sanitary landfills of Bisasar Road and Buffelsdraai were found to produce higher emissions than the co-disposal landfill of Shongweni. The smaller size and younger age of the Shongweni landfill most likely accounts for its lower emissions.

The LANDGEM model showed LFG to increase with increasing waste deposition and to peak at landfill closure. After closure, the emissions declined sharply but continued for a period of 200 years in all three case studies. The Hofstetter model which has been applied by DSW to the Bisasar Road landfill, does not predict emissions of individual chemical species but gives a total emission rate for all gases. At the time of peak emissions, a yield of 30 m^3 of LFG can be produced from one tonne of waste per year. According to this model, LFG reaches a peak within three years of waste deposition and then declines for a period of about forty years after the peak.

The Hofstetter model assumes 50 % of the deposited waste to biodegrade to generate gas. The biodegradation of waste in a landfill depends mainly on the type of waste deposited. Wastes that contain a high content of carbon such as food and yard wastes can increase the biodegradability of waste that is landfilled. The Hofstetter model predicted a total LFG emission rate of 3.285×10^7 m^3y^{-1} based on total waste capacity of 13, 678, 485 tonnes compared with the LANDGEM model which predicted a higher rate of 8.371×10^7 m^3y^{-1} for Bisasar Road landfill based on landfill capacity of 21,000,000 tonnes.

Carbon dioxide emissions in all three case studies were found to be higher than CH_4 emissions, contrary to expectations. This result may be explained by the process of microbial CH_4 oxidation to CO_2 in the landfill cover soil. It is most likely due to the high temperature and moisture conditions found in Durban.

Among the malodorous compounds investigated in this study, H_2S was found to be the odorous pollutant that had the highest emission rate. However, CH_3S is believed to be the most odorous compound responsible for the persistence of the LFG smell. Most of these organosulphur compounds and esters are more odorous during the working phase of a landfill. The best way to reduce these odours is by immediate covering of waste instantly after compaction. The application of diluting agents to dilute the smell is a secondary option, since such agents are generally very costly.

CFCs are trace components of LFG, yet are important because they are greenhouse gases. Dichlorodifluromethane is the most abundant halocarbon emitted. The disadvantage of flaring LFG containing a high content of these gases is their ability to produce the corrosive HCl gas, which is known to cause corrosion problems, especially in equipment that extracts and burns LFG.

Of the air pollutants that are significant from a perspective of public health, benzene and vinyl chloride, are the two most important. Benzene was emitted at higher rates than vinyl chloride. The NMOC class of compounds, which represents all hazardous and VOCs emitted from landfills except methane, was found to occur at emission rates lower than those of CH_4 and CO_2. More than 100 of these compounds are generated from a landfill, however, in this study, only about eight of this class were investigated.

The sensitivity of the LANDGEM model was investigated using some few input parameters. The model was found to be sensitive to the variations of the following parameters: CH_4: CO_2 ratio, magnitude of k and L_o, NMOC concentration and landfill design capacity. It was observed that there is no marked change in CH_4 emissions when the CH_4: CO_2 ratio was increased, however, CO_2 and NMOCs emissions decreased with increased ratio. The higher LFG emission estimates are produced by higher values of k and L_o. CAA default values were noticed to be more suitable for Durban climatic conditions than AP-42 defaults used for all landfill simulations in this study. Therefore this implies that the use of AP-42 default values may be underestimating LFG emissions. The change in NMOC concentration input parameter only affect the NMOCs and not other air pollutant emissions. LANDGEM predicts higher emissions to be produced from landfill of great design capacity. In this study, Buffelsdraai was anticipated to release highest emissions as result of its biggest size.

LANDGEM is a useful tool that can be used to estimate potential LFG emissions so as to avoid hazards associated with LFG, such as explosions, fires and health hazard emissions. Despite all the possible adverse health and environmental impacts of LFG, waste disposal and treatment by landfill is a most convenient and cost effective method of solid waste management. LANDGEM like other models require field validation measurements to determine if the model is realistic. Modelling LFG emissions accurately is very difficult due to the lack or limited information required for input parameters to the model.

7.2 RECOMMENDATIONS

LFG has been highlighted mainly as a potential hazard, but it should also be considered as a possible energy benefit for society. LFG will always be generated as long as waste is produced. The following set of recommendations includes those which relate specifically to improve the model predictions and those which are more general to the field of landfill management:

- The LANDGEM model should be run using site-specific parameters rather than default parameters.

- Validation of the LANDGEM model results against measured data would be useful, to know whether the model is giving correct order of magnitude. This is an important point for future studies since this is beyond scope of the study.
- The creation of a spatial map of LFG distribution would be essential to know the likely impacts of LFG on adjacent communities. To obtain the spatial map would need a model such as 'air pollution dispersion model', since this is beyond the capacity of the LANDGEM model used in this study.
- Health risk assessments for the key pollutants should be undertaken to determine the potential health risks posed to workers and nearby residents.
- The use of LFG prior to flaring should be encouraged since it is a valuable source of energy.
- The use of diluting agents to dilute LFG odour should be encouraged to mitigate the impact on residents in the neighbourhood of a landfill.
- A good soil cover should be used to cover the waste at the end of every working day to minimize odour emissions.
- Regulatory limits for LFG emissions should be introduced in order to ensure that human health is protected.

REFERENCES

Al-Omar M.A., Fauqm, S. Y., Kitto, A.M.N., Altaie, A.F. and Bader, N. (1987). Impact of Sanitary Landfill on Air Quality in Baghdad, Water, Air and Soil Pollution, Vol. 32, pp55-61.

Bagchi, A. (1990). Design, Construction, And Monitoring of Sanitary Landfill, John Wiley and Sons, Inc., USA.

Boeckx, P., Van Cleemput, O. and Villaralvo, I. (1996). Methane Emissions from a Landfill and the Methane Oxidising Capacity of its Covering Soil, Soil Biol. Biochem. Vol 28, pp 1397 – 1405.

Bogner, J., Meadows, M. and Czepiel, P. (1997). Fluxes of methane between landfills and the atmosphere: natural an engineered controls, Soil Use and Management, Vol. 13, pp 268-277.

Bogner, J., Spokas, M., Niemann, L., Niemann M. and Baker, J. (1997). Emissions of Non-Methane Organic Compounds at an Illinois (USA) Landfill Site: Preliminary field Measurements, Proceedings Sardinia 97, Sixth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, 13 – 17 Octorber 1997, Cagliari, Italy.

Borjesson, G., Galle, B., Samuelsson, J. and Svensson, B.H. (2000). Methane Emissions from Landfills: Options for Measurement and Control, Conference Proceedings Waste 2000, Waste Management at the Dawn of the Third Millenium, Stratfort-Avon, UK, 2-4 October 2000.

Campbell, D.J.V. (1996). Explosion and Fire Hazards Associated with Landfill Gas, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Card, G.B. (1992). Development On and Adjacent to Landfill, IWEM's Central Southern Branch Training Day on Engineering of Landfill – Problems and solutions, 30 October 1991, Swindon.

Cernuschi, S. and Giugliano, M. (1996). Emissions and Dispersion of Landfill Gas, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Chain, E.S.K. and Dewalle, F.B. (1976). Sanitary landfill leachates and their treatment, Journal of the Environment Engineering Division, Proceedings of the American Society of Civil Engineers 102 (no. EE2, April): 411-431.

Christensen, T.H., Kjeldsen, P. and Lindhardt, B. (1996). Gas-Generating Processes in Landfills, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Coops, O., Luning, L Oonk, H., A Weenk. (1995). Validation of Landfill Gas Formation Models, Proceedings Sardinia 95, Fifth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliary, Italy.

Cope, C.B., Fuller, W.H. and Willets, S.L. (1983). The Scientific Management of Hazardous Wastes, Cambridge University Press, UK.

Cossu, R., Andreottola, G. and Muntoni, A. (1996). Modelling Landfill Gas Production, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Couth, B. (2000a). Landfill Gas: Generation and Modeling, Proceedings for 1st International Training Seminar on Control, Management and Treatment of Landfill Emissions, University of Natal – Durban, 6 – 8 December 2000, South Africa.

Couth, B. (2000b). Gas Management and Extraction Systems, Proceedings for 1st International Training Seminar on Control, Management and Treatment of Landfill Emissions, University of Natal – Durban, 6-8 December 2000, South Africa.

Couth, B. (2001). Personal Communication, EnvirosAspinwall, Shrewsbury, Shropshire SY4 2HH, UK.

Crowhurst, D and Manchester, S.J. (1993). The measurement of methane and other gases from the ground, CIRIA Report 131, London.

Deipser, A., Poller, T. and Stegmann, R. (1996). Emissions of Volatile Halogenated Hydrocarbons from Landfills, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

DoE (Department of the Environment) (1991). Waste Management Paper No. 27: Landfill Gas, Her Majesty's Stationery Office, London.

DoE (Department of the Environment) (1995). Waste Management Paper 26B: Landfill Design, Construction and Operational Practice, Her Majesty's Stationary Office, London.

Doorn, M.R.J. and Barlaz, A.M. (1995). Estimate of Global Methane Emissions from Landfills and Open Dumps, Project Summary, Air and Energy Engineering, Research Laboratory, Research Triangle Park, NC 27711, EPA/600/SR-95/O19, February 1995.

Drennan, Maud & Partners (2000a). Preliminary Report on Engineering Design and Geotechnical Investigation for the Buffelsdraai Site, Durban Solid Waste, Durban Metro Water Services, Durban, May 2000.

Drennan, Maud & Partners (2000b). Site Development and Operational Plan Report for the Buffelsdraai Landfill, Durban Solid Waste, Durban Metro Water Services, Durban July 2000.

Drennan, Maud & Partners and Lombard & Associates (2000c). Durban Metropolitan Area: North Zone, Proposed New General Waste Landfill Sites, Permit Application Report, Durban Solid Waste, Department of Agriculture and Environmental Affairs (DAEA) and Department of Water Affairs and Forestry, KwaZulu-Natal, July 2000.

DWAF (Department of Water Affairs and Forestry) (1998a). Minimum Requirements for Waste Disposal by Landfill, Second Edition, Pretoria.

DWAF (Department of Water Affairs and Forestry) (1998b). Minimum Requirements for the Handling, Classification and Disposal of Hazardous Waste, Second Edition, Pretoria.

Eikmann, T.F. (1996). Health Aspects of Gaseous Emissions from Landfills, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Gardner, N., Manley, B.J.W. and Pearson, J.M. (1993). Gas Emissions from Landfills and their Contributions to Global Warming, Applied Energy, Vol. 44, pp 165 – 174.

Grantham, G., Latham, B. and Callen, G. (1997). Landfill Contribution to "greenhouse gas" emission, Proceedings Sardinia 97, Sixth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, 13-17 October 1997, Cagliari, Italy.

Grawford, J.F. and Smith P.G. (1985). Landfill technology, Butterworths, Anchor-Brendon Ltd, London.

Gregory R.G. (2000). Development of Technical Guidance on Landfill gas, Proceedings Waste 2000, Waste Management at the dawn of the third Millenium, Stratford-Upon-Avon, Warwickshire, England, 2 – 4 October 2000.

Haarstad, K. (1997). Methane in Landfills: Production, Oxidation and Emissions, Proceedings Sardinia 97, Sixth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliari, Italy.

Ham, R.K. (1998). Landfill Gas, Leachate, And Related Problems, Institute of Waste Management (South Africa) – Biennial Congress Durban, 9 – 11 August 1988, South Africa.

Hasan, S.E. (1996). Geology and Hazardous Waste Management, Prentice-Hall, Inc., USA.

HMIP (Her Majesty's Inspectorate of Pollution) (1989). Waste Management Paper No. 27: The Control of Landfill Gas, Her Majesty's Stationery Office, London.

Humer, M. and Lechner, P. (1999). Alternative Approach to the Elimination of Greenhouse Gases from Landfills, Waste Management and Research, Vol. 17, pp 443 – 452, ISWA, International Solid Waste Association.

IWM Landfill Gas Monitoring Working Group (1998). The Monitoring of Landfill Gas, Second Edition, Institute of Waste Management, London.

James, K.J and Stack, M.A. (1997). The Impacts of Leachate Collection on Air Quality in Landfills, Chemosphere, Vol. 34, No. 8, pp 1713 – 1721.

Johnston, A.G., Edwards, J.S., Owen, J. and Young, S.D. (2000). Research into Methane Emissions from Landfills, Proceedings Waste 2000, Waste Management at the dawn of third Millennium, 2 – 4 October 2000, Stratford-upon-A, UK.

Kerfoot, H.B. (1996). Effects of Landfill Gas on Groundwater, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Kidd, C. (2000). Personal Communication, EnviroServ Waste Management (PTY) Ltd, Shongweni Landfill, Shongweni.

Laister, G. and Stretch, D. (2000). Odour Trails from Landfill sites, Proceedings for 1st International Training Seminar on Control, Management and Treatment of Landfill Emissions, 6 – 8 December 2000, University of Natal, South Africa.

Landfill Gas and the Environment (2001). www.biogas.org.uk.

Letcher, T.M. and Schutte, R. (1993). Landfill Gas: Environmental Pollutant and Energy Resource, SPECTRUM 31, October 1993.

Letcher, T.M., Schutte, R. and La Trobe, B. (1991). Assessing the Energy Potential to a landfill Site, Journal of Energy R and D in Southern Africa, February 1991.

Letcher, T.M. (2001). Personal Communication, University of Natal-Durban, Durban, South Africa.

Little, R.H., Grogan, H.A., Smith, G.M. and Torres, C. (1993). Land Disposal Practices in European and North America, Institute of Water and Environmental Management, Vol. 7, No. 4, pp 354 – 362.

Lombard, R. (1992). The Treatment and disposal of Hazardous and Toxic Waste, IWM KwaZulu-Natal Waste Management Seminar, Durban.

Lombard, R. (1993). Rating Hazardous Substances, International Executive Communication, Auckland Park, South Africa.

Lombard and Associates (1994). Environmental Impact Control Report For the Existing Operation on the Bisasar Road Landfill Site on Various Lots of

Springfield and Resevoir Hill, Durban, Link Hills, South Africa.

Lombard and Associates (1997). Environmental Impact Control Report For the Upgrade of the Class H:h Shongweni Landfill Site Located on Portion of the Farm Rem of Kirkfalls No. 14227, County of Durban, Link Hills, South Africa.

Lombard and Associates (1997). Motivation Report in Terms of Section 20 of the Environment Conservation Act (Act 73 of 1989) For the Upgrade of the Shongweni Landfill Site Located on Portion of the Farm REM of Kirkfalls NO. 14227, County of Durban, Link Hills, South Africa.

Lombard, R., de Mattos, GWP., and Williams, N.M. (1998). Practical Landfill Extraction at Bisasar Road in Durban, Proceedings WasteCon '98, 14th Congress, IWM (SA), pp 470 – 483, Kempton Park, South Africa.

Lombard, R. and de Mattos, GWP. (1998). Landfill Gas Management, International Communications for Management – Waste Minimisation and Pollution Preventtion, 25 – 26 February 1998, Midrand, South Africa.

Lombard, R. (2001). Personal Communication, Lombard & Associates, Link Hills, South Africa.

Loudon and Partners (1994). Bisasar Road Landfill Site: Landfill Gas Recovery Investigation, Kloof., South Africa.

Marticorna, B., Attal, A., Camacho, P., Manem, J., Hesnault, D. and Salmon, P. (1993). Prediction Rules for Biogas Volorisation in Municipal Solid Waste

Landfills, Water Science and Technology, Vol. 27, No. 2, pp 235 – 241.

Massacci, G. (1996) Physico-Chemical Characteristics and Toxicology of Landfill Gas Components, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Maurice, C. and Lagerkvist, A. (1997). Seasonal Variation of Landfill Gas, Proceedings Sardinia 97, Sixth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliari, Italy, 13 – 17 October 1997.

Meadows, M., Franklin, C., Campbell, D. and Riemer, P. (1997). Global Methane Emissions from Solid Waste Disposal sites, Proceedings Sardinia 97, Sixth International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, 13-17 October 1997, Cagliari, Italy.

Micales, J.M. and Skog, K.E. (1997). The Decomposition of Forest Products in Landfills, International Biodeterioration and Biodegradation , Vol. 39, No. 2-3, pp 145 – 158.

Morris, J.W.F., Fourie, A.B., Blight, G.E. and Mistry, P. (1999). Greenhouse Gas Emissions from Landfill in Semi-arid Climates: A Field Study in South Africa, Proceedings Sardinia 99, Seventh International Waste Management and Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliari, Italy, 4 – 8 October 1999.

Muntoni, A., Manga, M.G. and Demurd, M. (1995). An International Model for the Prediction of Landfill Emissions, Proceedings Sardinia 95, Fifth International Landfill Symposium, CISA, Environmental Sanitary Engineering

Centre, Cagliari, Italy.

Neumann, U. and Christensen, T.H. (1996). Effects of Landfill Gas on Vegetation, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Novella, P.H., Ballard, R.H., Stow, J.G., Ross, W.R., Blight, G.E. and Voster, K. (1999). Practical Application of Special Waste Co-disposal with Municipal Refuse at the Coastal Park Landfill Bioreactor, WRC Report No. 606/1/99, Water and Waste Management Department Cape Metropolitan Council, Cape Town.

Park, J-W. and Shin, H-C. (2001). Surface Emissions of Landfill Gas from Solid Waste Landfill, Atmospheric Environment, Vol. 35, pp 3445 – 3451.

Pelt R., Thorneloe, S.A., Bass, R.L., Heaton, R.E., White, C., Blackard, A., Burklin, C. and Reisdorph, A. (1998). User's Manual Landfill Gas Emissions Model, U.S Environmental Protection Agency, United States.

REH (Rachel's Environment and Health Week No. 226) (1991). Toxic Gases Emitted from Landfills, Environmental Research Foundation, 27 March 1997.

Rees, J.F. (1980) The Fate of Carbon Compound in the Landfill Disposal of Organic Matter, Chem. Tech Biotechnical, Vol. 30, pp 161 – 173.

Rettenberger, G and Stegmann, R (1996). Landfill Gas Components, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Robinson, H.D. (1989). Development of Methanogenic Conditions within landfills, Sardinia 2nd International Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliari Italy.

Roe, S.M., Fields, P.G. and Coad, R. (1995). Methodologies for Quantifying Pollution Prevention Benefits from Landfill Gas Control and Utilization, Project Summary, National Risk Management, Research Laboratory, Research Triangle Park, NC 27711, EPA/600/SR-95/089, July 1995.

Senior, E. (1990). Introduction in Microbiology of Landfill Sites, CRC Press Inc., Florida, USA.

Spillmann P. (2000) Landfill Gas – What is it?, Hofstetter, www.hofstertter.ch.

Stegmann, R. (1996). Landfill Gas Utilization: An Overview, Landfill of Waste: Biogas, E & FN Spon, London.

Strachan, L. (2000). Personal Communication, Bisasar Road Landfill, Durban Solid Waste, Springfield, Durban.

Strachan, L. (2001). Personal Communication, Bisasar Road Landfill, Durban Solid Waste, Springfield, Durban.

Tchobanoglous, G., Theisen, H. and Vigil, S. (1993). Integrated Solid Waste Management: Engineering Principles and Management Issues, McGraw-Hill, Inc., New York.

Thorneloe S.A., Reisodorph, A., Laur, M., Pelt, R., Bass, R.L. and Burklin, C. (1999). The U.S. Environmental Protection Agency's Landfill Gas Emissions

Model (LANDGEM), Proceedings Sardinia 99, Seventh International Waste Management and Landfill Symposium, CISA, Environmental Sanitary Engineering Centre, Cagliari, Italy.

Thorneloe, S.A (1996). Influence of Landfill Gas on Global Climate, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Thorneloe, S.A. (1996). Options and Economics of Landfill Gas Utilization in the USA, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

U.S. EPA (United States Environmental Protection Agency) (1998). Read Me File for Landfill Gas Emissions Model, U.S. Environmental Protection Agency, United States, 9 November 1998.

U.S. EPA Landfill Methane Outreach Program (2001a). www.epa.gov.

U.S. EPA (2001b). Global Warming, April 6, 2001. www.epa.gov.

Vieitez, E.R. and Ghosh, S. (1999). Biogasification of Solid Wastes by two-phase Anaerobic Fermentation, Biomass and Bioenergy, Vol. 16, pp 299 – 309.

Visvanathan, C., Pokhrel, D., Cheimchaisri, W., Hettiaratchi and Wu, J.S. (1999). Methanotrophic activities in tropical landfill cover soils: effects of temperature, moisture content and methane concentration, Waste Management and Research, Vol. 17, pp 313 – 323.

Wetherill, T.D., Fobes, C.D. and Kerr, T. (1999). Promoting Cost-effective Landfill Gas-to-Energy Projects in Developing Countries, The US EPA's Landfill Methane Outreach Program, Internation Directory of Solid Waste Management 1998/9, The ISWA Year Book, James and James (Science Publishers) Ltd, UK.

Wheeler Environment Management (1998), LLC, 1997/1998, www.CH_4gas.com.

WHO (World Health Organisation) (1987). Air Quality Guidelines for Europe, European Series No. 23, Regional Office for Europe, Copenhagen.

Willumsen H.C. (1996). Actual Landfill Gas Yield, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Willumsen, H.C. (1996). Landfill Utilization: Statistics of Existing Plants, In Landfilling of Waste: Biogas (eds. Christensen, T.H., Cossu, R., Stegmann, R.), E & FN Spon, London.

Young, P.J and Heasman, L.A. (1985). An Assessment of the odour and toxicity of the trace components of landfill gas, Waste Research Unit, Harwell Laboratory, Didcot, Oxon, UK.

Young, P.J. and Parker, A. (1983). The identification and possible environmental impact of trace gases and vapours in landfill gas, Waste Management & Research, Vol. 1, pp213 – 226, May 1983.

Young, P.J. and Parker, A.. (1984). Origin and Control of Landfill Odours, Chemistry and Industry, No.9, pp 329 – 333, 7 May 1984.

INTERNET SOURCES (WEBSITES)

www.hofstertter.ch. (2001). Spillmann P (2000) Landfill Gas – What is it?, Hofstetter.

www.CH4gas.com. (2000). Wheeler Environment Management, LLC, 1997/1998.

www.epa.gov. (2001). EPA Landfill Methane Outreach Program

www.epa.gov. (2001). Global Warming, US EPA, April 6, 2001.

www.biogas.org.uk. (2000). Landfill Gas and the Environment.

PERSONAL COMMUNICATIONS AND INTERVIEWS

Clive Kidd (2000). Regional Manager for Landfill Management – Waste Disposal Services, EnviroServ Waste Management (PTY) Ltd, Shongweni Landfill, Shongweni, 10 August 2000.

Bob Couth (2001). Landfill Gas Principal Consultant, EnvirosAspinwall, Shrewsbury, Shropshire SY4 2HH, UK, November - December 2001.

Lindsay Strachan (2000). Senior Engineer for Durban Metro Landfills, Bisasar Road Landfill, Durban Solid Waste, Springfield, Durban, 01 August 2000.

Lindsay Strachan (2001). Senior Engineer for Durban Metro Landfills, Bisasar Road Landfill, Durban Solid Waste, Springfield, Durban.

Ray Lombard (2001). Environment Protection & Waste Management Consultant, Lombard & Associates, Link Hills, South Africa, 08 November 2001.

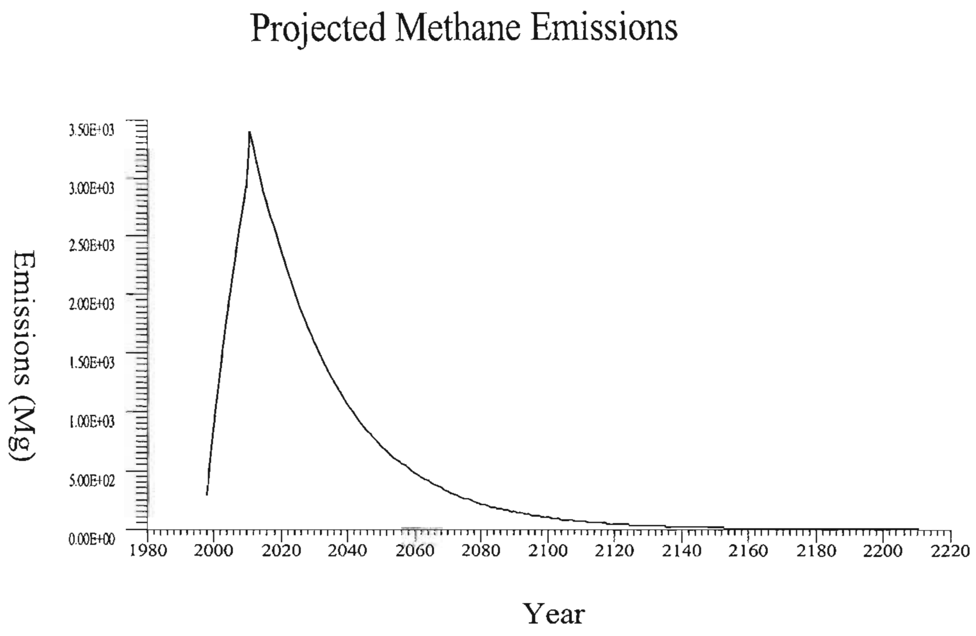
Trevor Letcher (2001). Professor at School of Pure & Applied Chemistry, University of Natal-Durban, Durban, South Africa, 16 August 2001.

APPENDICES

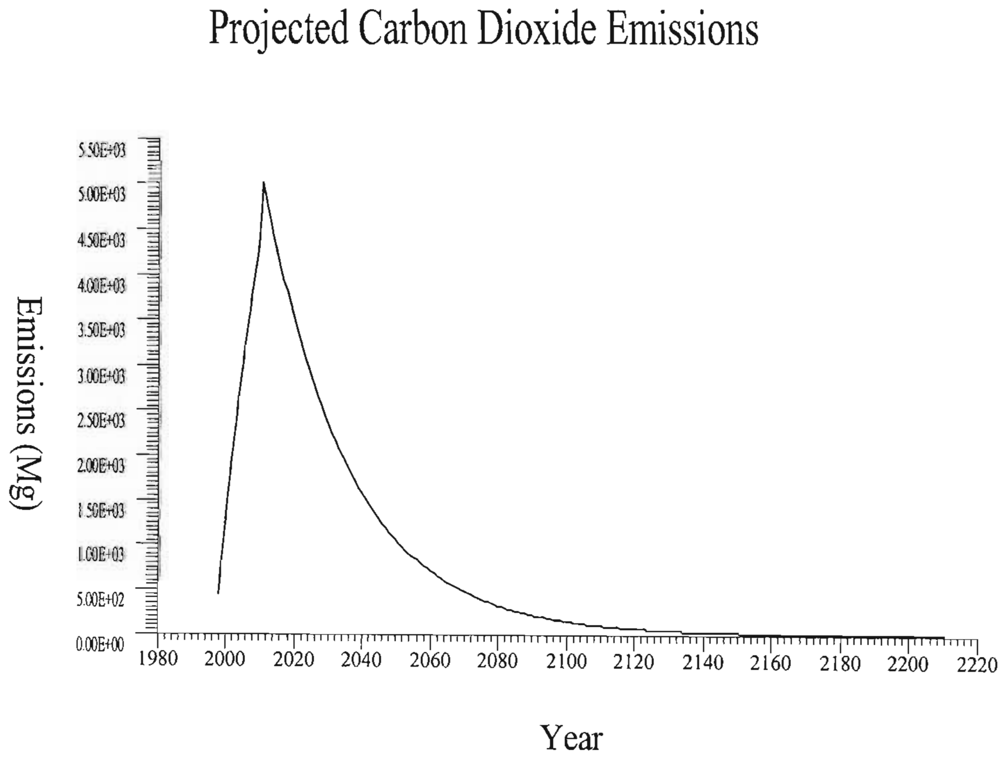
APPENDIX 1

LANDGEM RESULTS SHOWING AIR POLLUTANT EMISSIONS AS A FUNCITON OF TIME FOR THE SHONGWENI AND BUFFELSDRAAI LANDFILLS

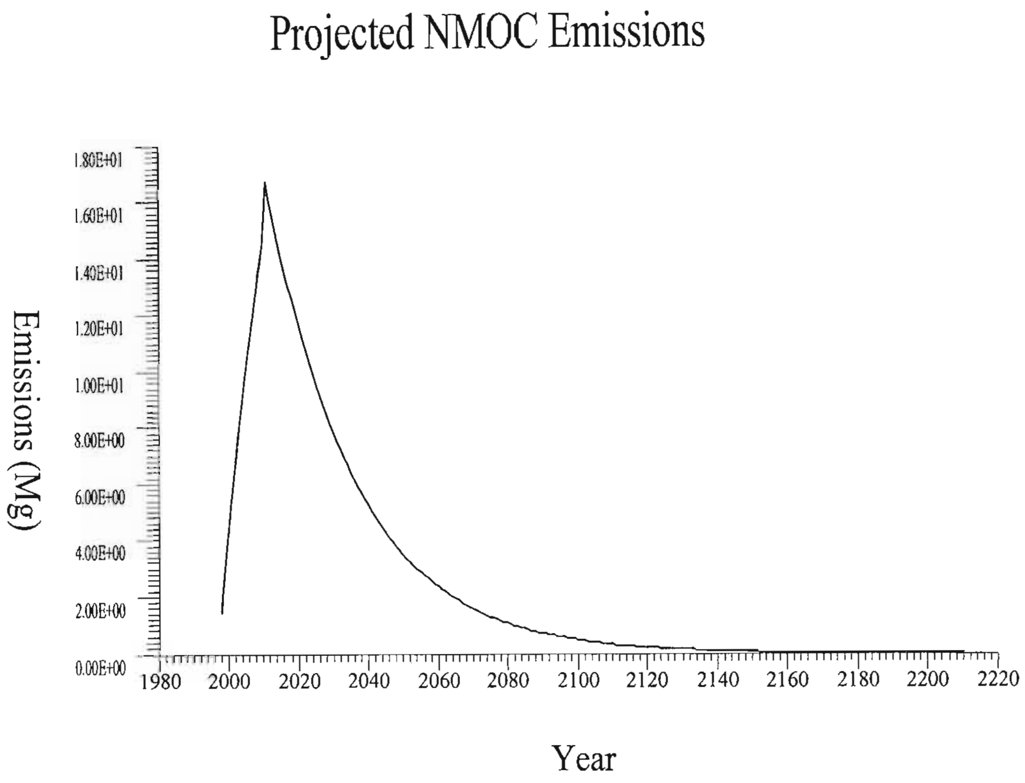
SHONGWENI AIR POLLUTANT EMISSIONS PROFILES


Projected Methane Emissions

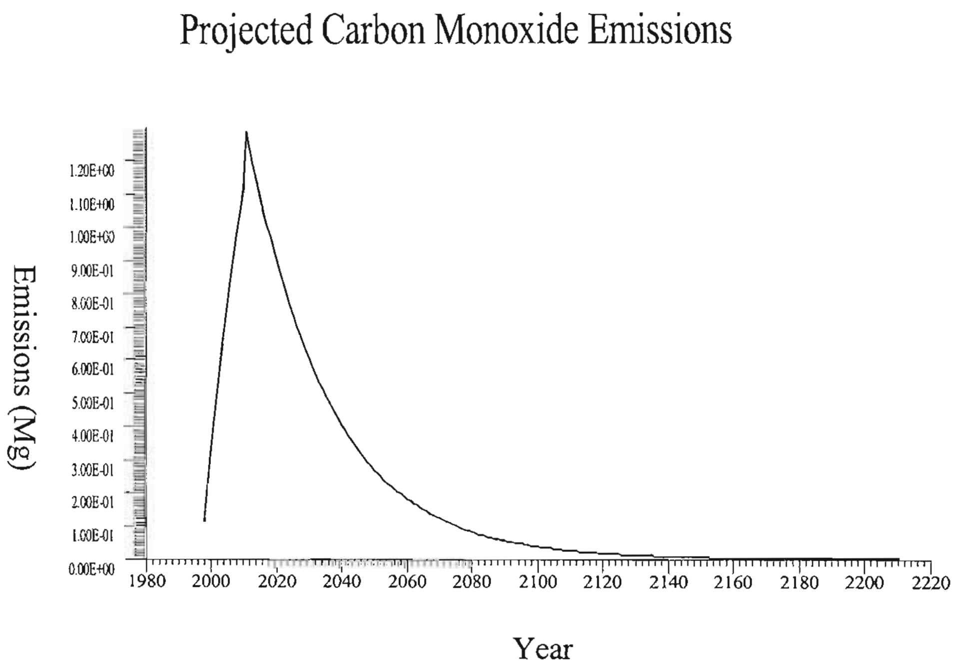
CH_4 emissions from Shongweni landfill


Projected Carbon Dioxide Emissions

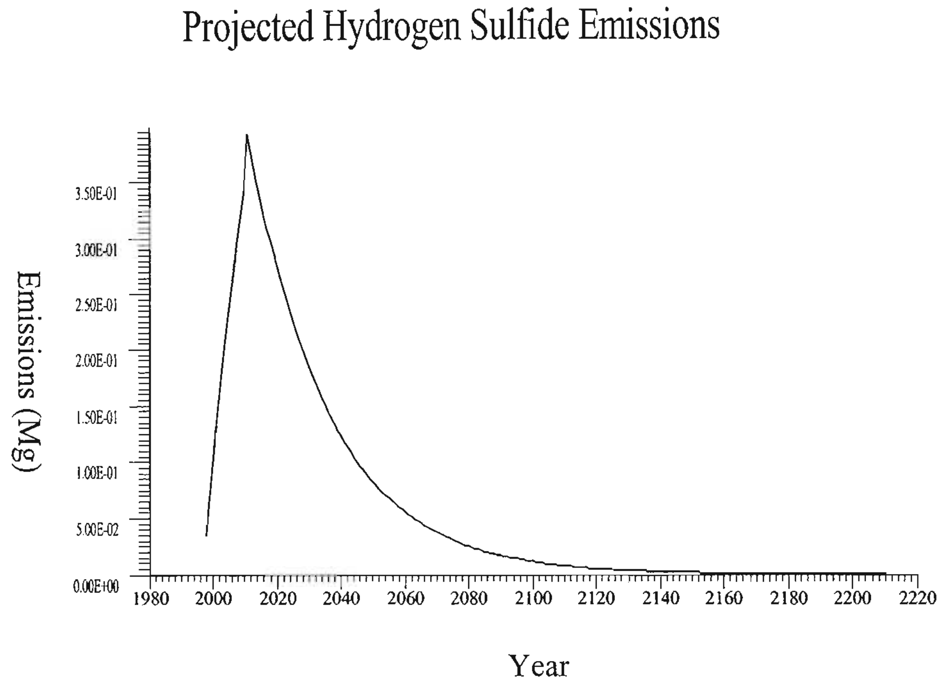
CO_2 emissions from Shongweni landfill



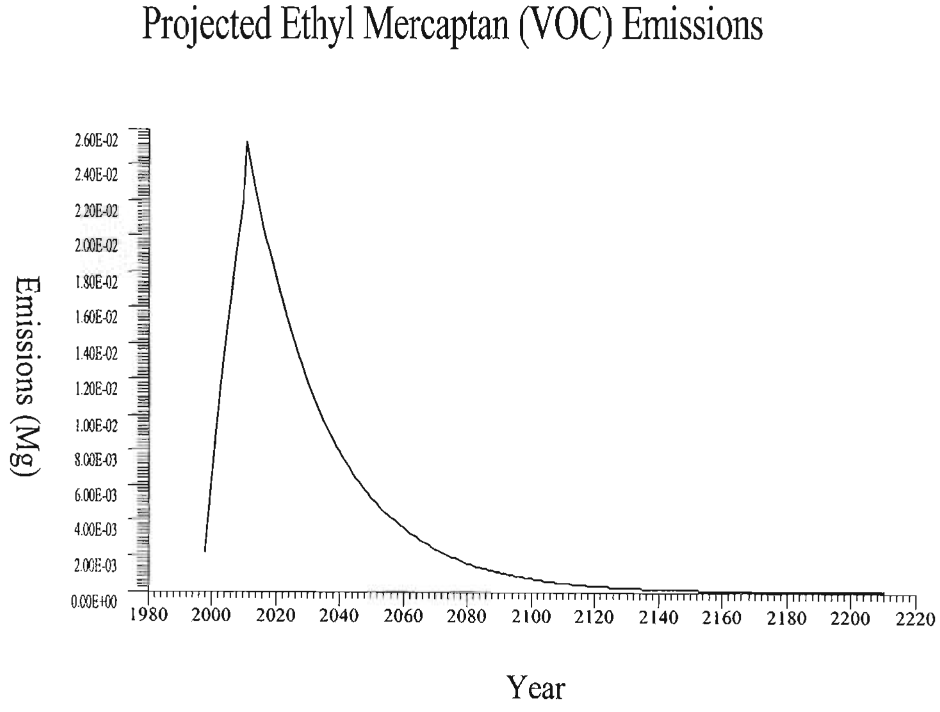
NMOC emissions from Shongweni landfill



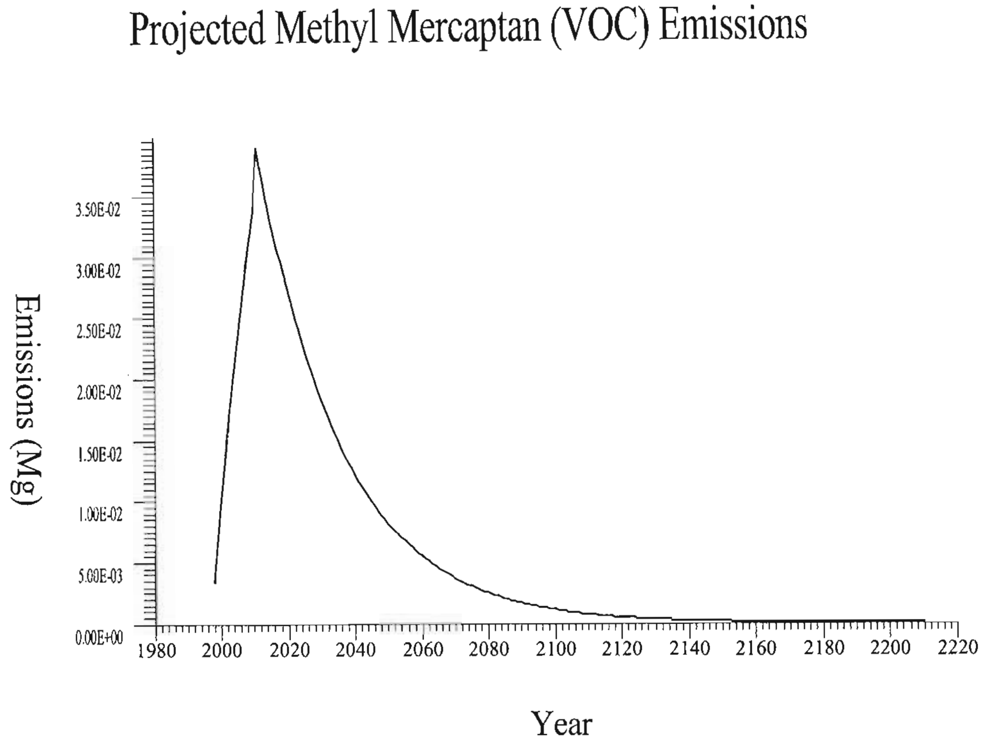
CO emissions from Shongweni landfill



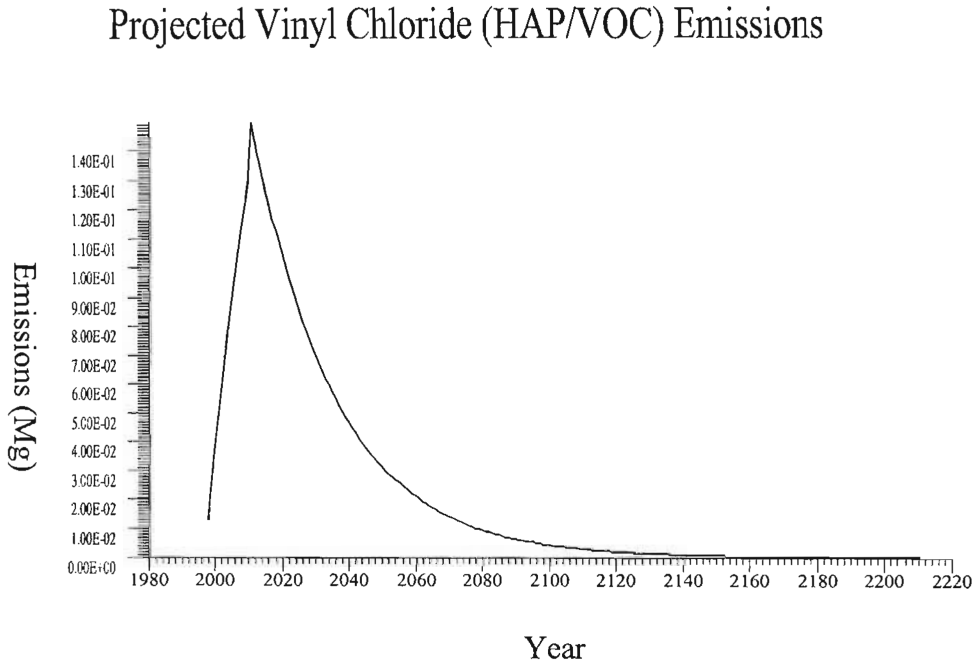
H_2S emissions from Shongweni landfill



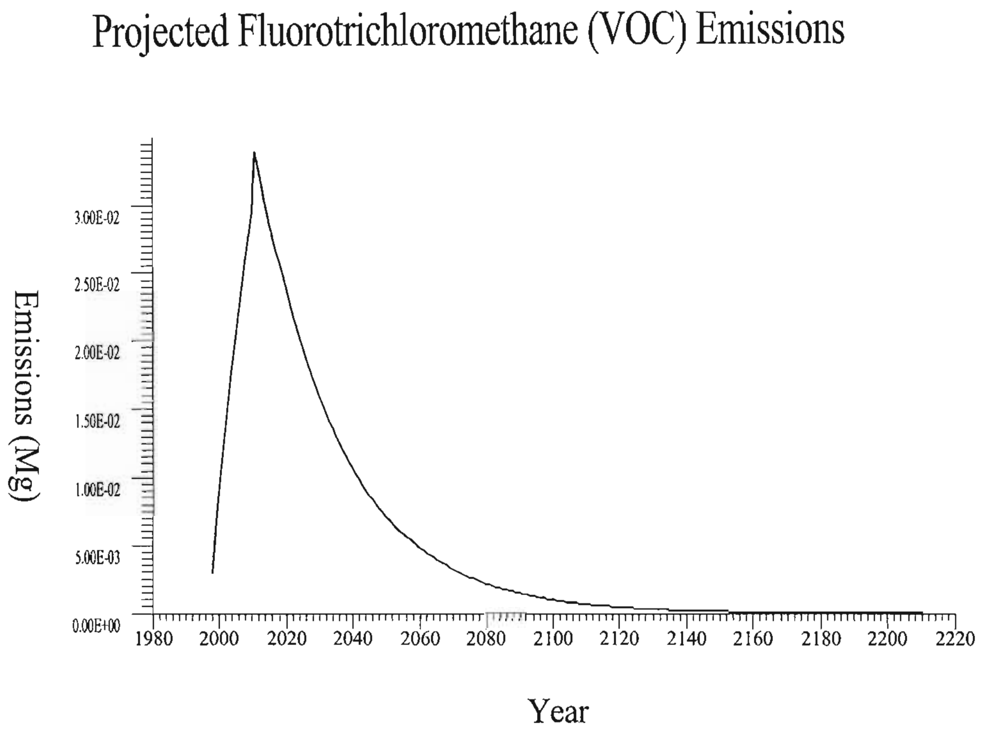
CH_3CH_2-SH emissions from Shongweni landfill



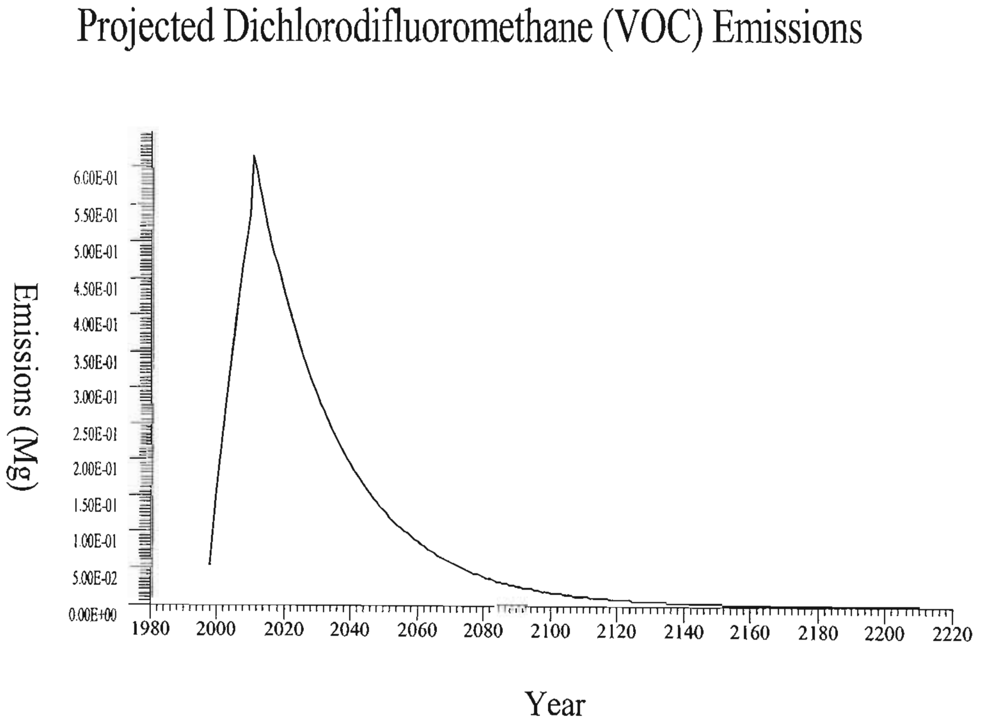
CH$_3$-SH emissions from Shongweni landfill



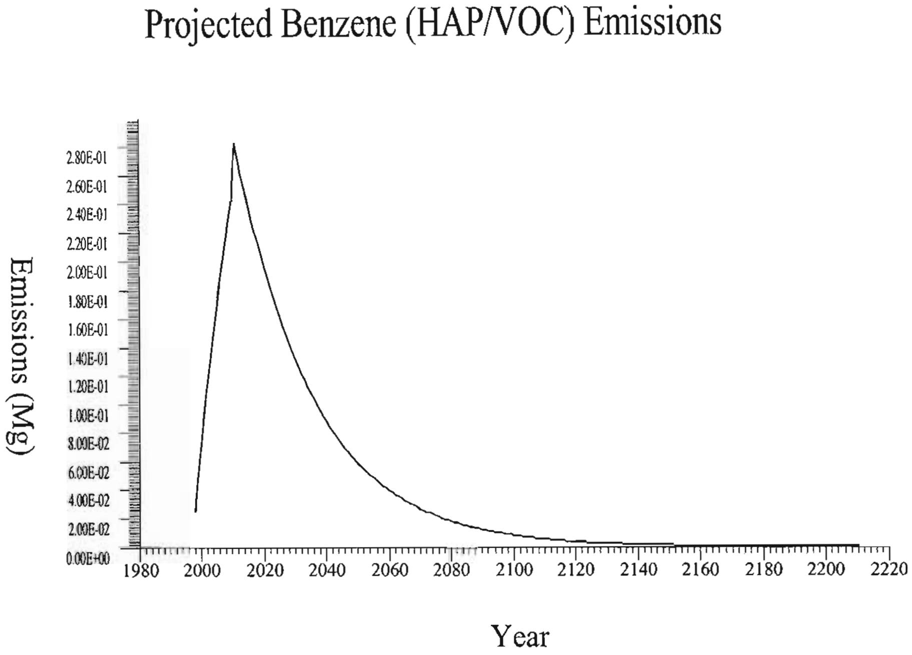
CH$_2$=CHCl emissions from Shongweni landfill



$CFCl_3$ emissions from Shongweni Landfill.

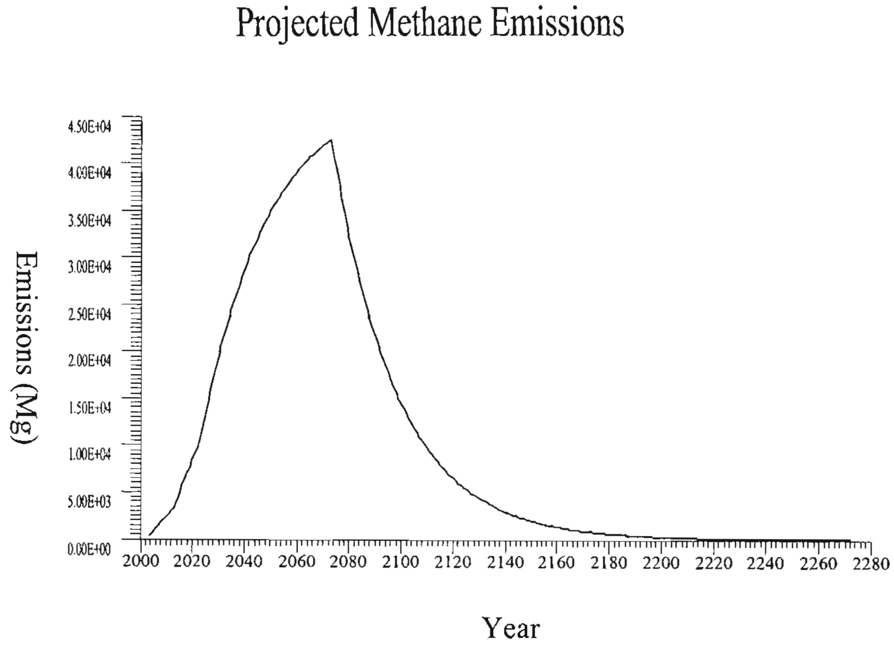


Cl_2CF_2 emissions from Shongweni Landfill.

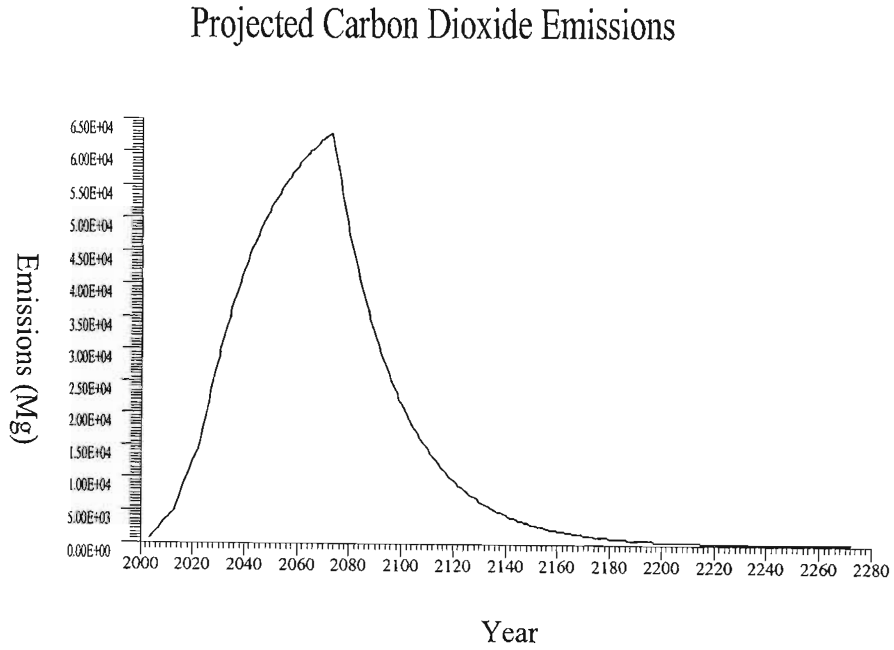


C_6H_6 emissions from Shongweni Landfill.

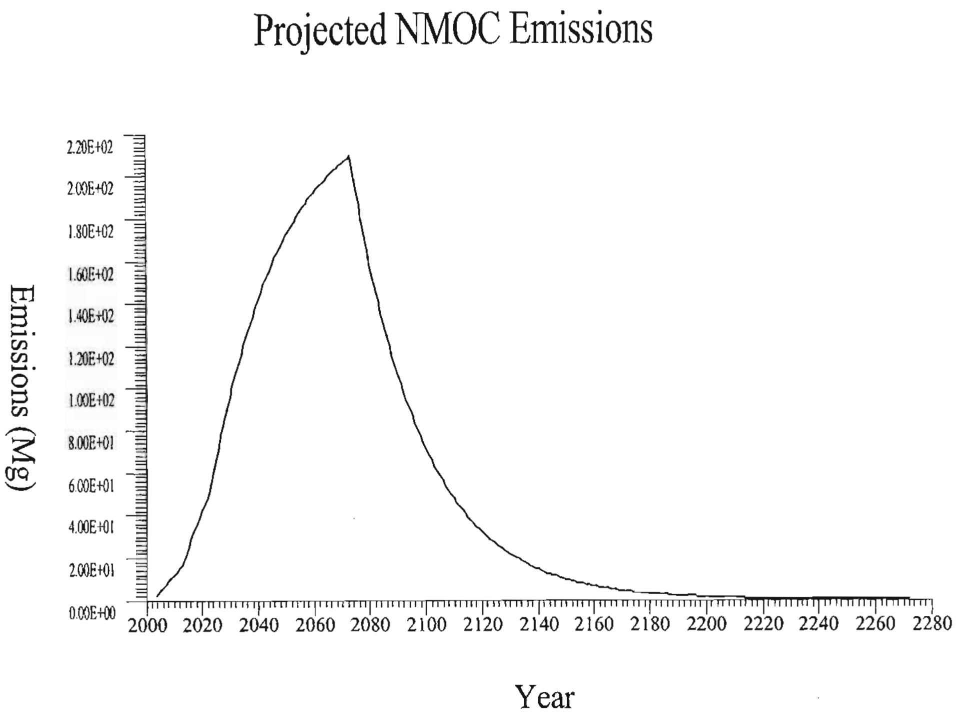
POFILES OF AIR POLLUTANT EMISSIONS AT BUFFELSDRAAI LANDFILL



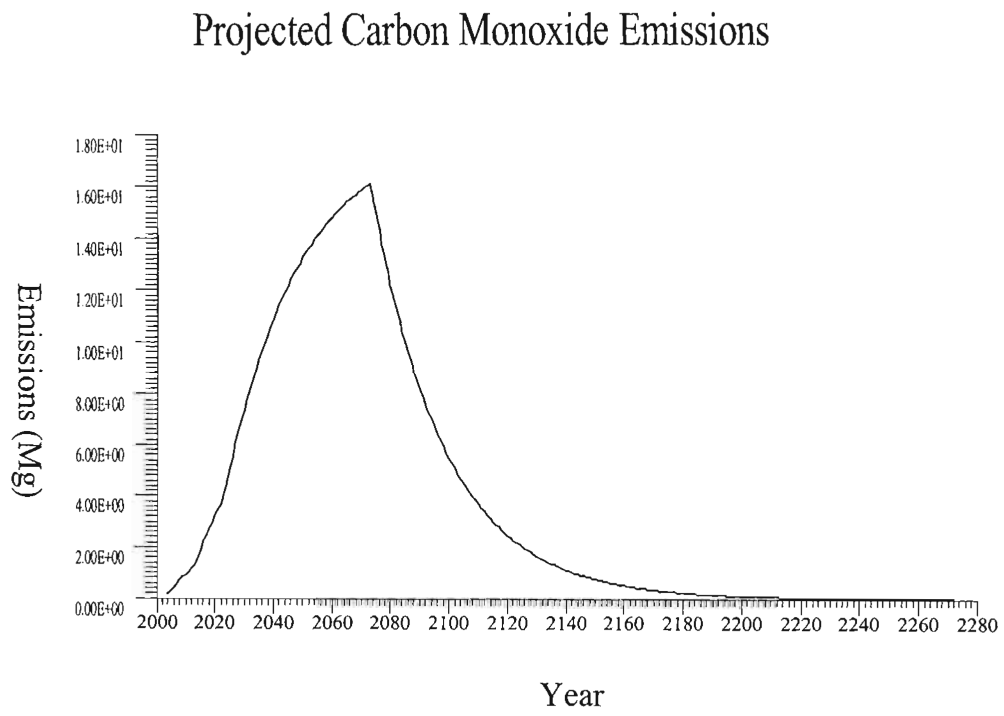
CH_4 emissions at Buffelsdraai landfill



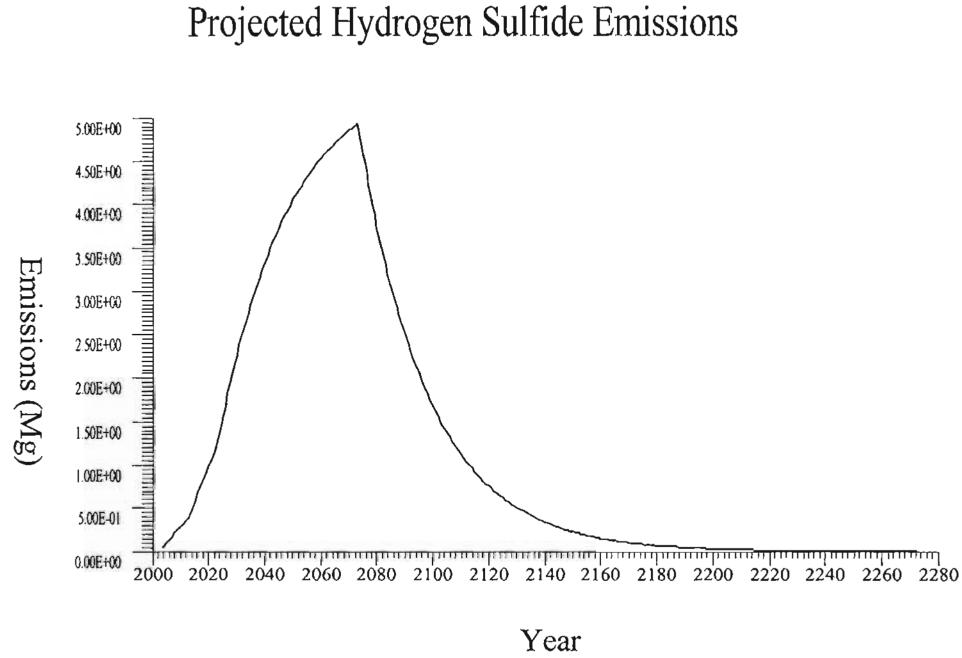
CO_2 emissions at Buffelsdraai landfill



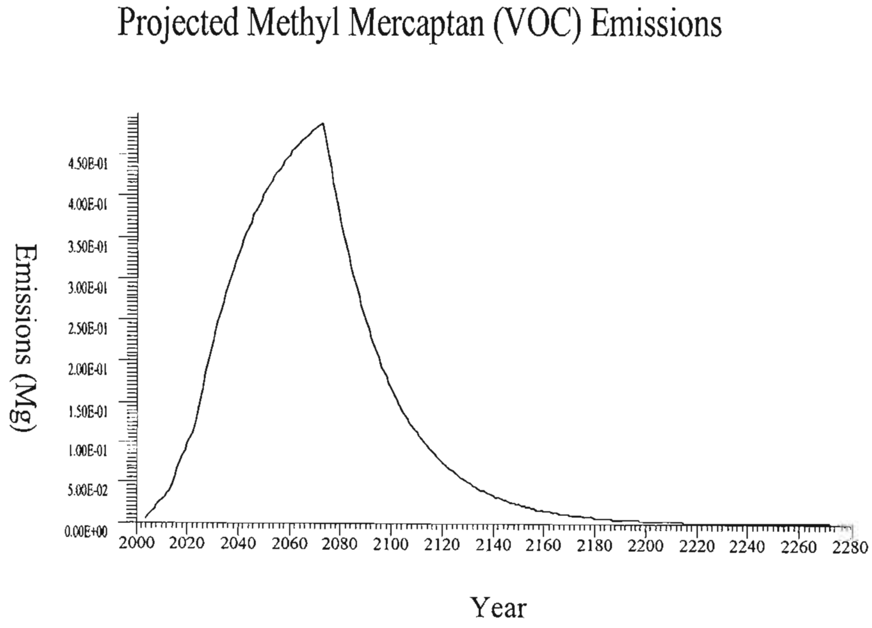
NMOC emissions at Buffelsdraai landfill



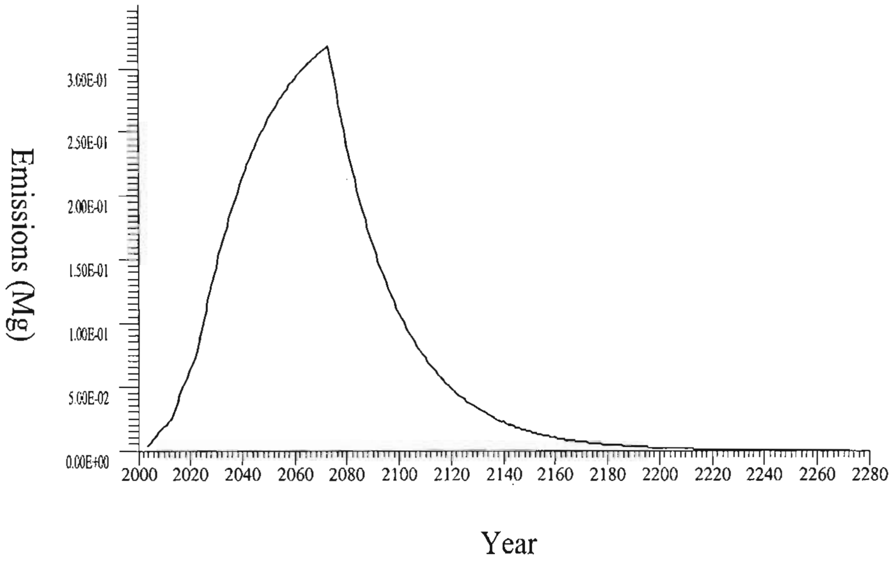
CO emissions at Buffelsdraai landfill



H_2S emissions at Buffelsdraai landfill

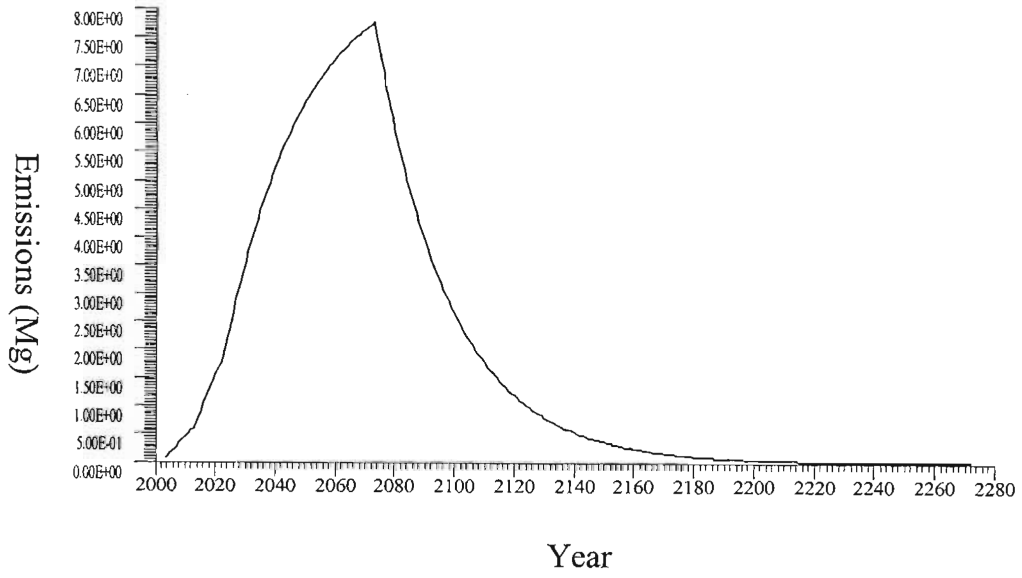


CH_3-SH emissions at Buffelsdraai landfill



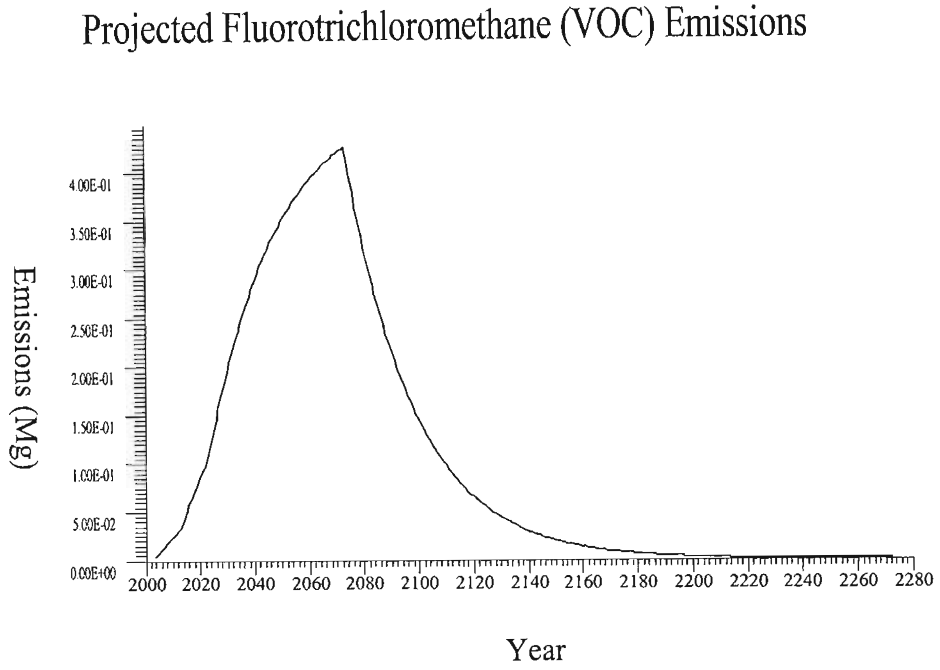
Projected Ethyl Mercaptan (VOC) Emissions

CH_3CH_2-SH emissions at Buffelsdraai landfill

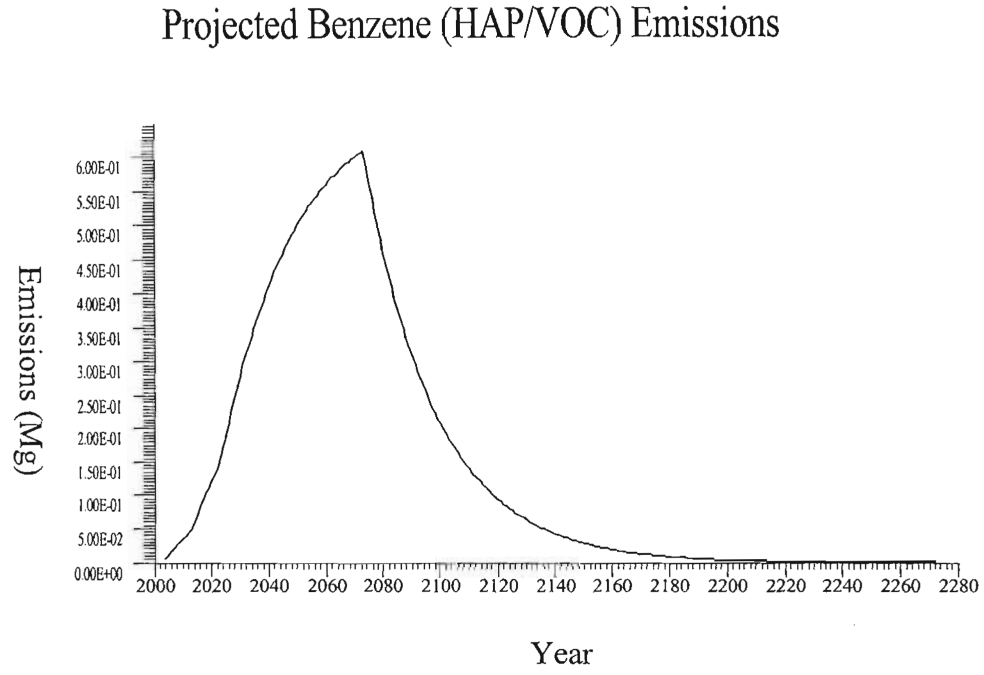


Projected Dichlorodifluoromethane (VOC) Emissions

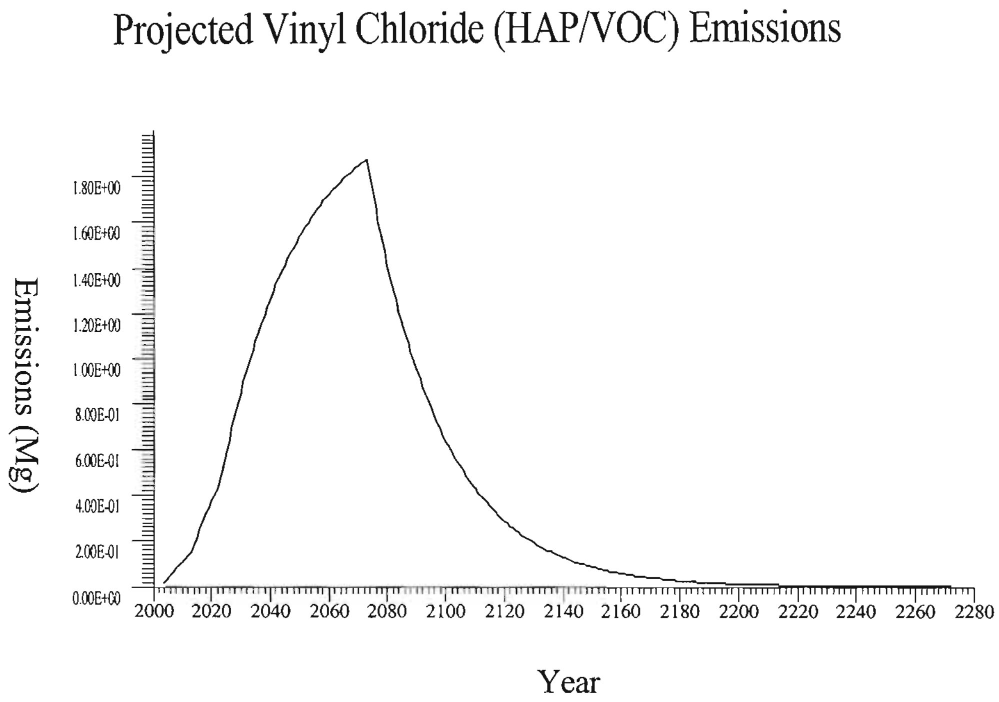
CCl_2F_2 emissions at Buffelsdraai landfill


Projected Fluorotrichloromethane (VOC) Emissions

$CFCl_3$ emissions at Buffelsdraai landfill


Projected Benzene (HAP/VOC) Emissions

C_6H_6 emissions at Buffelsdraai landfill



CH_2=CHCl emissions at Buffelsdraai landfill

APPENDIX 2

LANDFILL AND MODEL PARAMETERS INPUT IN THE LANDGEM MODEL

2.1 BISASAR ROAD LANDFILL

Model Parameters

Lo : 100.00 m^3 / Mg
k : 0.0400 1/yr
NMOC : 595.00 ppmv
Methane : 65.0000 % volume
Carbon Dioxide : 35.0000 % volume

Landfill Parameters

Landfill type : No Co-Disposal
Year Opened : 1980 Current Year : 2001 Closure Year: 2012
Capacity : 21000000 Mg
Average Acceptance Rate Required from
Current Year to Closure Year : 844199.13 Mg/year

2.2 SHONGWENI LANDFILL

Model Parameters

Lo : 100.00 m^3 / Mg
k : 0.0400 1/yr
NMOC : 2420.00 ppmv
Methane : 65.0000 % volume
Carbon Dioxide : 35.0000 % volume

Landfill Parameters

Landfill type : Co-Disposal
Year Opened : 1997 Current Year : 2001 Closure Year: 2011
Capacity : 1600000 Mg
Average Acceptance Rate Required from
Current Year to Closure Year : 105023.90 Mg/year

2.3 BUFFELSDRAAI LANDFILL

Model Parameters

Lo : 100.00 m^3 / Mg
k : 0.0400 1/yr
NMOC : 595.00 ppmv
Methane : 65.0000 % volume
Carbon Dioxide : 35.0000 % volume

Landfill Parameters

Landfill type : No Co-Disposal
Year Opened : 2003 Current Year : 2023 Closure Year: 2073
Capacity : 40000000 Mg
Average Acceptance Rate Required from
Current Year to Closure Year: 698456.98 Mg/year

2.4 MODEL SENSITIVITY ANALYSIS (TEST STUDY)

The following are initial parameters used to test the sensitivity of the LANDGEM model. It must be noted that the following parameters were varied during the sensitivity test analysis of the model.

Model Parameters

Lo : 100.00 m^3 / Mg
k : 0.0400 1/yr
NMOC : 2420.00 ppmv
Methane : 50.0000 % volume
Carbon Dioxide : 50.0000 % volume

Landfill Parameters

Landfill type : Co-Disposal
Year Opened : 1975 Current Year : 1995 Closure Year: 2001
Capacity : 3000000 Mg
Average Acceptance Rate Required from
Current Year to Closure Year : 200000.00 Mg/year

APPENDIX 3

Summary of volume of waste types in tonnes accepted at Bisasar Road landfill, for the period July 1997 to December 2000 (DSW, 2001).

	Waste Type									
Periods	Solid waste	Garden refuse	Rubble	Mixed Loads	Condem Foods	Sand etc	Whole tyres	Asphalt	Sani waste	Mondi pulp
July-Dec 97	42512	24007	34214	25598	183	102209	507	2775	104	0
Jan-Jun 98	47659	24827	36680	80695	296	100809	792	2448	655	0
July-Dec 98	25246	15754	35502	4657	124	80578	552	2725	12	0
Jan-Jun 99	35532	17041	44205	4675	168	69104	643	2752	0	0
July-Dec 99	51416	16824	36137	5804	189	94300	804	1555	0	0
Jan-Jun 00	58612	19158	42248	7158	158	72929	808	1592	1	0
July-Dec 00	25636	18096	33731	6186	118	66196	561	2086	2	28968

APPENDIX 4

HOFSTETTER GAS YIELD MODEL

(BISASAR ROAD LANDFILL CASE STUDY, 1998)

BISASAR ROAD LANDFILL

The following information on Hofstetter model used to estimate biogas production at Bisasar Road was adapted from Lombard *et al.*(1998).

Operating data of the landfill

Start of waste depositing	January 1979 [Month,year]
Deposited quantity of waste (gas producing+inert)	13,678,485 [to]
Gas producing deposited waste	6,839,243 [to]

Features of the decomposable waste

Organic carbon in waste	C	150	[kg/to]
Percentage of easy decomposable material	Sl	60	[%]
Percentage of medium decomposable material	Sm	30	[%]
Percentage of heavy decomposable material	Ss	10	[%]
Starting phase of CH4 production	Aph	0.5	[year]
Half decay time for the easy decomposable material	Zl	2.0	[year]
Half decay time for the medium decomposable material	Zm	7.5	[year]
Half decay time for heavy decomposable material	Zs	15	[year]
Average landfill temperature	Tm	45	[C]
Methane content in native landfill gas	CH4	50	[vol.%]
Calorific value of native landfill gas	Hu	5.0	[kW/m^3]
Specific gas production per ton in 50 years (t95-time)	Ge50	321	[Nm^3/to]
Specific end gas quantity per ton of waste	Gse	255	[Nm^3/to]
Degree of gasification after 50 years	Kver	125.97	[%]
Parameter for degree of gasification	Ks	1.06	--

Specific gas production of the decomposable waste

Year	Specific gas Production	
(1-50)	[m^3/to.Ja]	[m^3/to]
0	0	0
1	18.195	18.2
2	18.836	47.03
3	29.775	76.81
4	27.729	104.54
5	24.857	129.39
6	21.918	151.31
7	19.189	170.5
8	16.756	187.26
9	14.631	201.89
10	12.793	214.68
11	11.21	225.89
12	9.85	235.74
13	8.68	244.42
14	7.673	252.09
15	6.803	258.89
16	6.051	264.94
17	5.397	270.34
18	4.828	275.17
19	4.33	279.5
20	3.894	283.39
21	3.51	286.9
22	3.171	290.07
23	2.871	292.95
24	2.604	295.55
25	2.367	297.92
26	2.155	300.07
27	1.965	302.04
28	1.795	303.83
29	1.641	305.47
30	1.503	306.98
31	1.378	308.35
32	1.265	309.62
33	1.163	310.78
34	1.07	311.85
35	0.985	312.84
36	0.908	313.75
37	0.838	314.58
38	0.774	315.36
39	0.715	316.07
40	0.661	316.73
41	0.612	317.35
42	0.567	317.91
43	0.525	318.44
44	0.487	318.92
45	0.451	319.38
46	0.419	319.79
47	0.389	320.18
48	0.361	320.55
49	0.336	320.88
50	0.312	321.19

Gas Production and Quantity

Depositeduntil January	Deposited waste [tonne]	Degassa-ble percent %	Collect-able Gas Quan. %	Gasr **Gpn**[a] [m3/h]	quantity **Gpe**[b] [m3/h]	Degassed waste quantity [tonne]
1979	0			0	0	0
1980	307500	50	80	319	255	153750
1981	525000	50	80	1051	841	262500
1982	516000	50	80	1923	1538	258000
1983	390150	50	80	2633	2107	195075
1984	363350	50	80	3164	2531	181675
1985	377400	50	80	3599	2879	188700
1986	240000	50	80	3831	3065	120000
1987	262100	50	80	3952	3161	131050
1988	297600	50	80	4073	3259	148800
1989	391023	50	80	4295	3436	195511.5
1990	420455	50	80	4596	3676	210227.5
1991	452102	50	80	4941	3953	226051
1992	486131	50	80	5322	4258	243065.5
1993	522722	50	80	5735	4588	261361
1994	562067	50	80	6181	4945	281033.5
1995	604373	50	80	6660	5328	302186.5
1996	649863	50	80	7175	5740	324931.5
1997	701283	50	80	7730	6184	350641.5
1998	750373	50	80	8325	6660	375186.5
1999	802899	50	80	8957	7165	401449.5
2000	859102	50	80	9628	7703	429551
2001	919239	50	80	10342	8274	459619.5
2002	992888	50	80	11112	8889	496444
2003	63743	50	80	10900	8720	31871.5
2004	65655	50	80	10061	8048	32827.5
2005	67625	50	80	9101	7281	33812.5
2006	69654	50	80	8182	6546	34827
2007	71743	50	80	7354	5883	35871.5
2008	73896	50	80	6628	5303	36948
2009	76113	50	80	6001	4800	38056.5
2010	78396	50	80	5461	4369	39198
2011	80748	50	80	5000	4000	40374
2012	83171	50	80	4606	3684	41585.5
2013	85666	50	80	4269	3415	42833
2014	88236	50	80	3982	3186	44118
2015	90883	50	80	3738	2991	45441.5
2016	93609	50	80	3531	2825	46804.5
2017	96417	50	80	3355	2684	48208.5

2018	99310	50	80	3206	2565	49655
2019	0	0	80	2974	2379	0
2020	0	0	80	2698	2158	0
2021	0	0	80	2429	1943	0
2022	0	0	80	2182	1746	0
2023	0	0	80	1961	1569	0
2024	0	0	80	1765	1412	0
2025	0	0	80	1591	1273	0
2026	0	0	80	1437	1150	0
2027	0	0	80	1301	1041	0

[a] **Gpn** = native gas production

[b] **Gpe** = recoverable native gas quantity