CHARACTERISATION AND MANAGEMENT OF LANDFILL EMISSIONS UNDER A SUB-TROPICAL CLIMATE USING FULL-SCALE LANDFILL CELLS

by

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ABSTRACT

It is now widely understood that landfills, comprising municipal solid wastes, typically undergo biological degradation processes in what are referred to as *Bio-Reactor Landfills*. These microbiological processes cause the release of gaseous and liquid emissions, which are commonly called landfill gas (LFG) and landfill leachate respectively. They are formed through mass transfer and biodegradation processes, which occur between percolating water and the solid waste matrix. Such emissions, if not correctly managed, may pose a threat to the natural environment surrounding landfills, and, specifically, landfill leachate may cause significant pollution of the ground water regime. The changes that landfilled wastes undergo to achieve a relatively stable, methanogenic state of decomposition are now well understood, however little is known on the rate at which biodegradation processes take place, and particularly the timescale over which degradation of waste materials is completed.

This dissertation presents research work demonstrating the behaviour of landfill emissions under specific climatic conditions encountered in South Africa in three containment landfill cells situated within the Bisasar Road and Mariannhill Landfill Sites. The containment cells, which are equipped with leachate extraction systems, proved to be ideal full-scale 'pilot plants' where changes in leachate and biogas emissions could be monitored. The characterisation of the landfill emissions allowed for the qualitative determination of the time-scales involved in reaching methanogenic conditions under a sub-tropical climate. Using this information, two landfill gas production models (adapted for the prevalent climatic conditions) were applied to two containment cells in order to predict the volume and duration of gas emissions. The results of the emissions characterisation show that the management of landfill developments in the form of small cells within the larger landfill footprint ('cellular' landfilling) can enhance waste degradation processes, and hence achieve desired levels of stabilised waste conditions relatively quickly. The results of the landfill gas models show that relatively large volumes of gas are emitted early in the lifetime of a landfill cell, and that the maximum emissions will be produced within a relatively short period of time (six to twelve months) after the last deposition of waste. This would allow for the extraction and treatment of landfill gas almost immediately after the closure of a cell, thereby shortening the time span over which potentially harmful emissions can occur.

For

Mom, Dad, and Natalie

PREFACE

The work presented in this dissertation was carried out under the supervision of Dr. Cristina Trois and Professor Deneys Schreiner of the School of Civil Engineering, Surveying and Construction, University of Natal, Durban, South Africa. This dissertation has been prepared in accordance with the *Style Guide for Dissertations* prepared by the Civil Engineering Programme, University of Natal, Durban.

Research work on the characterisation and management of landfill emissions has been performed by numerous waste scientists and institutions worldwide. South Africa, as an emerging country, is moving towards the high standards for waste disposal and treatment set in developed countries. In this regard, a collaboration between the University of Natal and the local waste disposal unit, Durban Solid Waste (DSW) was established. The research was conducted at the Bisasar Road and Mariannhill Landfill Sites in Durban and at the University of Natal. It is hoped that the research presented in this dissertation will provide insight into landfill processes related to specific climatic conditions encountered in South Africa, and assist landfill managers with regards to appropriate management techniques.

This dissertation was written by Aiden James Bowers, and unless stated to the contrary in the text, is the authors' own work and has not been submitted in part, or in whole, to any other University.

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Aiden James Bowers
April 2002

This dissertation has been approved for submission by my supervisor, Dr. Cristina Trois and my co-supervisor Professor Deneys Schreiner.

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Dr. C. Trois Prof. D. Schreiner

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CHAPTER 1
INTRODUCTION

The deposition of unwanted materials (waste) on the surface of the earth is the oldest and most widely utilised method for the disposal of solid wastes (WHO, 1995). The traditional development of landfill sites paid little attention to their polluting potential and nuisance to homeowners living near a landfill. Rapid urbanisation, particularly in developing countries, resulted in ever-increasing waste volumes and the unavoidable establishment of residential areas in close proximity to landfill sites. In recent years, the hazards associated with poorly sited and managed 'dumps' were realised – vital groundwater resources were being polluted and explosive gases were migrating from the fill.

Growing public awareness with regard to the harm and nuisance caused to the surrounding environment resulted in extensive research being conducted on the composition, characteristics and treatment of landfill emissions. This research highlighted the shortcomings of landfill design and management techniques in general and in South Africa in particular. These techniques were generally based on European conditions and were often not suitable for the climatic conditions. As a direct result, legislation for acceptable waste disposal was drafted in the form of the Governments "Minimum Requirements for Waste Disposal by Landfill" (DWAF, 1994; amended 1998). This document provides guidelines on what is considered 'best practice' for locating new sites, managing a site, managing landfill emissions, and closing a site.

1.1 LANDFILL EMISSIONS

Wastes placed in a landfill undergo microbial decomposition via a large consortium of bacteria, which consume the organic portion in the waste. The decomposition of waste is a complex combination of physical, chemical and biological processes. The biologically mediated reactions constitute the major mechanisms of waste degradation and, in practice, control the physico-chemical kinetics (Trois et al, 2000). Landfills may be regarded as bioreactors, with refuse and water as inputs and liquid (leachate) and gas (landfill gas) as products. Landfill emissions pose hazards of fire and explosion, they can create health risks and odour nuisances, damage vegetation, pollute groundwater and have global climate effects.

Despite an initial aerobic phase, which is limited both spatially to the top layers, and temporally to a few days, the waste decomposition develops in two major anaerobic phases. These extend through the lifetime of the landfill and their products can pose a threat to the environment many years after the closure of the site. The first anaerobic phase is termed 'acetogenesis', and occurs when anaerobic and facultative bacteria hydrolyse and ferment cellulose and other putrescible materials producing simpler, soluble compounds such as volatile fatty acids and ammonia. This phase may last from years to decades. The second phase is termed 'methanogenesis', and arises when more sensitive and slower growing methanogenic bacteria gradually become established and start to consume the simple organic compounds, producing a mixture of carbon dioxide and methane (and various trace components) which is released as landfill gas. Once the transition from the acetogenic stage is complete (which may take many years); the methanogenic phase can last for decades, and perhaps even centuries. Waste in this phase is often referred to as 'stabilised', however at this stage the landfill is at its most active, with a dynamic equilibrium eventually being established between acetogenic and methanogenic bacteria (Robinson, 1989). The active production of gas during this stage can occur for several years at a relatively high rate.

The changes in composition of landfill emissions due to the transition from acetogenic to methanogenic stages are well understood. Farquhar and Rovers (1973), Robinson (1989), Christensen and Kjeldsen (1989) report typical characteristics of emissions associated with each stage, however the time-scales involved are purposely omitted. This is because the rate of waste decomposition depends on a number of variables, in both the waste body and in the prevailing climatic conditions. Consequently, there is little knowledge on the time scales involved in achieving relatively stable, methanogenic conditions

1.2 SCOPE OF THE RESEARCH

This dissertation presents research work conducted at two Municipal Solid Waste (MSW) landfill sites in Durban, South Africa, namely the Bisasar Road Landfill Site and the Mariannhill Landfill Site. As stated previously, knowledge on waste degradation rates is lacking. In addition, there are few works available on leachate characterisation under a sub-tropical climate, in particular with regards to South African conditions. The Durban climate, with an average annual rainfall in excess of 1000 mm and average temperatures ranging from 23 to 28^{0}C (Durban Metro, 1999), is typical of such a region.

The objectives of the research were:

- To achieve a quality characterisation of leachate and biogas emissions from a MSW landfill site and to draw comparisons between the actual data and quality models commonly reported and used in international literature.
- To correlate leachate and biogas quality and behaviour with different parameters such as type and age of waste, rate/stage of decomposition, climate, and management of the landfill site
- To refine existing biogas production models in order to predict, more accurately, gas volumes related to specific conditions experienced in the Durban Metropolitan Area.

The Bisasar Road Landfill was located and developed prior to the implementation of the "Minimum Requirements", which brought about enforced change in landfilling techniques. The continued development of the site therefore occurred in the form of small containment cells within the larger landfill footprint, culminating in the construction of a fully engineered/lined valley landfill (named the 'Randles Cell'). The Mariannhill Landfill was developed after the enforced changes in landfill management in 1994 (DWAF, 1994) and was therefore located and managed to engineering standards. The landfill has been developed in the form of three relatively small, lined cells (a fourth cell is currently under construction) equipped with separate leachate collection systems (named 'Cell 1', 'Cell 2' and 'Cell 3'). Cells 1 and 2 also have active gas extraction systems in place.

These three cells proved to be ideal full-scale 'pilot plants' for the monitoring of landfill emissions under a sub-tropical climate. Leachate samples were obtained from the collection systems (at the discharge points) and landfill gas was sampled from shallow probes and gas extraction wells placed into the waste body. The composition of leachate and landfill gas in the Randles Cell, Cell 1 and Cell 2 was monitored over the course of the research. Two landfill gas models were studied and applied to Cells 1 and 2 to predict the volume and rate of gas emission. A validation of a method to measure surface emissions was also conducted.

This dissertation consists of eight chapters. Chapters 2, 3 and 4 present an extensive literature review, comprising landfill management, leachate production and characterisation and landfill gas characterisation, modeling and management. Chapter 5 includes a description of the landfill sites where the research was conducted and the experimental procedures adopted. Chapter 6 presents the results of the leachate characterisation. Chapter 7 presents the results of the landfill gas characterisation, application of the two gas production models and validation of the method to measure surface emissions. Chapter 8 summarises the findings of the research (in a conclusive chapter).

CHAPTER 2

LANDFILLING OF WASTE

2.1 WASTE DISPOSAL

The generation of solid waste, and particularly Municipal Solid Waste (MSW), is a consequence of modern living and an increasingly urbanised society. Waste generation is of global concern, and in the context of South Africa as a developing country, the volume of solid waste generated can be expected to increase.

As the volume of waste has increased in the last decade, municipalities are allocating larger proportions of their budget to the collection and disposal of solid wastes, which has resulted in more attention being paid to the waste industry and the development of a new environmental awareness. A philosophy of waste reduction is currently being implemented, particularly at grass roots level, as the only real long-term solution to dealing with ever increasing waste volumes.

In the past, the problems associated with the generation of large volumes of waste were generally underestimated or even ignored. The lack of formal management systems and poor management of disposal facilities may result in the contamination of important natural resources (most notably groundwater) and irreparable environmental damage. Research conducted, in the last two decades particularly, has focused predominantly on the landfilling of waste and landfill operations (Christensen et al, 1989, 1992; Qasim and Chiang, 1994)

Solid waste in today's society is controlled by a formal waste management system, consisting of functional elements that deal with the activities associated with the generation of solid wastes through to their final disposal. Figure 2.1 illustrates the route that a particular waste may follow, and the relationships between the functional elements.

The functional elements are described below (Peavy et al, 1985):

- Waste generation – Materials that are identified as no longer having value are either thrown away, or gathered together for disposal.

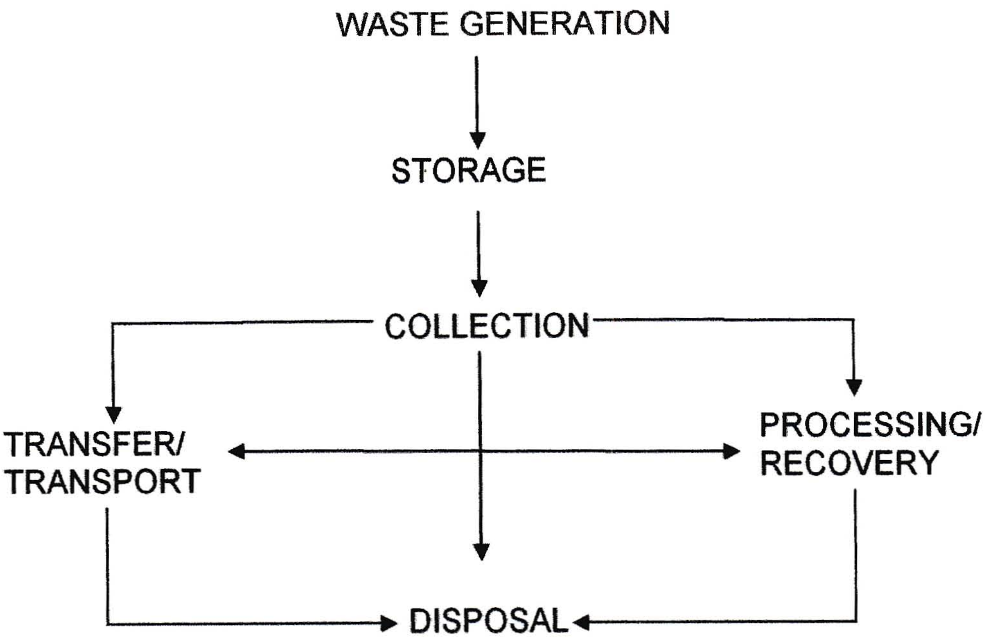


Figure 2.1 Functional elements in an integrated waste management system (Tchobanoglous et al, 1977)

- Storage – This functional element involves the activities associated with the handling, storage and processing of solid wastes at or near their point of generation.
- Collection – This is the gathering of solid wastes and subsequent hauling after collection to the point to where the collection vehicle is emptied.
- Transfer and Transport – This functional element involves two steps: the transfer of waste from the smaller collection vehicle to the larger transport equipment and the subsequent transport of wastes to the disposal site.
- Processing and recovery - This functional element includes all the techniques, equipment, and facilities used to improve both the efficiency of the other functional elements and to recover usable materials, conversion products and energy from solid wastes.

2.1.1 Waste Generation

It is important in any waste management system to classify the types of waste generated, as they directly affect the type of landfill-disposal facility. The two main distinctions made in classifying wastes are general and hazardous. Further classification is then required in order to assess the likely emissions that they will produce after they are landfilled. The types of solid wastes that are generated are summarised in Figure 2.2.

Wastes classified as hazardous are those that can, even in low concentrations, have an adverse effect on public health and/or the environment (DWAF, 1998). Hazardous wastes are generated throughout most industrial activities. The concern, in terms of generation of hazardous wastes, is related to the quantities and types of materials developed at each source. Table 2.1 shows an estimate of the size of the South African waste steam.

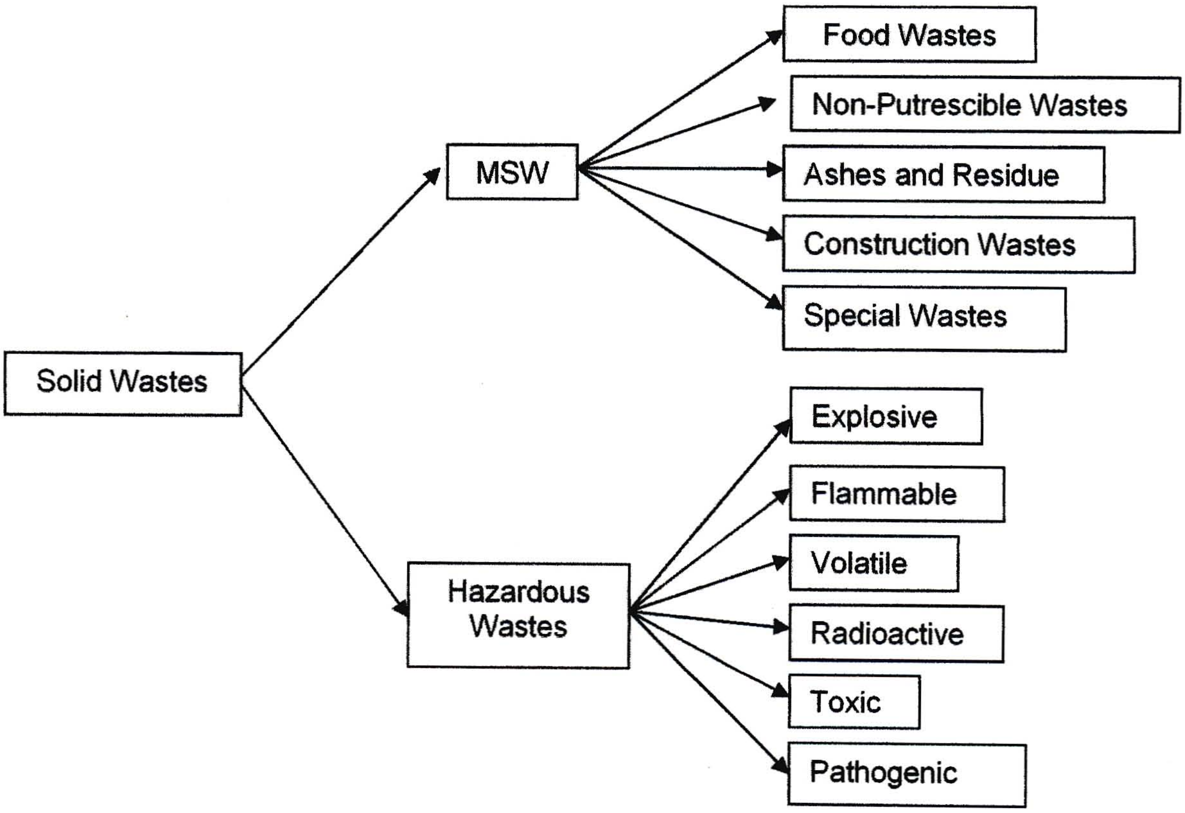


Figure 2.2 Types of wastes generated

Table 2.1 RSA Solid Waste Stream (Lombard, 1997)

Waste Type	**Mass (10^3 tonnes per year)**
Mining Tailings (1990)	238 500
Pulverised Fuel Ash (1990)	22 200
Agricultural Waste (1989)	20 000
Urban Waste (1990)	15 000
Chemical Waste (1990)	12 200
Sewage Sludge (1993)	12 000
Metallurgical Slag (1993)	5 400
Other Wastes (1993)	4 800
Total	329900

2.1.2 Properties of Solid Wastes

The information related to the properties of solid wastes is important in evaluating alternative equipment needs, systems and management programs and plans. The properties of waste, which include density, moisture content and chemical composition are discussed below:

- Density – The density of solid waste varies markedly with geographic location, season and length of time in storage and depends on the composition and degree of compaction of the waste. Qasim and Chiang (1994) suggest uncompacted MSW densities of approximately 150 kg/m^3, and the density of collected MSW of 235-350 kg/m^3.
- Moisture Content – The moisture content of waste is dependant on the composition of the waste and the prevailing climatic conditions and is usually expressed as a mass of moisture per unit mass of dry or wet material. Peavy et al (1985) and Qasim and Chiang (1994) report typical moisture contents in the range 10 - 25%.
- Chemical composition – There is a wide variation in the chemical composition of waste, dependant on the source of the waste, waste type, the processes that produced the waste etc. It is necessary to know the chemical composition in order to gain an understanding of the associated hazards of that waste. The chemical composition of the waste also has a direct impact on the emissions

that the waste body will produce. Information relating to the chemical composition of the organic portion of MSW is important to assess the biodegradability and for many waste management processes such as incineration and composting (Qasim and Chiang, 1994).

2.2 WASTE DISPOSAL BY LANDFILL

Landfills are the oldest and most widely utilised method of disposing of solid wastes. The term 'landfilling' refers to the deposition of waste on land, whether it is the filling in of excavations or the creation of a landfill above grade (DWAF, 1998). Other waste management options, such as incineration, recycling, composting, and so forth, still rely on a landfill for the disposal of wastes that are undesirable to the process, or for the disposal of process residues (Strachan, 2000). At present, ultimate waste disposal by landfill is the only viable option in developing countries, and for the foreseeable future will arguably present the Best Practical Environmental Option (BPEO).

Landfilling has the potential to cause severe adverse environmental impacts, both in the short and long term, if not managed in an environmentally acceptable manner. It is important to note the difference between 'dumps' or 'tip-sites' and engineered landfill sites. The former names describe the uncontrolled, sometimes illegal, unmanaged, or perhaps even mismanaged, disposal of solid wastes (Strachan, 2000). These sites are often malodorous, are unsightly and are of concern to general public health. By contrast, landfills are solid waste disposal sites that are engineered to a pre-determined design plan, managed efficiently and to high standards and cause little comparative nuisance to public health. The evolution of dumps to engineered landfill sites came about as public awareness levels increased and adverse environmental impacts were realised.

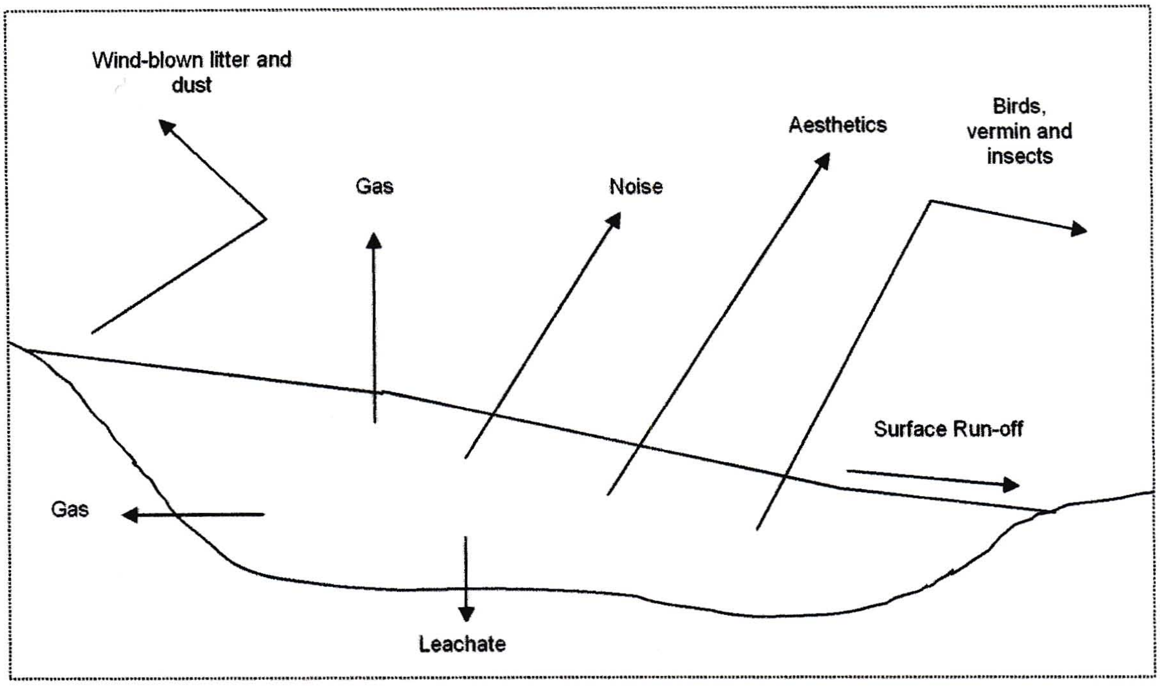


Figure 2.3 Schematic description of the major environmental aspects related to an active landfill (adapted from Christensen, 1989)

A landfill can be considered as a bio-reactor, with the input (waste) undergoing a complex combination of physical, chemical and biological processes, producing gaseous (landfill gas) and liquid compounds (leachate) as outputs. Leachate may be defined as "An aqueous solution with a high polluting potential, arising when water is permitted to percolate through decomposing waste. It contains the final and intermediate products of decomposition, various solutes and waste residues" (DWAF, 1998). Landfill gas is a product of decomposing waste and predominately consists of methane (highly explosive) and carbon dioxide (potential asphyxiation for both humans and vegetation), together with many other trace components. Figure 2.3 illustrates the major environmental aspects associated with an active landfill.

The daily operation of a landfill will generally cause 'short-term' impacts on the environment, which include noise, flies, unsightliness, dust, odour, air pollution and wind-blown litter. The decomposition processes that take place within the waste body may lead to 'long-term' environmental impacts such as pollution of the groundwater regime and the generation and migration of landfill gas.

2.3 BIOCHEMICAL PROCESSES IN LANDFILLS

All Municipal Solid Wastes undergo biological decomposition. A large proportion of all waste is putrescible and hence will be subject to natural biological degradation when discarded as waste.

The decomposition of solid wastes is a complex combination of physical, chemical and biological processes, all of which interact to give an overall decomposition pattern. Biological decomposition is the major mechanism by which refuse decomposes, and in practice actually controls the chemical and physical processes (Ham, 1998). Physical decomposition is regarded as the "physical rinsing" of material from the waste. Chemical decomposition is the dissolution of materials from the waste by leachate.

Landfilled waste will undergo microbial degradation as soon as it is disposed of, and within a short period of time the bacterial processes will become anaerobic (without the presence of air). These microbes degrade the organic carbon in the waste, eventually converting the solid organic carbon to methane and carbon dioxide. This mixture of gases is commonly referred to as landfill gas. The methane-generating ecosystem consists of a complex consortium of interacting bacteria in an anaerobic environment. Figure 2.4 illustrates the most important interactions between the bacterial groups, the substrates and intermediate products involved. The anaerobic degradation can seen to proceed in three stages (Christensen and Kjeldsen, 1989).

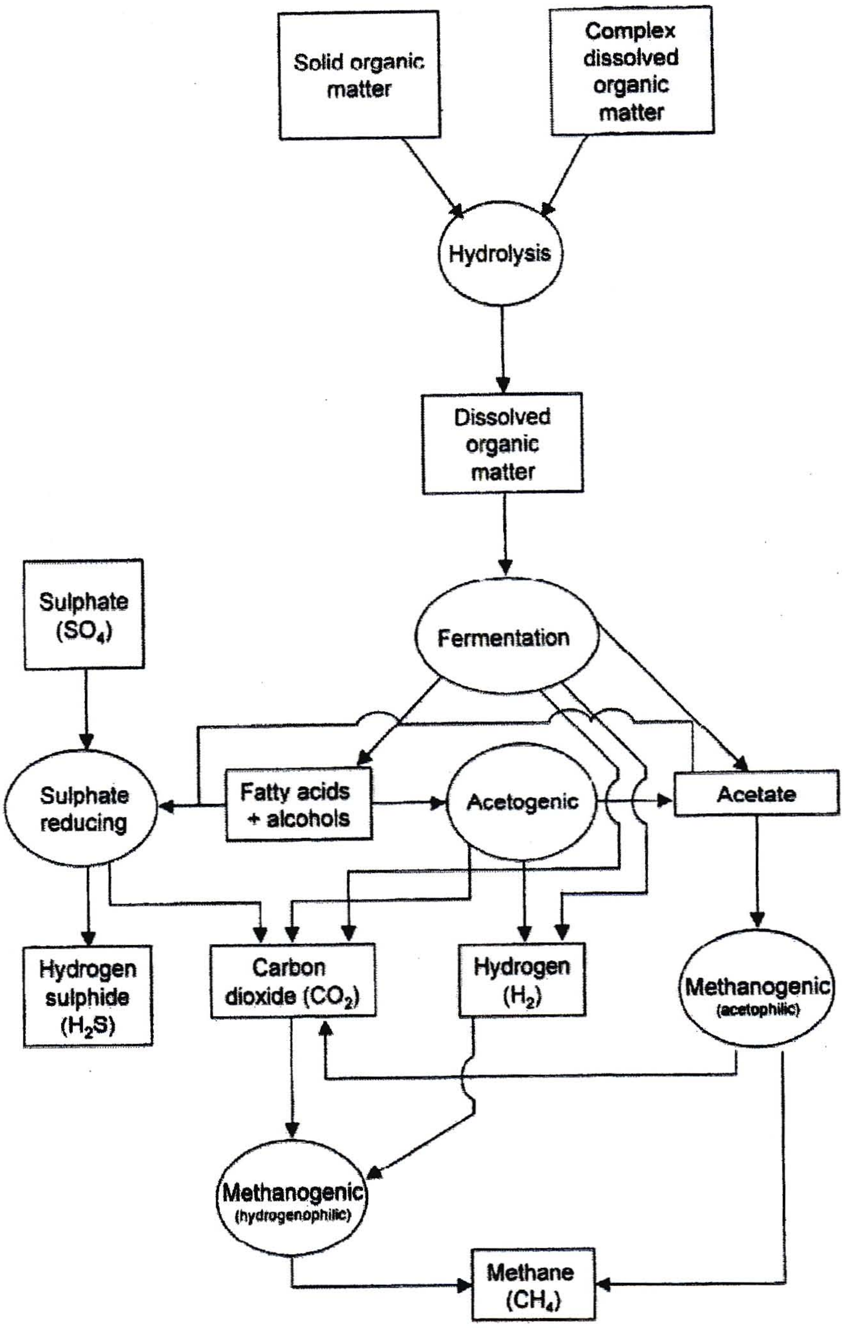


Figure 2.4 Methane generation from organic matter (Christensen and Kjeldsen, 1989)

The first stage is hydrolysis, where fermenting bacteria convert the solid and complex dissolved organic compounds into primarily volatile fatty acids, alcohol's and hydrogen and carbon dioxide. The second stage (acetogenesis) involves a group of acetogenic bacteria that convert the products from hydrolysis to acetic acid, hydrogen and carbon dioxide. In the final stage (methanogenesis) methanogenic bacteria produce methane, either through acetophilic bacteria converting acetic acid to methane and carbon dioxide, or through hydrogenophilic bacteria converting hydrogen and carbon dioxide to methane. The overall process of converting organic compounds to methane and carbon dioxide is stoichiometrically expressed in Equation 2.1.

$$C_nH_aO_b + \left(n - \frac{a}{b} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{4} + \frac{b}{4}\right)CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 \qquad \textbf{EQ 2.1}$$

The hydrolysis (caused by extracellular enzymes produced by the fermenting bacteria) is an important process in the landfill environment, as the solid organic waste must be made soluble before the microbes can convert it. After the smaller, easily soluble part of the organic matter has been converted, the hydrolysis may prove to be the overall rate-limiting process in the landfill environment (Leushner, 1983; McInerney and Bryant, 1983).

The fermenters are a large, heterogeneous group of anaerobic and facultatively anaerobic bacteria (Christensen and Kjeldsen, 1989). The acetogenic bacteria are also a large heterogenic group. The methanogenic bacteria are obligate anaerobic and require low redox potentials. The conversion of acetic acid to methane is by far the most important part of the methane forming process, accounting for approximately 70% of all methane generated (Christensen and Kjeldsen, 1989).

2.4 LEGISLATION AND LANDFILL CLASSIFICATION

A landfill typically produces gaseous and liquid emissions for time-scales spanning decades, and hence poses a serious threat to the environment if the landfill is not managed in an environmentally sound manner. In South Africa, a series of waste management documents have been published by the national Government's Department of Water Affairs and Forestry (DWAF, 1994; revised 1998), with the aim of protecting the environment and the public from the impacts of poor waste disposal practices (Strachan, 2000). The *Minimum Requirements for Waste Disposal by Landfill* forms part of this series and provides criteria for the selection, design, permitting, preparation, operation, closure and monitoring of landfills (Ball et al, 1995). The stated objectives of the Minimum Requirements are:

- To improve the standard of waste disposal in South Africa

- To provide guidelines for environmentally acceptable waste disposal for a spectrum of landfill sizes and types
- To provide a framework for minimum waste disposal standards within which to work and upon which to build.

The first step in providing for environmentally acceptable landfilling was to implement a control system, involving permits for landfill sites. Although there are as many as thirty-six acts which relate to waste disposal, there is little legislation in South Africa that relates directly to the environmentally acceptable development, operation and closure of landfills. However, the Environment Conservation Act (Act NO. 73 of 1989) makes provision for the permitting of landfills. The Act states that any person who operates or who intends to operate a waste disposal site must apply to the Department for a permit.

DWAF (1998) requires that to be eligible for a permit, a landfill must meet and maintain certain standards, with the Minimum Requirements providing these standards. The Minimum requirements are implemented through and enforced by the Landfill Site Permit. The document sets guidelines on what is considered best practice, but does allow flexibility as it acknowledged that no two landfill sites are the same. For example, obtaining a permit is a Minimum Requirement for all operating waste disposal sites, however the detail required for the Permit Application will vary for different classes of landfill. With increasing size, more detail is required and hence more investigation. The Permit Application is thus based on Site Specific Risk Assessment (SSRA), where due consideration is given to the needs of the community served by the waste disposal site, the size of the waste disposal operation and the potential impact on the environment.

The siting of a new landfill is an integrated process, which involves a detailed environmental impact assessment, geohydrological survey and public participation. Generally, several candidate sites are chosen based on preliminary assessments and then gradually eliminated until a site that meets all the relevant Minimum Requirements is selected.

2.4.1 Landfill Classification

A system for classifying landfills is necessary in terms of providing both affordable waste disposal and protecting the environment. The Minimum Requirements provide an adaptable classification system that caters for the range of landfills that exist, with graded requirements dependent on site-specific conditions. The system recognises the inherent qualities and differences that characterise any landfill operation, i.e. the types of wastes involved, the size of the waste stream and the potential for significant leachate generation (DWAF, 1998).

Previous landfill classification systems took into account only waste type (i.e. general or hazardous waste), making no provision for the size of the waste disposal operation or the potential for leachate generation. The current legislation (Minimum Requirements) requires the landfill developer to look at the potential for leachate generation, in terms of 'significant leachate generation' and 'sporadic leachate generation'. Where significant leachate generation is expected, the developer is required to install a leachate management system. This method is preferred due to leachate being the main cause of water pollution from landfills. The objectives of this landfill classification system are (DWAF, 1998):

- To consider waste disposal situations and needs on terms of combinations of waste type, size of waste stream and potential for significant leachate generation.
- To develop landfill classes that reflect the spectrum of waste disposal needs.
- To use the landfill classes as the basis for setting graded Minimum Requirements for the cost-effective selection, investigation, design operation and closure of landfills.

The landfills in this classification system are thus grouped according to:

- The type of waste involved
- The size of the waste stream
- The potential for significant leachate generation.

Table 2.2 shows the landfill classification system in the Minimum Requirements.

Table 2.2 Landfill Classification System (Adapted from DWAF, 1998)

WASTE CLASS	**G General Waste**								**H Hazardous Waste**	
SIZE OF LANDFILL OPERATION	**C Communal Landfill**		**S Small Landfill**		**M Medium Landfill**		**L Large Landfill**		**H:h Hazard Rating 3 & 4**	**H:H Hazard Rating 1 & 2**
SITE WATER BALANCE	**B^-**	**B^+**	**B^-**	**B^+**	**B^-**	**B^+**	**B^-**	**B^+**	**B^-**	**B^+**
MINIMUM REQUIREMENTS										

Notes:

B^- = No significant leachate will be generated in terms of the Site Water Balance (Climatic Water Balance plus Site Specific Factors), so that leachate management system is not required

B^+ = Significant leachate will be generated in terms of the Site Water Balance (Climatic Water Balance plus Site Specific Factors), so that a leachate management system is required

H = A containment landfill which accepts **H**azardous waste with Hazard Ratings 3 and 4

H = A containment landfill which accepts all **H**azardous waste, i.e. with Hazard Ratings 1, 2, 3 and 4

2.5 SANITARY LANDFILLING

Ever since waste was first produced, man has deposited organic wastes and other refuse in open dumps. The refuse, which was allowed to decompose in open air, created nuisances such as odours, air-born litter, the occurrence of disease vectors such as rates, mice and flies, as well as the generation of gaseous emissions and leachates by rainwater filtering through the tipped waste (Gendebien et al, 1992). These problems lead to the controlled dumping of organic waste and the concept of a Sanitary Landfill.

Sanitary landfilling implies three conditions of operation (Gendebien et al, 1992):

- A minimum daily cover of the no longer dumped but filled waste with an inert material.

- No burning of the filled waste.
- No pollution of the surface or ground waters below and around the landfill site

Landfill sites have the potential to produce large volumes of polluting leachate. Past landfill practices have relied on the absorptive capacity of the environment to reduce the contaminants in leachate to acceptable levels before reaching the groundwater. It was found that groundwater was being polluted by such sites however, mainly due to poor siting (lack of geohydrological knowledge) and poor landfilling practices. It has therefore followed, in recent times, that landfills have been designed and developed such that the waste body is effectively sealed-off from the natural environment by a constructed barrier system (Strachan, 2000). Figure 2.5 shows the four types of landfill that typically exist.

2.5.1 Containment Landfill

Containment landfill implies that the waste body is separated or sealed off from the surrounding environment. There are generally two types of containment landfills – total containment (encapsulation) and containment with leachate control.

Encapsulation of waste prevents any infiltration and percolation of water and consequently, any generation and emission of leachate beyond the moisture already present in the waste at the time of disposal – as long as the containment system remains intact (Knox, 2000). The landfill is contained at the base and on the side slopes by an 'impermeable' or low permeable liner system and on the surface by a low permeability soil (typically clay). The lack of infiltrating water may result in the encapsulated waste remaining virtually unchanged (presenting maximum risk to the environment) for a long period of time, as biological activity (which leads to waste stabilisation) is prevented. Failure of the containment system may lead to an uncontrolled plume of leachate migrating into the surrounding environment. Total containment does not bring the waste to final storage quality, and it implies acceptance of an indefinite responsibility for a potential environmental risk on behalf of future generations (Knox, 2000; Robinson, 1996).

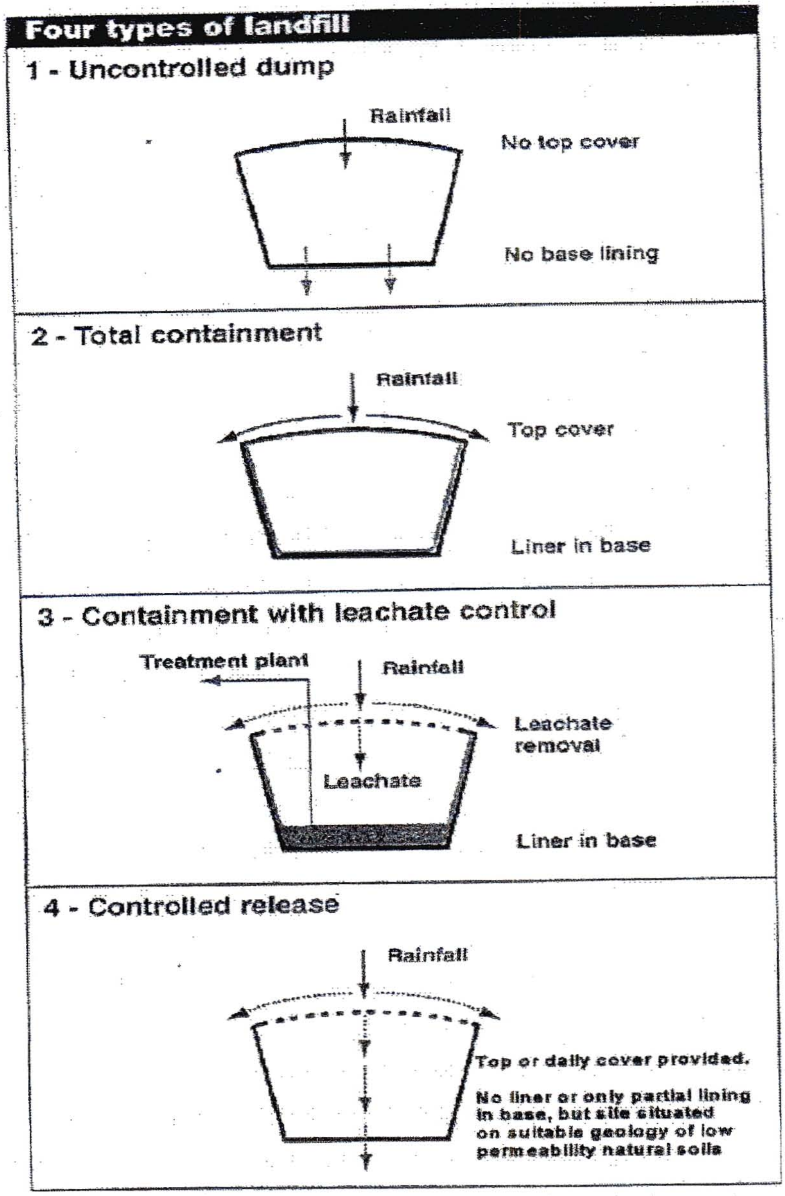


Figure 2.5 Schematic description of four general landfill types that may be found, illustrating the landfill design concepts (WHO, 1995).

The problems associated with a non-sustainable 'total containment' landfill has resulted in modern landfill design and operation being directed towards allowing the waste body to stabilise by allowing water to percolate through the waste body in a controlled manner. The concept of a 'sustainable' landfill is discussed further in section 2.5.4.

The containment landfill with leachate collection has become the most commonly occurring landfill scenario. Although many South African landfills remain unlined, new landfill developments in both South Africa and abroad are aimed at containing the waste body from the natural surroundings. The leachate generated by the infiltration of precipitation is contained by an impermeable liner system (as for total encapsulation), and collected in a drainage system. The leachate is then pumped out and may be subjected to treatment prior to discharge to a surface water body, either directly or via a sewage works (Knox, 2000). A low permeability top cover is sometimes used to reduce the volume of leachate produced (and therefore the volume that has to be treated), however the problems of a non-sustainable landfill remain in this instance.

2.5.2 Landfill Barrier Systems

The migration of landfill emissions (gaseous and leachate) from the waste into the surrounding environment is addressed by a landfill barrier system. The Minimum Requirements (DWAF, 1998) provide the guidelines for barrier systems for South African landfills. The actual component requirements of the barrier system are dependent on site-specific aspects, and relate to the size of the landfill, the type of wastes that are deposited and the potential for leachate generation.

Landfill liners may be composed of synthetic and/or natural materials. The natural liners include mineral or clay layers, and bentonite enriched silty or composite soils. Flexible membrane liners (FML), commonly referred to as geomembrane liners, are the most widely used synthetic liners, with high-density polyethylene (HDPE) and flexible polypropylene (FPP) currently being two of the most popular materials utilised in South Africa (Strachan, 2000). Considerable research has been performed on the quality and durability of such synthetic geomembrane liners (Giroud et al, 1994).

A landfill lining system, as opposed to a single liner (a low permeability barrier used to impede the flow of liquids), consists of a combination of drainage media and liner(s). Even though lining systems are more difficult to fund, place and construct than a single liner, they are necessary because large scale liners commonly leak. Landfill leakage can only be prevented through the use of lining systems. Fluet et al (1995) showed that migration rates through a lining system can be two or more orders of magnitude lower than through a single lining layer. Lining systems are usually designed to incorporate three facets - a lining, a leachate collection system and a leachate detection system. In many instances, both synthetic and natural materials are used in tandem, in what are known as composite lining systems. Figure 2.6 shows a typical lining system.

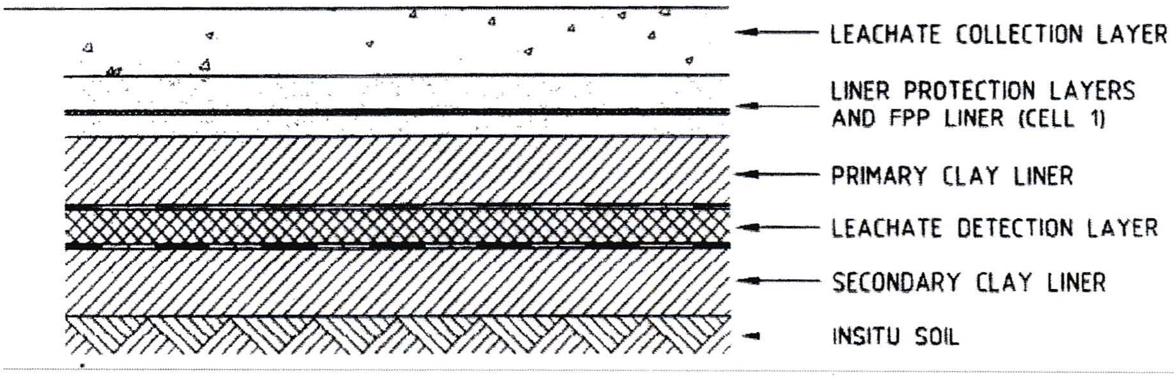


Figure 2.6 Cross-section of a typical composite lining system for a South African MSW landfill.

2.5.3 Attenuation Landfill

A major objective of landfill design is to return the products of stabilisation of landfilled wastes to the environment in a controlled manner, at a rated which the environment can accept without harm (Robinson, 1996). Attenuation landfill implies that leachate is allowed to flow into the surrounding environment as it is formed. Natural mechanisms at the liquid-solid interface, such as adsorption, biological uptake, cation and anion exchange, dilution, filtration and precipitation all have the ability to reduce the pollutant load of leachate. One of the methods to attenuate leachate is to allow it to percolate through the landfill base and unsaturated soil zone beneath the landfill to reach the groundwater aquifer harmlessly (Gendebien et al, 1992). Robinson et al (1996) showed, through extensive, prolonged monitoring in the unsaturated zone beneath the Stangate landfill in the UK, that degradation in the unsaturated zone is a significant mechanism in reducing concentrations of organic contaminants.

The complete containment of landfill emissions for all time is not attainable, and it is accepted that landfill lining systems will invariably leak. When this occurs, the attenuation of contaminants from sites by the natural surroundings should be relied on. Pretreatment of the waste may reduce both the contamination potential and the permeability. Installation of geologically stable, sloped top covers with surface drainage systems and surface vegetation with high evapotranspiration could ensure a very low rate of infiltration of precipitation and, consequently, a very low rate of release of contaminants to the environment (Knox, 2000). Since contaminants are being removed from the waste, even if at low rates, a continuous reduction of the potential of the landfilled waste to pollute will occur. The controlled contaminant release represents a sustainable short and long-term solution to many waste types.

2.5.4 Sustainable Landfilling

It is widely accepted among landfill scientists that the time-scales involved in the complete degradation of domestic wastes in a typical, high-density modern landfill site are likely to be centuries rather than decades (Robinson, 1996; Hjelmar et al, 1995). The Landfill Permit system in operation in South Africa has meant that landfill operators are now responsible for a landfill both during its operation and after its closure. Current "best landfill practice" (as stipulated in the Minimum Requirements) advises that water be excluded from the waste body, which is in contrast with the need to achieve a stabilised waste mass within a sensible timescale. Legislation is aimed at minimising the volume of leachate that is produced and hence treatment costs or impacts on the environment.

The need for a sustainable solution to landfilling is necessary, as future generations should not have to deal with poor practices of the past. If a landfill is to be left to the future generation in a relatively inert state, it means that the waste body must be stabilised in one generation (which is usually given as 30 – 50 years). Stabilised waste is defined as a point where a landfill has stabilised physically, chemically and biologically to such a degree that its contents are unlikely to pollute the environment and harm human health, so that gas and leachate management systems have ceased to be necessary (Robinson, 1996).

Setting theoretical time-scales for the completion of a landfill seems relatively simple, however in practice very little is known on the time-scales involved in waste degradation. Robinson (1996) showed that the hydraulic retention time for a percolating leachate may be as high as one hundred years. This makes no allowances for the long time-scales involved in biological degradation of solid wastes such as wood or paper, which continue to release contaminants. Further to this, the heterogeneity of the waste body, both in terms of waste type and distribution of moisture within the fill means that parts of the fill remain relatively dry and unreactive while others remain wet (as water flows along preferential pathways). This leads to zones where waste is highly degraded and others that are poorly degraded. Because of this, the criteria of 'completion in a generation' cannot be achieved with landfills of today and significantly higher rates of flushing will be necessary for this objective to be met.

Out of these considerations has arisen the concept of a "Flushing Bioreactor Landfill", capable of meeting the criteria imposed by sustainable development, in all circumstances (Robinson, 1996). All landfills are bioreactors, but very inefficient ones. There is scope for increasing the rates of biological decomposition, however the problems of accelerating the decomposition rates within a practical landfill and achieving much higher rates of flushing remain. The development of flushing bioreactor sites requires engineering designs that differ vastly to those adopted presently. The aim of the new design would be to distribute moisture more evenly through the waste body, and raising the moisture content above field capacity, as this is commonly accepted to increase the rate of reaction. The other aim is to flush out the products of these reactions. The increased volumes of leachate would be treated and re-introduced back into the environment at acceptable rates.

There are problems facing the flushing of contaminants from the waste body however, including:

- Introduction of liquids into the wastes at high rates (irrigation)
- Downward percolation of liquids through wastes
- Collection of leachates at the base of the landfill

It is likely that achieving the downward percolation of liquids through the waste would prove to be most difficult, as wastes typically have hydraulic conductivities in the order of 10^{-6} – 10^{-7} m/s at depths of 30 – 60 metres (depths typically encountered in modern landfills). Other problems related to increased rates of flushing is that greater volumes of leachate will have to be collected and treated earlier on in the life-time of a site – necessitating higher initial capital expenditure, although this may be offset in the long term by a shorter life-span of the site.

At present it is not possible to design and operate a flushing bioreactor landfill that will guarantee complete stabilisation of wastes in a generation, however landfill operators can significantly reduce the overall time-scales involved (Robinson, 1996). This is particularly applicable to 'dry entombment' landfills where the ingress of water is prevented, inhibiting the biological activity.

2.5.5 Landfill Management and the *Cellular Method*

Landfill practices in South Africa have undergone an enforced evolution in recent years, as South Africa has moved towards the World's developing standards. The introduction of the Government's Minimum Requirements in 1994 (revised in 1998) has lead to landfills designed, constructed and operated to government guided levels.

Of particular concern are relatively old landfills situated in water surplus areas (B^+ landfills) where significant leachate is generated. These sites were not lined and leachate was allowed to flow into the surrounding environment. The Minimum Requirements require a lining system for such sites, whilst not meeting these requirements could lead to closure of the site. Economic considerations and the time-scales involved in developing new sites has meant that many of these sites have to remain active, with appropriate engineering measures applied to prevent further groundwater pollution.

The Bisasar Road Landfill Site in Kwa-Zulu Natal is an example of an unlined site producing high volumes of leachate. Engineering measures to collect leachate include combined eductor and pumping systems placed in vertical gas collection wells driven to the full depth of the waste body, and deep-seated cut-off drains situated immediately down slope of the site. One contentious issue that has arisen in trying to deal with the problem of existing unlined landfills is the concept of a 'piggy-back' vertical extension landfill (Strachan et al, 1999). This possible solution involves lining the existing waste body, and continuing landfilling operations on top of the now sealed waste body. This technique however, is unproven and may be unnecessarily expensive. Consolidation settlement effects, coupled with settlement owing to the natural biodegradation processes are questions of concern with regard to the integrity of the liner. The active extraction of landfill gas and leachate would also require that wells be driven the near full depth of the entire waste body, which would require that the separation barrier between the old and new wastes be perforated (Strachan et al, 1999).

In the case of the Bisasar Road Landfill Site, Durban Solid Waste (the Durban City Council waste disposal unit) decided to develop the existing waste body to final level as an attenuation landfill, with the engineering measures discussed previously to collect leachate. The existing waste body would then be flanked by newly engineered containment landfills, with barrier systems against virgin soils and the existing waste body. This relatively new method of landfilling, where small containment landfills/small cells with independent leachate collection systems are created within the larger landfill footprint area may be termed *Cellular Landfilling.* Plate 2.1 illustrates the development of a small landfill cell.

Plate 2.1 The progression of a landfill cell illustrating the method of *Cellular Landfilling* – a) Preparation of cell; b) Lining of cell; c) Filling of cell; d) Closure of cell.

Newly developed landfills are also using the cellular method of landfilling, as the costs and practical aspects of lining large areas are unrealistic. There are a number of possible benefits that may be gained from cellular landfilling:

- Capital costs are evenly spread over the life span of the landfill as a result of lining relatively smaller cells.
- Accurate monitoring of leachate and landfill gas quality and therefore of waste degradation processes is possible.
- In warm, sub-tropical and tropical climates, gas will be produced relatively soon after the first waste in the cell is placed, and thus will be suitable for gas extraction almost immediately after the cell is closed.
- Smaller cells allow for better control of landfill operations. Waste may be placed more evenly and homogeneously, allowing for better distribution of moisture in the landfill, thereby enhancing degradation rates.
- Future landfill developments are more easily planned.

The possible disadvantages of this landfilling method could be:

- Capital has to be regularly available for lining projects
- Design of a leachate treatment works may be difficult because the leachate characteristics will be constantly changing as the development of new cells contributes younger, stronger leachates.

CHAPTER 3

LEACHATE PRODUCTION AND CHARACTERISATION

3.1 INTRODUCTION

The biochemical processes that lead to the degradation of waste in a landfill play a crucial role in determining the potential adverse impacts a landfill will have during and beyond its active life (Robinson, 1989). The leachate produced by the waste body undergoes changes in its composition as the sequence of waste degradation proceeds. Of particular importance is the change from the early acetogenic stages, where high organic strength leachates are generated, to later methanogenic stages, where these organic compounds are actively reduced to landfill gases and are therefore not found to the same extent in the leachate (Robinson, 1989; Robinson, 1993).

Leachates are characterised in terms of their physical, chemical and biological composition. The characterisation of leachates is vital for not only observing the progression of the waste degradation and stabilisation of the waste mass, but also for providing information on possible treatment requirements.

3.2 LEACHATE PRODUCTION

As stated previously, leachate is formed by the percolation of water through the waste body. Water balance calculations are used to predict the volume of leachate produced by a site. This calculation compares the quantities of all liquids entering and leaving the site during a specified period, with any imbalance leading to a change in the quantity of water held within the site. The water balance does not provide information on leachate levels or volumes because water in landfills can be held either as free leachate or as water absorbed in solid waste materials (Knox, 1991). The amount that these two mechanisms can hold depends on the storage characteristics of the waste.

No prediction on the amount or levels of leachate can be made without knowledge of the storage characteristics. These characteristics however are one of the most uncertain in water management in landfills, due to the heterogeneity of wastes and the changes the waste undergoes as it ages, decomposes and settles. In practice, most water balance calculations incorporate assumed values for the absorption of water by solid wastes, so that volumes of free leachate can be estimated (Knox, 1991). Despite the inherent uncertainties, landfill cells are increasingly being sized and leachate volumes predicted by the outputs of water balance calculations. Canziani and Cossu (1989) report successful prediction of leachate volumes, although it is acknowledged that good approximations depend above all on climatic parameters and waste characteristics, which should be measured on site.

3.2.1 The Water Balance

The climatic water balance was described briefly in section 2.4.1, however landfill operators in South Africa are further required to perform a site water balance by the Minimum Requirements. This takes into account site specific factors and is a more accurate indicator as to whether significant quantities of leachate will be produced. The basic water balance for a landfill can be stated as in Equation 3.1 (Blight et al, 1992)

$$\text{Water Input} = \text{Water Output} + \text{Water Retained} \qquad \textbf{EQ 3.1}$$

Each term in equation 3.1 represents a rate of accumulation or loss. Water input includes precipitation (P) and the water content of the incoming waste (U_w) (which makes a one-off contribution to the annual water balance of a given mass of landfill). Water output includes Evapotranspiration (ET), water vapour entrained in gas (G), water lost in leachate (L), and run-off (R). The water retained includes the water absorbed and retained by the waste (ΔU_w) and the soil cover (ΔU_s). The annual water balance can therefore be given by Equation 3.2:

$$P + U_w = ET + G + L + R + \Delta U_w + \Delta U_s \qquad \textbf{EQ 3.2}$$

In most water balances G is ignored because it makes a small contribution compared to the other terms. The annual water balance as applied to an established landfill can be simplified, and rearranged to yield the volume of leachate produced, as shown in Equation 3.3 (Blight et al, 1992):

$$L = P - ET - R - \Delta U_w - \Delta U_s \qquad \textbf{EQ 3.3}$$

When Equation 3.3 is applied to an actual landfill, difficulty often arises in determining accurate values for the individual terms. The absorptive capacity of the waste body (ΔU_w) is generally the most difficult to determine, and is usually estimated by a model of the process by which water is taken up by wastes.

Figure 3.1 illustrates a relatively complex absorption model, where the uptake of water is split into two stages. The primary absorption phase (a_1) is when the waste readily takes up water (infiltration). The secondary absorption phase (a_2) is when the liquid that remains in the waste, takes the waste to field capacity. Simplified models, where the waste is given an 'average' absorption capacity have also been used in practice (Knox, 1991). Various authors (Newton, 1976; Robinson et al, 1981; Campbell, 1982; Blakey, 1982; Holmes, 1980; Pohland, 1975) have performed laboratory-scale experimental studies to obtain absorptive capacities for domestic refuse. There is very little data from industrial wastes or full-scale landfills however (Knox, 1991).

Rainfall data may be obtained from on-site rain gauges or nearby weather stations. The evaporation from a soil surface can be estimated from A or S-pan evaporation (Blight et al, 1992). Chow et al (1998) also provides various methods to calculate evapotranspiration, infiltration and run-off.

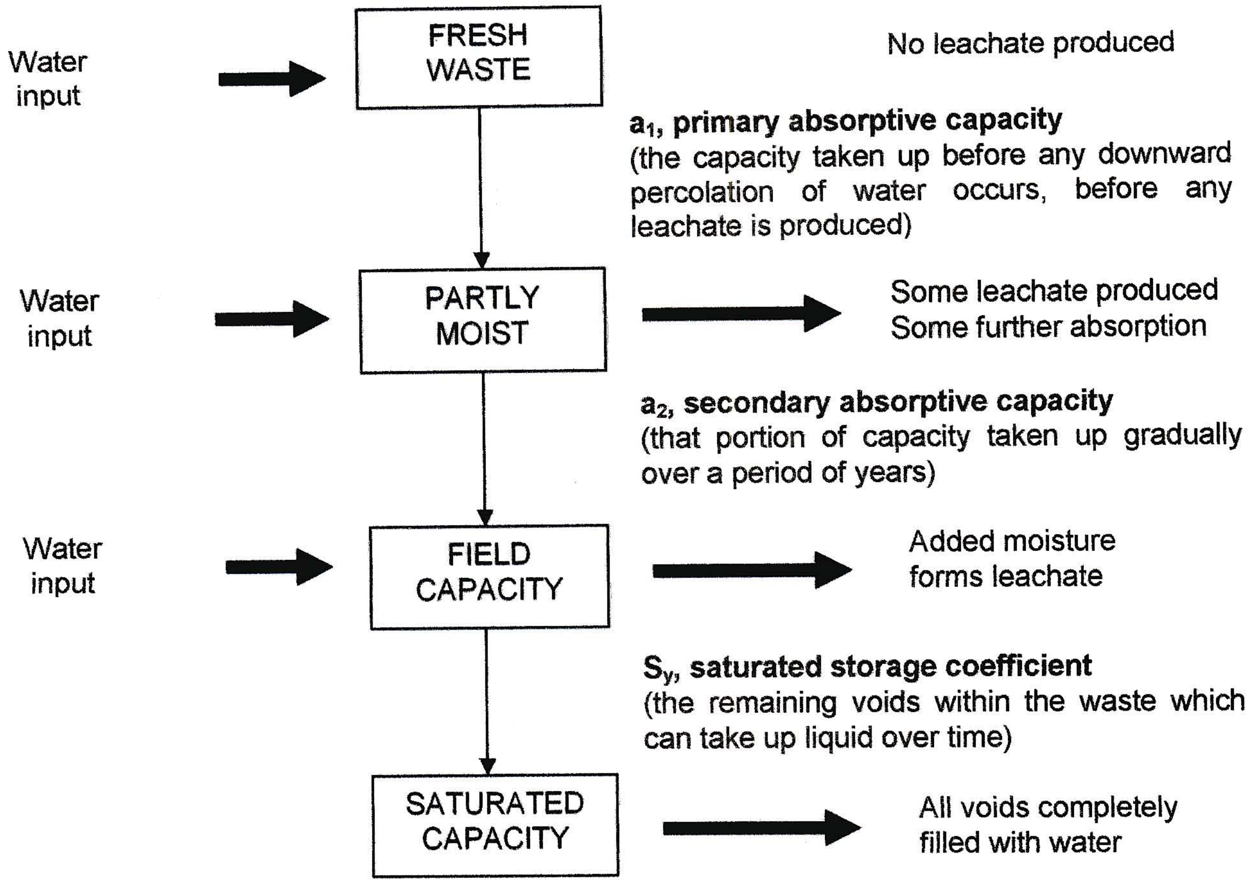


Figure 3.1 Theoretical model of the process by which water is taken up by waste (Couth, 2000)

3.3 LEACHATE COMPOSITION AND ASSOCIATED PROBLEMS

The composition of leachate is highly variable and often contains considerably larger pollutant loads than raw sewerage or many industrial wastewaters (Qasim and Chiang, 1994). It is known that leachates are highly site specific; however leachates have typical characteristics related to the age of the waste body. The development in leachate composition as the waste body ages and degrades is discussed in section 3.3. It is important to note that each stage in the decomposition cycle occurs simultaneously due to continued landfilling operations, and that the leachate composition cannot be attributed to a single decomposition phase alone. The typical constituents found in leachate are presented in Figure 3.1.

The leachate composition at any time will depend on a number of factors, as shown below (Strachan, 2000):

- Moisture content of the waste
- Temperature
- Waste density
- Age of the waste
- Composition of the wastes
- Waste particle size (shredded, pulverised or crude)
- Substrate and nutrient availability for micro-organisms
- pH values
- Microbial populations existent in the waste.
- Use of cover materials.

The composition of leachate has a potentially detrimental effect on the environment due to the nature of the contaminants present. Table 3.1 lists the most common contaminants found in leachate and their potential risk.

Leachate characteristics are typically split into three categories, namely physical, chemical and biological. The physical parameters define those characteristics that respond to the senses of sight, touch, taste, or smell (Peavy et al, 1985). The chemical characteristics are related to the solvent capabilities of the water infiltrating the waste body. The biological characteristics relate to the large number of biological species that may be present in landfill leachate.

3.3.1 Physical Characteristics

The most significant physical characteristic of a leachate is its total solids content, which is composed of floating, settleable, colloidal, soluble matter (Metcalf and Eddy, 1991). The other physical characteristics include odour, temperature, density, colour and turbidity.

Table 3.1 Major contaminants present in leachates (adapted from Corbitt, 1989; Metcalf and Eddy, 1991)

CONTAMINANT	POTENTIAL ENVIRONMENTAL RISK
Suspended Solids	Suspended solids are important for aesthetic reasons and they can lead to the development of sludge deposits and anaerobic conditions in water courses
Biodegradable Organics	Composed partially of proteins, carbohydrates and fats, biodegradable organics are measured most commonly in terms of BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand). If discharged untreated to the environment, the biological stabilisation of these materials can lead to the depletion of natural oxygen resources and to the development of septic conditions.
Nutrients	Carbon, nitrogen and phosphorus are essential nutrients for growth. When discharged to the environment, these can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can pollute groundwater.
Heavy metals	Due to their toxic nature, certain heavy metals can negatively impact upon biological wastewater treatment processes and stream life.
Dissolved Inorganic Solids	Inorganic constituents such as calcium, sodium and sulphate are found in leachates and have to be removed if disposed to watercourses.
Pathogens	Communicable diseases can be transmitted by pathogenic organisms in leachate.
Priority Pollutants	Organic and inorganic compounds selected on the basis of their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity. Many of these compounds are found in leachate
Refractory Organics	These organics tend to resist conventional methods of biological leachate treatment. Typical examples include surfactants, phenols, and agricultural pesticides.

Figure 3.2 shows the relationships of solids found in water, wastewater and leachate. The total solids in a leachate sample is defined as the matter that remains as residue upon evaporation at 103 – 105^{0}C. Settleable solids are those solids that will settle to the bottom of a cone-shaped container (called and Imhoff cone) in one hour. The total solids may be further classified into non-filterable (suspended) or filterable solids, by passing a known volume of leachate through a filter.

The filterable solids fraction consists of either colloidal or dissolved solids. The colloidal fraction consists of particulate matter, while the dissolved fraction consists of both organic and inorganic molecules and ions that are present in true solution in water (Metcalf and Eddy, 1991).

Each of the categories of solids may be further classified on the basis of their volatility at 550 +/- 50^{0}C. The organic fraction will oxidise and will be driven off as gas at this temperature, and the inorganic fraction remains as ash. The terms 'volatile suspended solids' and 'fixed suspended solids' therefore refer to the organic and inorganic (or mineral) content of the suspended solids (Metcalf and Eddy, 1991).

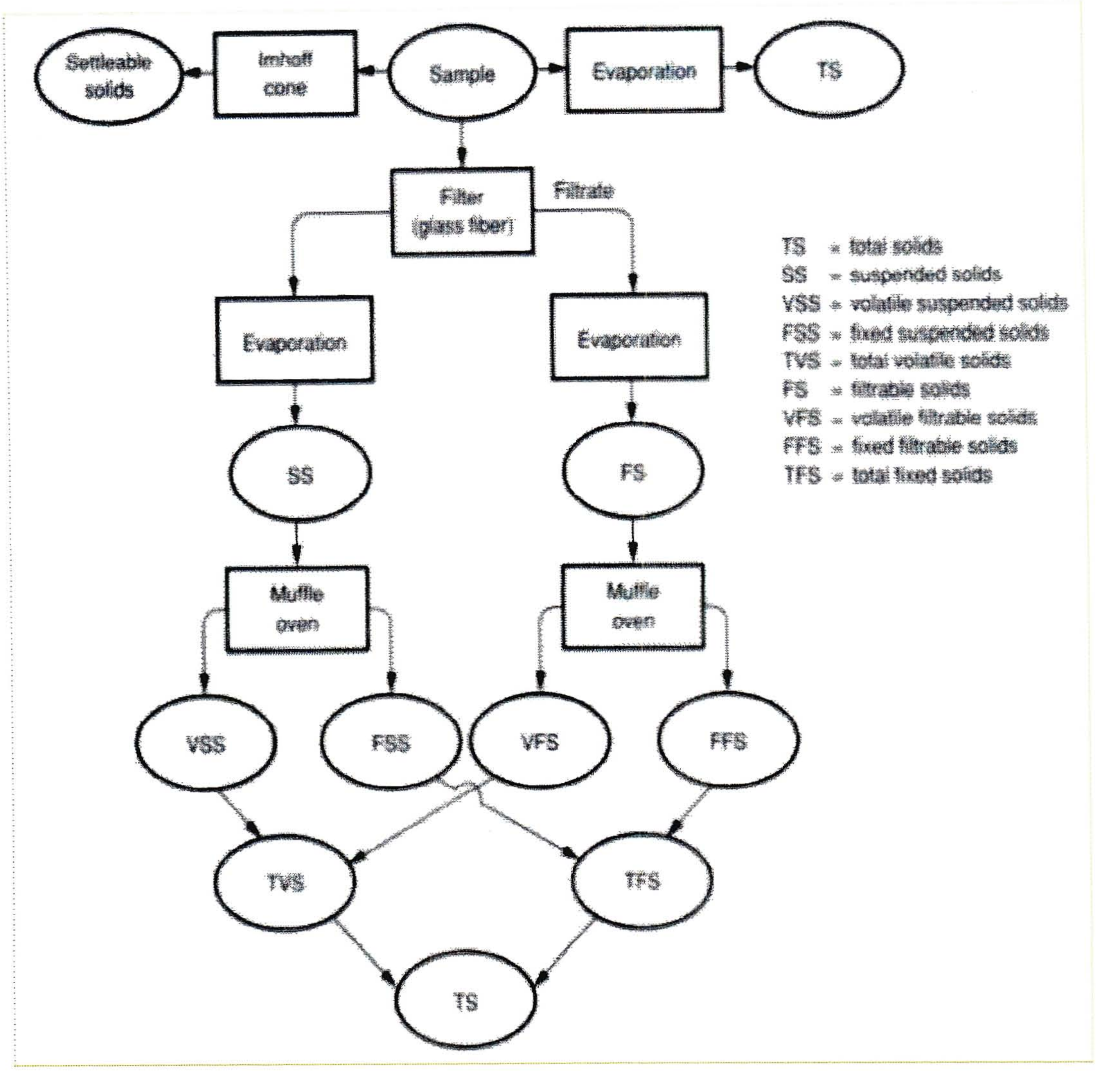


Figure 3.2 Interrelationships of solids found in leachate (From Metcalf and Eddy, 1991)

Leachates tend to have relatively high solids concentrations (compared with industrial or domestic wastewater), and hence their release into open water courses may result in objectionable conditions. Suspended materials may be aesthetically displeasing and provide adsorption sites for chemical and biological agents. Suspended organic solids may be degraded biologically, yielding undesirable products, whilst biologically active suspended solids may include disease-causing organisms as well as organisms such as toxin-producing strains of algae (Peavy et al, 1985). Dissolved solids may produce aesthetically displeasing colour, tastes and odours. Some chemicals may be toxic, and some of the dissolved organic constituents have been shown to be carcinogenic (Peavy et al, 1985).

The remaining physical characteristics (odour, colour, temperature, density and turbidity) are seldom determined when characterising leachates. They are typically qualitative parameters used in characterising potable water, and hence are generally determined once a wastewater has been treated and is to be released into a natural water course.

3.3.2 Chemical Characteristics

Leachates typically contain relatively high concentrations of organic and inorganic compounds, which are potentially harmful if discharged to the environment.

- *Organic matter* - The degradation of landfilled waste leads to the solubilisation of organic compounds. The principal, readily biodegradable organic substrates in leachate are volatile fatty acids (propionic, butyric, lactic and formic acid) (DoE, 1995). The organic matter in a leachate sample is measured as the amount of oxygen that is required for the complete oxidation of organic matter and is most commonly determined by two methods, namely: the Chemical Oxygen Demand (COD) and the Biochemical Oxygen Demand (BOD).

  The COD is the oxygen equivalent of the organic matter that can be oxidised, and is measured using a strong chemical oxidising agent (potassium dichromate) in an acidic medium (Metcalf and Eddy, 1991). The test is performed at an elevated temperature and requires a catalyst (silver sulphate) to aid in the oxidation of certain organic compounds (Metcalf and Eddy, 1991).

  The BOD is defined as "the oxygen consumed by a waste through bacterial action" (Corbitt, 1989). The five-day BOD test is the most widely used parameter of organic pollution. The BOD test is a batch reactor procedure in which microbes are typically allowed to degrade organic matter in the sample for a five day period (BOD_5) at 20^0C. By noting the volume of sample placed in the reactor and determining the amount of oxygen used in the bottle over a five day period, the BOD of the sample may be calculated (Corbitt, 1989). It is used because the results of the test are used to determine the approximate quantity of oxygen that will be required for the stabilisation of the organic matter present (Metcalf and Eddy, 1991).

Although the COD and BOD tests are both used to measure the amount of organic matter present in a leachate sample, the COD tends to be higher than the BOD because more compounds can be chemically oxidised than can be biologically oxidised.

- *Inorganic matter* – The inorganic constituents of concern in leachates, including pH, chlorides, alkalinity, nitrogen, phosphorus, sulphur and heavy metals, are discussed in the paragraphs below.

The pH range (concentration range of hydrogen ions) (pH 5 – 9.5) suitable for the existence of biological life is quite narrow and critical (Metcalf and Eddy, 1991). The range of pH values of a leachate can vary considerably over its lifetime. Adverse concentrations of the hydrogen ion often make biological treatment difficult, and if the concentration is not altered before discharge, the leachate effluent may alter the concentration in natural waters.

Leachate typically has a high chloride concentration, which will persist in the landfill, because the biological decomposition of chlorides in a landfill is limited. Fish and aquatic communities cannot survive in high levels of chlorides and hence chlorides present in high concentrations can contaminate freshwater streams and lakes. Chloride can corrode metal and affect the taste of food products.

Alkalinity in leachate results from the presence of hydroxides, carbonates, and bicarbonates of elements such as calcium, magnesium, sodium, potassium or ammonia (Metcalf and Eddy, 1991). The alkalinity in leachate acts as a buffer and helps to resist the changes in pH caused by the addition of acid (from the acidogenic bacteria), which is particularly important for sustaining the sensitive methane producing bacterial population.

Nitrogen in leachate can exist as organic nitrogen, ammonia, nitrite and nitrate. The ammonia concentration in leachates is of greatest concern because it is produced in the landfill in relatively high concentrations and biological processes in the landfill do not remove the ammonia to any great extent (Blakey et al, 1995). Depending on the pH of the solution, ammonia may exist as a gas or as the ammonium ion in solution.

Nitrite nitrogen is relatively unstable and is easily oxidised to nitrate. Although generally existing in low concentrations, nitrite can be an important characteristic because it is extremely toxic to fish (Peavy et al, 1985; Metcalf and Eddy, 1991).

Nitrate nitrogen is the most highly oxidised form of nitrogen in leachate, and is a parameter of concern because of its serious and occasional fatal effect on infants (Peavy et al, 1985; Metcalf and Eddy, 1991).

Phosphorus appears exclusively as phosphate in aquatic environments (Peavy et al, 1985). Although phosphates do not represent a serious direct health threat to humans or other organisms, they do represent a serious indirect threat to water quality. Along with nitrogen, phosphorus is one of the essential nutrients for plant and animal reproduction and growth, and hence any increase in supply can result in rapid growth of aquatic plants, which can have severe consequences (Peavy et al, 1985).

The sulphate ion occurs naturally in most water supplies. The concentration of sulphates in landfills is related to the waste composition, with high concentrations usually attributed to the disposal of gypsum. Although the initial concentrations of sulphates in leachate may be high, they are rapidly reduced by biological organisms to sulphides (Qasim and Chiang, 1994).

A wide range of metals is commonly found in leachate. Copper, lead, silver, chromium, arsenic and boron are toxic in varying degrees to microorganisms (Metcalf and Eddy, 1991). Sodium and potassium are toxic at high concentrations. Leachates may also contain trace quantities of heavy metals, some of which are necessary for growth of biological life. Many heavy metals are classified as priority pollutants because of their toxicity.

3.3.3 Biological Characteristics

Municipal Solid Waste contains a large microbial population and may be contaminated by pathogenic microorganisms. There is very little data on the microbiological characteristics of leachate. Most leachates have a significant bacterial population with varying entity and composition with landfill age (Andreottola and Cannas, 1992).

Viruses in leachate (enteroviruses) can be attributed to the presence of faecal material of varying origin in MSW, however the presence of enteroviruses occurs only in extremely rare cases (Andreottola and Cannas, 1992). Knowledge on the presence of fungi and parasites is limited. Parasites such as protozoa, helminths, and nematodes could be observed in leachate in the presence of animal and human faeces in landfills (Andreottola and Cannas, 1992).

3.4 DEVELOPMENTS IN LEACHATE COMPOSITION

The general biochemical processes that occur in landfills as discussed in section 2.3 give rise to changes in leachate composition as the waste degrades and stabilises. Experience from full-scale landfills has shown that the decomposition of a waste body proceeds in an idealised sequence of degradation stages. Each stage of the process has an impact on the characteristics of the intermediate and final breakdown products and the quality and rate of generation of leachate (DoE, 1995). Figure 3.3 illustrates the theoretical developments in leachate and gas composition as a function of the age of the landfill, and are arguably the most widely produced in the field of landfill science. Various authors have described the sequence of degradation (Farquhar and Rovers, 1973; Robinson, 1989; Qasim and Chiang, 1994; Andreottola and Cannas, 1992; Senior, 1995; Christensen and Kjeldsen, 1989), the most common showing the sequence proceeding in five stages. No time scale is given for duration of the various phases because of their dependence on site-specific conditions.

3.4.1 Aerobic Degradation Stages

The first and fifth stages in the idealised sequence of degradation occur under aerobic conditions (in the presence of oxygen). In the first stage of hydrolysis/aerobic degradation, which occurs both during and for a period after waste placement, a proportion of the organic fraction of waste is metabolised by aerobic microorganisms (oxygen consumers) in the waste (DoE, 1995). These microorganisms convert readily biodegradable carbohydrates to simple sugars such as glucose, carbon dioxide and water (DoE, 1995; Andreottola and Cannas, 1992). Proteins are degraded into amino acids, and then into carbon dioxide, water, nitrates and sulphates (Andreottola and Cannas, 1992). Fats are hydrolysed to fatty acids and glycerol. The intense microbial activity in this stage generates heat (exothermic reactions) which can cause elevated temperatures in the landfill (Andreottola and Cannas, 1992; DoE, 1995). The aerobic stage is usually short (days to months) and no substantial leachate generation takes place (Andreottola and Cannas, 1992).

In older landfills, where only refractory organic carbon remains in the waste body, the production of methane will be sufficiently low to allow the diffusion of air into the waste body from the atmosphere. Aerobic zones and zones with redox potentials to high for methane formation will appear in the upper layers of the landfill (Christensen and Kjeldsen, 1989).

3.4.2 Anaerobic Degradation Stages

The anaerobic (absence of oxygen) degradation of waste in a landfill dominates for the majority of the landfills lifetime. As stated in section 3.1, the most important change in leachate composition is from the earlier acetogenic stage to the later methanogenic stage.

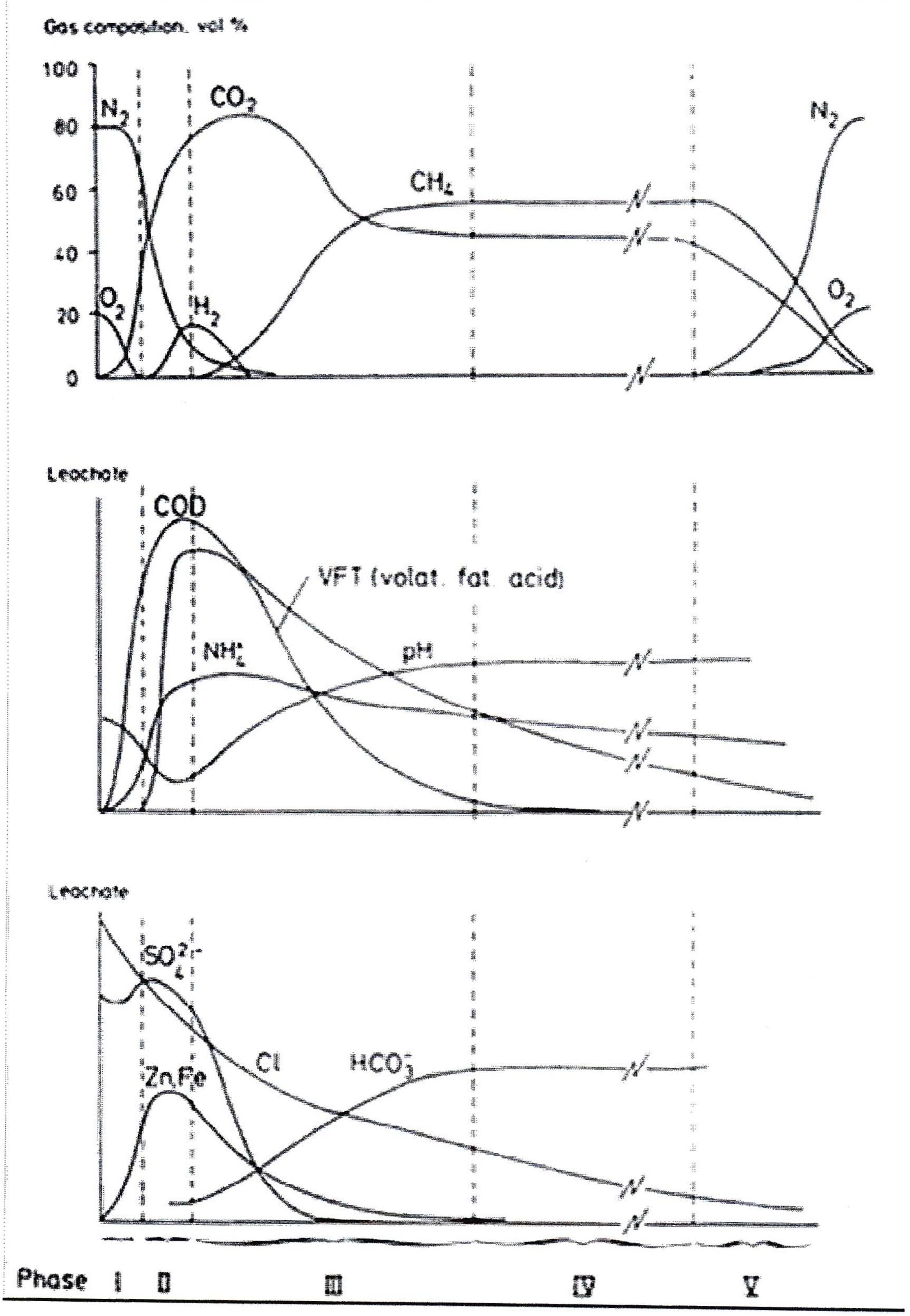


Figure 3.3 Theoretical waste degradation phases in landfills, illustrating the variations in leachate and biogas compositions with time (Farquhar and Rovers, 1973). Diagram from Christensen and Kjeldsen (1992).

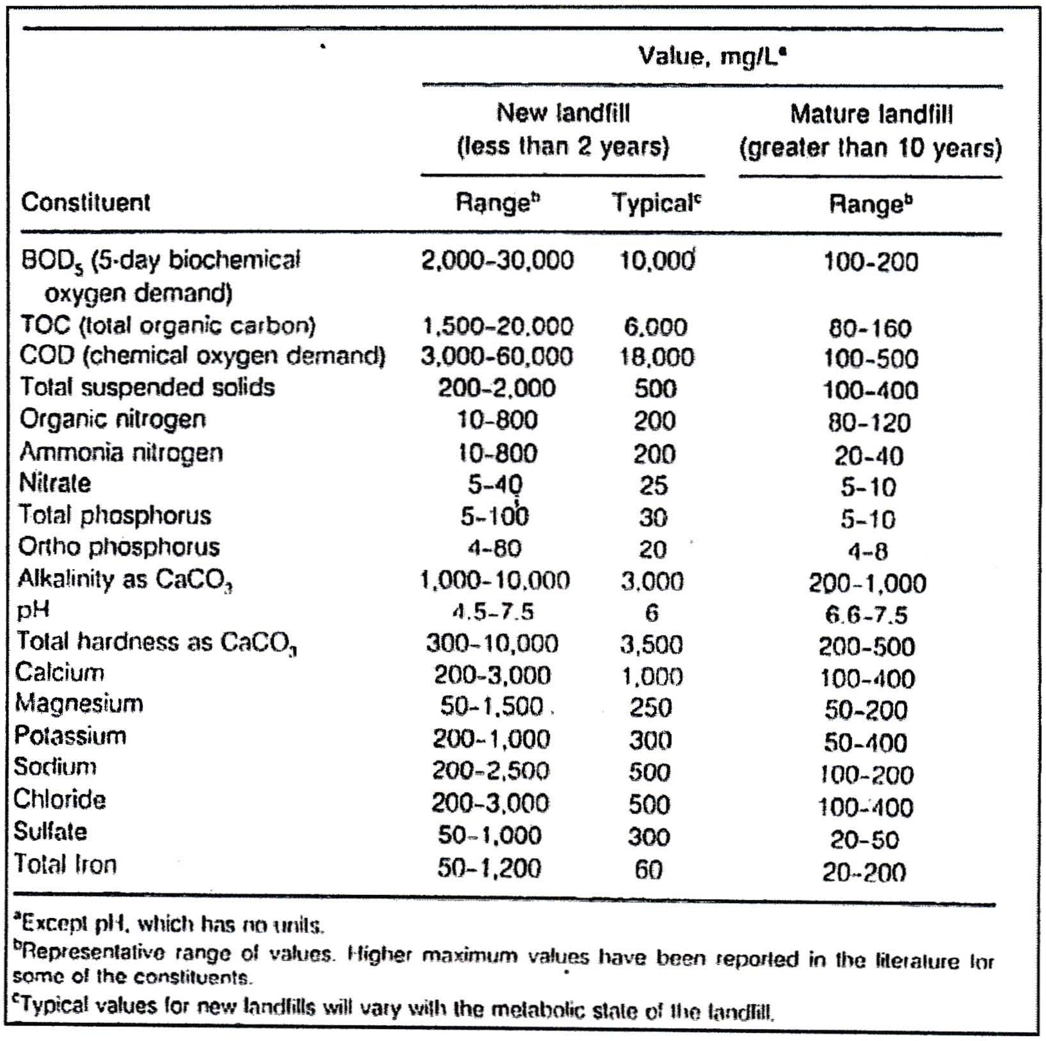
The first stage of anaerobic degradation is termed acid-fermentation or the acetogenesis. In this stage, carbohydrates, lipids and proteins are first hydrolysed to simple sugars and then fermented by bacteria to soluble intermediates (such as volatile acids), acetate, carbon dioxide, hydrogen and inorganic salts, such as sulphate and ammonium (DoE, 1995). The type of volatile acid generated, for example propionic, butyric, lactic and formic acid depends on the initial substrate and the prevailing in-situ conditions. Leachate produced in this phase is characterised by high BOD values (commonly greater than 10000 mg/litre) and a high BOD to COD ratio (>0.7) (Andreottola and Cannas, 1992; DoE, 1995; Robinson 1989). The generation of volatile fatty acids leads to a decrease in leachate pH and may cause an increase in the metal concentrations, as they are more easily solubilised at a lower pH. The high concentration of anions and cations is due to the leaching of easily soluble material available in the waste and those made available by the degradation processes. The degradation of the proteinaceous materials leads to high concentrations of ammoniacal nitrogen (often 500 – 1000 mg/litre) and organic nitrogen (Andreottola and Cannas, 1992; DoE, 1995; Robinson 1989).

The second anaerobic phase begins with the slow growth of methanogenic bacteria. These bacteria start to consume the simple organic compounds made available by the acetogenic bacteria (Robinson, 1989). The methane content in the gas rises, and the concentration of the volatile fatty acids begins to decrease. The concentration of sulphate in the leachate drops owing to biological degradation (to sulphides). The consumption of the volatile acids leads to an increase in pH and as a consequence the concentrations of calcium, iron, manganese and heavy metals decline, as they become less soluble. The metals are probably precipitated as sulphides (Andreottola and Cannas, 1992).

The third anaerobic stage is commonly termed the methanogenic stage. With the onset of methanogenisis, many of the fatty acids responsible for the high BOD and low pH have been converted to methane and carbon dioxide. Methanogenic leachates are characterised by low concentrations of fatty acids, a neutral or alkaline pH, a relatively low BOD and a low BOD to COD ratio (DoE, 1995). Ammonia continues to be released by the first stage acetogenesis process, though it is not found to the same extent in methanogenic leachates (Andreottola and Cannas, 1992; DoE, 1995).

Table 3.2 summarises the changes in leachate composition as the waste body ages and the degradation passes from the acetogenic to the methanogenic stage.

Table 3.2 Typical data on the composition of leachate from young and mature landfills (from Qasim and Chiang, 1994)



	Value, mg/L[a]		
	New landfill (less than 2 years)		Mature landfill (greater than 10 years)
Constituent	Range[b]	Typical[c]	Range[b]
BOD_5 (5-day biochemical oxygen demand)	2,000-30,000	10,000	100-200
TOC (total organic carbon)	1,500-20,000	6,000	80-160
COD (chemical oxygen demand)	3,000-60,000	18,000	100-500
Total suspended solids	200-2,000	500	100-400
Organic nitrogen	10-800	200	80-120
Ammonia nitrogen	10-800	200	20-40
Nitrate	5-40	25	5-10
Total phosphorus	5-100	30	5-10
Ortho phosphorus	4-80	20	4-8
Alkalinity as $CaCO_3$	1,000-10,000	3,000	200-1,000
pH	4.5-7.5	6	6.6-7.5
Total hardness as $CaCO_3$	300-10,000	3,500	200-500
Calcium	200-3,000	1,000	100-400
Magnesium	50-1,500	250	50-200
Potassium	200-1,000	300	50-400
Sodium	200-2,500	500	100-200
Chloride	200-3,000	500	100-400
Sulfate	50-1,000	300	20-50
Total Iron	50-1,200	60	20-200

[a] Except pH, which has no units.

[b] Representative range of values. Higher maximum values have been reported in the literature for some of the constituents.

[c] Typical values for new landfills will vary with the metabolic state of the landfill.

CHAPTER 4

LANDFILL GAS GENERATION AND MODELLING

4.1 INTRODUCTION

Landfill gas (biogas) is the generic term given to describe the gaseous components generated through microbial degradation and/or by chemical reaction/volatilisation consequent to the disposal of waste in landfill sites. Typically, landfill gas consists of methane and carbon dioxide as major components in a wide range and combination of concentrations. Landfill gas may also contain numerous minor (trace) components, of which over 300 have been identified (Couth, 2001). The methane in landfill gas can cause fires, explosion, asphyxiation, damage to vegetation, and it is a potent greenhouse gas. Carbon dioxide can cause asphyxiation, can be toxic to vegetation, and has corrosive properties. The trace components may cause health risks, odour nuisances and groundwater pollution and have corrosive properties.

This chapter describes the generation of landfill gas and related issues, which include:

- Gas generation and characterisation
- Identifying risks associated with landfill gas
- Monitoring of gaseous emissions
- Effective management of landfill gas emissions
- Modeling of landfill gas production

4.2 CHARACTERISATION OF LANDFILL GAS

4.2.1 Gas Generating Processes

The generation of landfill gas is a complex process, predominated by anaerobic digestion. As stated in section 2.3, biochemical processes degrade primarily cellulose and other similar materials, releasing methane and carbon dioxide as final products of waste decomposition. In a typical landfill, biogas consists of 60 – 65 % methane and 35 – 40% carbon dioxide relatively soon after the waste is placed (within one to three years). The five idealised stages of waste degradation (section 3.4) that give rise to the changes in leachate composition, are further sub-divided into eight phases by Christensen et al (1996) when describing the developments in landfill gas composition. Figure 4.1 illustrates the changes in gas composition as the landfilled wastes degrade. The various phases are described in Table 4.1. The time scales for the length of each phase have again been omitted (as with the developments in leachate composition) because of their dependence on abiotic and site specific factors.

The landfill environment is a highly diverse, but rather inefficient ecosystem and abiotic factors at the landfill will influence the gas generating processes, as described below (Christensen et al, 1996):

- Oxygen – An absence of free oxygen is required for the anaerobic bacteria to grow, and the sensitive methanogenic bacteria in particular require very low redox potentials. Oxygen may enter the landfill by diffusion from the atmosphere or through advection if a substantial vacuum is created in the landfill by extensive gas extraction. The methanogenic community is not completely wiped out by the introduction of oxygen however, and will recover upon the depletion of the introduced oxygen.
- Hydrogen – The methanogenic processes are affected by the hydrogen partial pressures in the landfill. When the partial pressures are low, fermentative bacteria yield hydrogen, carbon dioxide and acetic acid. When the partial pressures are high, the bacteria yield hydrogen and carbon dioxide, as well as the organic acids ethanol, butyric acid and propionic acid. The organic acids may be further converted if the hydrogen partial pressure is low. In the event that the hydrogen pressure increases, organic acids will be generated but not further converted leading to a build-up of volatile organic acids, a decrease in the pH and possibly inhibition of the methane formation.
- pH and Alkalinity – The optimum conditions in which methanogenic bacteria may operate efficiently is relatively narrow (pH 6 – 8) whereas the fermentative and acetogenic bacteria can tolerate a much wider range of pH values. The conversion of hydrogen and acetic acid by methanogenic bacteria may reduce if they are stressed by other factors, leading to a build up of volatile organic acids and consequently a drop in pH, which may inhibit methane formation. This may eventually lead to a stop in methane generation.

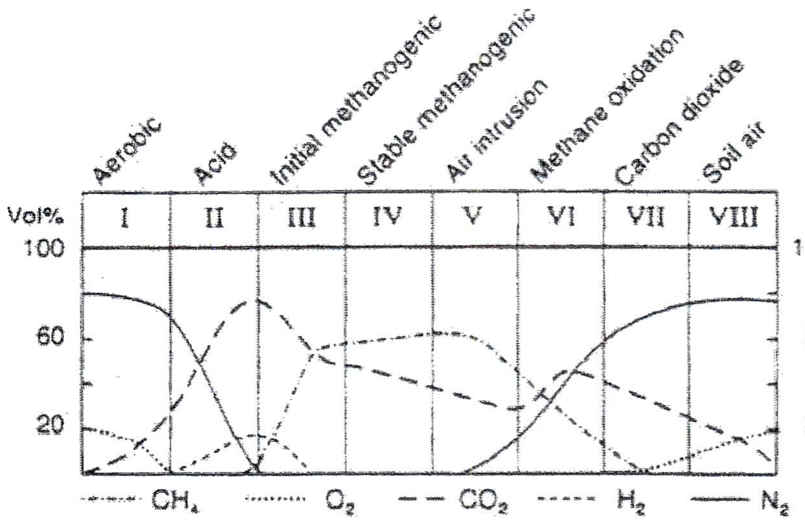


Figure 4.1 Developments in gas composition in a landfill cell (Christensen et al, 1996)

Table 4.1 Phases of landfill gas generation (adapted from Christensen et al, 1996)

PHASE	DESCRIPTION
1. Aerobic	A short aerobic phase by composting of easily degradable organic matter to carbon dioxide
2. Acid	Fermentative and acidogenic bacteria produce, under anaerobic conditions volatile fatty acids, CO_2 and H_2. The presence of these gases reduces the content of N_2
3. Initial methanogenic	In a second anaerobic phase, methanogenic bacteria start to grow producing CH_4, while CO_2 and H_2 decrease.
4. Stable methanogenic	The stable methanogenic phase is characterised by 50-60% CH_4 and low concentrations of H_2. The latter being oxidised by CO_2 to CH_4.
5. Air Intrusion	Air starts to intrude into the outer part of landfill body reducing the formation of CH_4. The lower rates lead to a relatively more significant washout of CO_2 and a relative increase in CH_4 content in the gas.
6. Methane oxidation	Methane produced in the centre of the waste is oxidised to CO_2 as it migrates through the outer part of the landfill body. N_2 is now present in significant concentrations in the gas
7. Carbon dioxide	Methane formation is now negligible and intruding air now oxidises solid organic carbon (and reduced inorganic species) yielding CO_2.
8. Soil air	The rates of the processes now approach the rates found in an active soil and the landfill gas starts to resemble soil air

- Sulphate – The sulphate-reducing and methanogenic bacteria both convert acetic acid and hydrogen. Experiments (e.g. Stegmann and Spendlin, 1985) have shown that when sulphate is present in high concentrations the formation of methane is significantly reduced. The presence of sulphate is not toxic to the methanogenic bacteria, however the development of sulphate-reducing bacteria can lead to the suppression of methane formation due to substrate competition.
- Nutrients – The anaerobic ecosystem must have access to, in addition to organic matter, all the required nutrients and in particular nitrogen and phosphorous. All the necessary micronutrients e.g. sulphur, calcium, magnesium, potassium, iron, zinc, copper, cobalt, molybdenite and selenium are considered to be available in most landfills (Christensen et al, 1996). Nitrogen and phosphorous in anaerobic degradation are less critical than in aerobic systems. The optimal ratio between organic matter, nitrogen and phosphorous is 100: 0.44: 0.08 (McCarty, 1964). In most landfills, the presence of nitrogen and phosphorous will not be limited, but insufficient homogenisation of the waste may lead to areas in the fill that are nutrient-limited. The nutrient (if any) most likely to limit the anaerobic degradation is phosphorous.
- Inhibitors – The methane-forming ecosystem is generally considered to be sensitive to inhibitors. The presence of volatile organic acids in concentrations below 6000 mg/l does not inhibit methane formation, whilst carbon dioxide may inhibit the conversion of acetic acid to methane. Macro-ions such as sodium, potassium, calcium, magnesium and ammonium may have inhibitory effects on the formation of methane when present in high concentrations (>2000 mg/l). Johnson (1981) reported that inhibition by specific organic compounds rarely occurs because the levels required for inhibition are too high to be found in the landfill environment. The effects of these inhibiting compounds are generally limited because they are present in the landfill at concentrations too low to be detrimental to methane formation, though they may cause a reduction in the formation rate (Christensen et al, 1996).
- Temperature – As with all microbial processes, the anaerobic waste degradation is highly affected by temperature. The methanogenic bacteria contains of a Mesophilic group (temperature range 16 – 40 ^{0}C) with a rate maximum of 38 ^{0}C and a Thermophilic group (temperature range 40 - 70 ^{0}C)

with a maximum of around 70 °C. The latter are not relevant in the landfill environment. Researchers (e.g. Buivid, 1980; Ehrig, 1984) have shown in laboratory experiments that a rise in temperature from 20 – 30 and 40 °C can increase the methane production rate by up to 100 times. The aerobic and anaerobic degradation of waste both yield heat, though the anaerobic heat generation is only about 7% of that of the aerobic heat generated and is often neglected (Rees, 1980; Lagerkvist, 1986). Landfills that are deep and have a moderate water flux will lose little heat to the surroundings due to the insulating capacity of the waste body, and the heat generated by the anaerobic processes may lead to a temperature rise in the landfill (Rees, 1980). Landfill temperatures of 35 – 40°C should be possible even in moderate climates (Christensen and Kjeldsen, 1989). Not all landfills may reach these temperatures however, as it requires substantial waste thickness, a high methane production rate and a low water flux through the landfill.

- Water Content – It has been shown in laboratory experiments (Buivid, 1980; Rees 1980) that the methane production rate increases for increasing moisture content of the waste. The main effect of the increased water content, besides limiting oxygen transport from the atmosphere, is probably the facilitated exchange of substrate, nutrients, buffer, and dilution of inhibitors and spreading of micro-organisms between the waste micro environments (Christensen and Kjeldsen, 1989).

Daily landfill operations may have an effect on the gas production, however they cannot control abiotic factors individually. Although a specific operation procedure may aim at improving one of the abiotic factors, the procedure can simultaneously affect several abiotic factors making the overall affect difficult to predict (Christensen et al, 1996). Table 4.2 summarises the landfill operation procedures and their possible effects on gas production.

Table 4.2 Influence of landfill operations on biogas production (Couth, 2001)

FACTOR	INFLUENCE
Waste composition	Greater amount of easily decomposable matter (putrescibles), greater production rate and volume.
Waste input rate	Greater input rate, greater gas production.
Depth	Greater depth, greater density, and reduced risk of air ingress, greater heat retention and potentially greater gas production
Waste density	Depending on moisture, the greater the waste density, the greater the theoretical gas production.
Sewage sludge addition	The addition of sewage sludge into the landfill can lead to early gas production at increased rates.
Pre-treatment of wastes	Shredding of wastes can improve homogeneity and early gas production.
Moisture content	The greater the moisture (up to the waste field capacity) the greater the movement of nutrients, the greater the gas production. Moisture movement is improved by gas extraction
Leachate Management	Leachate can be recirculated to optimise the moisture content and gas production. Saturated waste with high leachate levels may reduce gas generation. Leachate removal can reduce nutrients and gas production rates
Daily cover	Low permeability daily cover can lead to perched water tables, reduced moisture movement and less gas production
Mono-disposal cells	Mono-disposal cells can be designed to enhance or reduce gas production

4.2.2 Landfill Gas Characteristics

The typical concentrations of methane and carbon dioxide given in section 4.2 remain relatively constant over the life of the landfill, though higher methane concentrations may be observed in older landfills (Rettenberger and Stegmann, 1996). The composition of the gas will change when oxygen enters the landfill, which may occur during active gas extraction when air is sucked into the fill.

Landfill gas typically contains a volumetric ratio of CH_4/CO_2 of 1.2 to 1.5 (Wilhelm, 1993). The volatile organic compounds (VOC) generally account for less than 1% of landfill gas by volume. Carbon dioxide is heavier than air, having a density (relative to air) of 1.53, whilst methane is lighter than air, having a density (relative to air) of 0.55. Landfill gas will thus be lighter than air when methane is in excess of 54% (0.54*0.55 + 0.46*1.53 = 1.0008), and heavier than air when it is less than 54% (Massacci, 1996). Generally, landfill gas will be denser than air however, as it is actually a mixture saturated by water vapour. Couth (2001) reports that in England and Wales landfill gas tends to rise due to the difference in temperature of the gas and the ambient air. Table 4.3 gives the characteristics of the bulk components of landfill gas.

Table 4.3 Characteristics of landfill gas components (Couth, 2001)

COMPONENT	DENSITY g/l	ODOUR	COLOUR	FLAMMABLE	COMMENT
Methane (CH_4)	0.71	Odourless	Colourless	Yes	Very low solubility in water at STP. Important greenhouse gas
Carbon Dioxide (CO_2)	1.98	Odourless	Colourless	No	Slightly acidic at high concentrations. Very soluble in water, forming corrosive liquids of low pH
Hydrogen Sulphide (H_2S)	1.53	Rotten eggs	Colourless	Yes	-
Hydrogen (H_2)	0.09	Odourless	Colourless	Yes	-
Oxygen (O_2)	1.42	Odourless	Colourless	No	-
Nitrogen (N_2)	1.25	Odourless	Colourless	No	-

In addition to the methane and carbon dioxide, landfill gas will also contain numerous trace components. The composition of the landfilled wastes will determine the type and concentration of the trace components, although these may change due to chemical and biological processes that take place in the landfill. Trace components may cause damage to technical equipment (especially that used for landfill gas extraction) and have an adverse impact on the environment, atmosphere and on the health of humans and animals (Rettenberger and Stegmann, 1996). There are generally two sources from which trace components are generated in the landfill - those generated during anaerobic degradation and those produced by man (anthropogenic trace components) and deposited together with the wastes.

- *Trace compounds generated during anaerobic degradation* - Oxygen compounds, sulphur compounds and hydrocarbons are the three main groups of trace elements that are generated during biodegradation processes in the landfill. The compounds containing oxygen only appear in the gas in the early phase of generation, and arise from the degradation of the organic waste components. The compounds containing sulphur in landfill gas are responsible for the odour of the gas and compounds like hydrogen sulphide and the mercaptans are amongst the more toxic landfill gas components. The sulphur components originate from easily degradable material, and some of these components (e.g. mercaptans) occur mainly during the operation phase of the landfill. Other sulphur compounds, in particular hydrogen sulphide, are generated in all phases of landfill gas production. Hydrocarbons (specifically the terpene hydrocarbons) may be naturally generated in the landfill, as well as deposited with the landfilled waste.

- *Anthropogenic trace components* - These trace components can be divided into two groups – the aromatic hydrocarbons and the chlorinated hydrocarbons. The aromatic hydrocarbons are common compounds found in landfill gas due to their widespread utilisation. The production of aromatic hydrocarbons in the landfill is negligible when compared to other sources (e.g. traffic) and hence their effect on the environment is limited. These components are of importance for the people working on the landfill site due to their possible health effects however, and benzene in particular should be monitored owing to its proven carcinogenic properties.

The chlorinated hydrocarbons are used for cleaning purposes (metal industry, laundries etc.). Freons (chlorinated and fluorinated hydrocarbons) may be used in sprays and in the chemical industry (Rettenberger and Stegmann, 1996). The majority of these substances have low toxicity, however due to their persistence in landfill gas they are the most significant trace components with regard to environmental impacts. Hydrogen chloride may be generated from the chlorinated hydrocarbons, which may cause corrosion problems if the landfill gas is used in gas motors. The chlorinated hydrocarbons also pose a serious potential environmental hazard.

The biochemical degradation of aromatic hydrocarbons under methanogenic conditions is very limited, and most aromatic hydrocarbons will persist in the landfill (Rettenberger and Stegmann, 1996). The biochemical degradation of chlorinated hydrocarbons leads to toxic substances that are of more significance than the chlorinated hydrocarbons themselves. The conversion of tetrachloroethylene leads to the generation of the carcinogen vinyl chloride, which besides benzene and methylmercaptan is the most hazardous substance emitted from landfills.

4.3 HAZARDS ASSOCIATED WITH LANDFILL GAS

Landfill gas will migrate from the fill in response to pressure, temperature or concentration gradients (diffusion), or density effects (IWM, 1998). Although some landfills may have an active gas extraction system in place, some of the gas may escape to the natural surroundings, as the extraction systems are never 100% effective. The majority of landfills do not have extraction systems, owing mainly to low economic profitability, and hence biogas is emitted to the atmosphere directly through uncovered waste, through top covers, or by migrating through the surrounding soil layers.

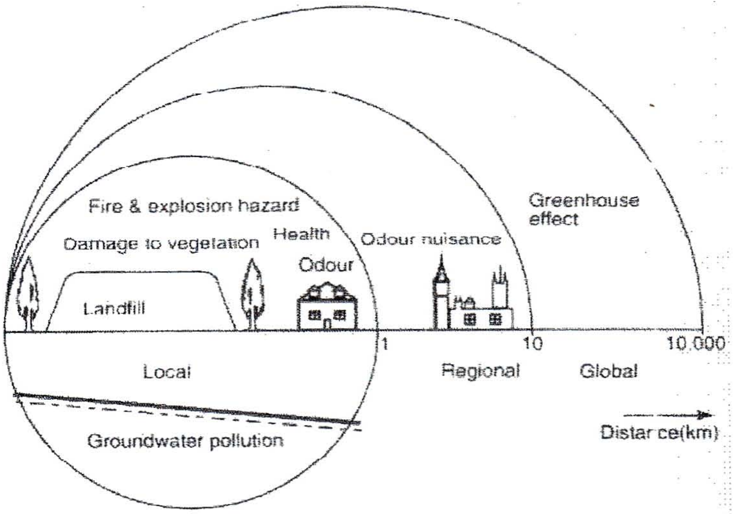


Figure 4.2 The different scales of landfill gas effects (from Kjeldsen, 1996)

The migration and emission of landfill gas may potentially lead to the following different effects on the surroundings (Kjeldsen, 1996):

- Fire and explosion hazards
- Health risks
- Odour nuisance
- Damages to vegetation
- Groundwater pollution
- Global climate effects

Figure 4.2 illustrates the different scales of landfill gas effects.

As shown in Figure 4.2, the effects of landfill gas are connected to different scales of distance, and can have an impact both locally and globally. A description of the different effects that landfill gas may have on the surroundings is given in Sections 4.3.1 to 4.3.6.

4.3.1 Fire and Explosion Hazards

Landfill gas is explosive owing to its methane content. The most commonly accepted flammability ranges for methane in air mixtures are 5.3 – 14% (by volume in air). The flammability range becomes slightly extended to 5.0 – 15% when mixtures in air are retained within a small vessel or void (Campbell, 1996). The main environmental hazard relating to landfill gas is considered to be the explosion hazard caused by gas entering houses/buildings through cracks in foundations, penetrating services etc. After the gas has mixed with air, a spark can initiate the explosion. The spark energy that is required for ignition will depend on the methane concentration in the gas. Figure 4.3 illustrates the flammability range of landfill gas.

Relatively old, closed landfill sites are most likely to pose serious fire hazards because there were very few, if any specific controls introduced and designed to prevent migration and emissions. There have been several incidents reported of explosions, fires and human injury due to migration of gaseous emissions. Gendebien et al (1992) described 115 cases in Europe and North America alone. In well run, modern landfills the dangers of fire hazards have been significantly reduced, as barrier systems and gas extraction wells prevent off-site migration.

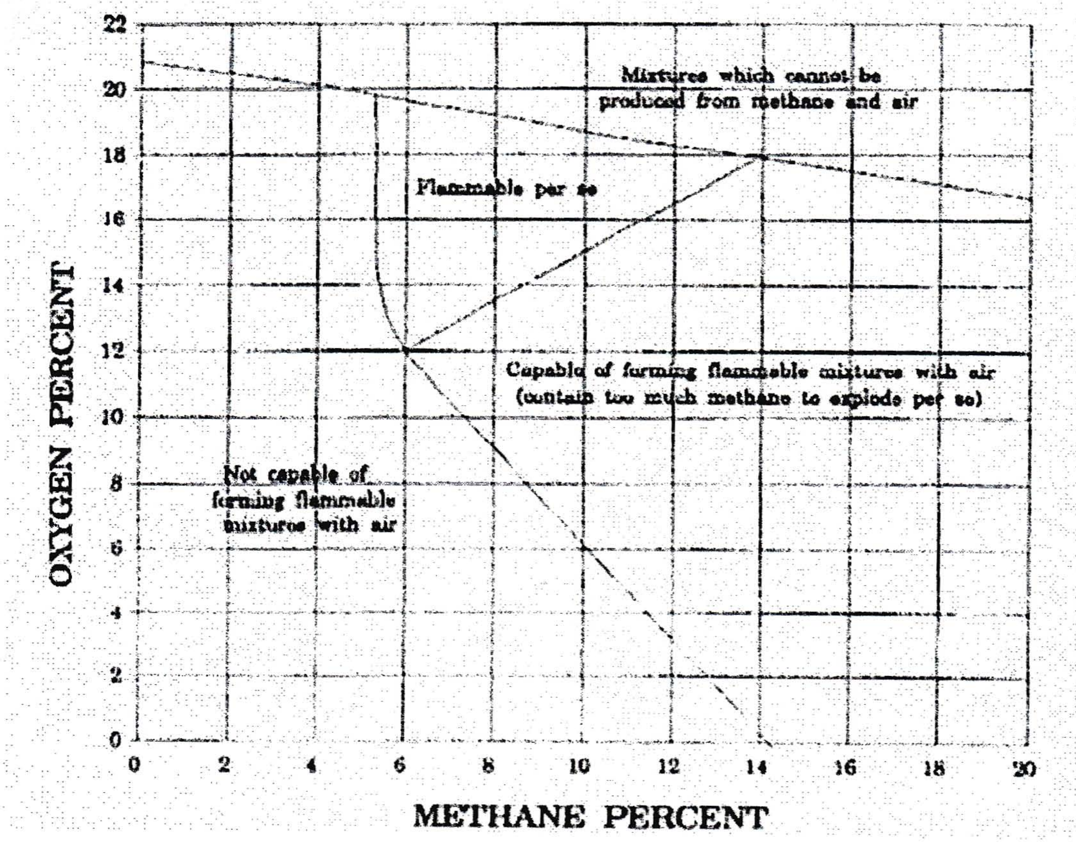


Figure 4.3 Flammable limits for methane (from Campbell, 1996)

4.3.2 Health Aspects

The residents in the vicinity of landfill sites often complain of being irritated by odours and gaseous emissions, and are concerned not only about the environmental nuisance posed, but also about the potential toxicological effects associated with the escaping gases. The main components of landfill gas, carbon dioxide and methane, have associated potential health risks for humans however the most concern is assumed to be related to organic trace components in the gas (Eikmann, 1996). There is limited available qualitative or quantitative information on the possible physiological effects of trace components of landfill gas (Gendebien et al, 1992). As stated in section 4.2.2, some of the components found in landfill gas are however carcinogenic.

The two organic trace compounds in landfill gas that are carcinogenic and therefore of concern are benzene and vinyl chloride, with potential health effects of leukaemia and tumours (Couth, 2001). Non-carcinogenic compounds include carbon disulphide, ethylbenzene and hydrogen sulphide, however, these may cause damage to the nervous system, development and neurological concerns (Couth, 2001). The toxic significance of aromatic hydrocarbons is based on irritant and narcotic properties (Gendebien et al, 1992). The effect is cumulative for products such as toluene, xylene and propylbenzene (Gendebien et al, 1992). Atmospheric dilution will, in most instances, reduce the concentrations of toxic compounds in the atmosphere to well below dangerous levels, however there are concerns that some people could be more susceptible than others.

Hydrogen sulphide (H_2S) is a highly toxic, flammable gas that affects the nervous system and has a repugnant (rotten egg) odour.

Carbon dioxide (CO_2) is classified as intermediary between toxic and non-toxic products (Gendebien et al, 1992). The toxicity of CO_2 is not due to the CO_2 itself, but due to the displacement of oxygen in the respiratory system. Carbon dioxide may pose a further threat if it is allowed to pass through a heat source (such as a warm air recirculating heater), as it may produce the highly toxic gas carbon monoxide (CO).

Methane (CH_4) is a colourless, odourless, asphyxiant, flammable, non-toxic gas. The components of landfill gas that are considered "non-toxic" such as methane, nitrogen and hydrogen still pose a significant health hazards because they act as asphyxiant. These components of landfill gas take up the place of oxygen in breathing air in closed spaces and the lack of oxygen in the work or living environment leads to the asphyxia (Gendebien et al, 1992. Oxygen levels should not be allowed to fall below 18 vol.% at normal atmospheric pressure (Couth, 2001).

4.3.3 Odour Nuisance

Odour emissions from landfill sites were until recently considered secondary emissions, however the annoyance they may cause around the landfill site has received increasing attention.

A quantitative measure of odour is its concentration. An odour detection threshold of a substance is the concentration above which the odour of that substance can be detected (Laister et al, 2001). The odour concentration, usually expressed as a number of odour units (ou), can be defined as the dilution required to reach the detection threshold. Odours are usually characterised using a panel of human odour assessors. The inherent subjectivity of odour panel assessment can lead to large variability in odour detection thresholds (ODT) (Laister et al, 2001). In order to minimise this subjectivity, electronic odour monitors are now being used to measure odour concentration.

The rate of gas production, the method of landfill operation and the local topography as well as the age of the waste, all affect the spreading of odour from the site (Gendebien at al, 1992). Landfill odour effects also depend on the type of deposited wastes. Meteorological conditions such as humidity, high temperatures, or inversion and prevailing winds also contribute to the broadcast of odours. Rapid drops in atmospheric pressure may release large quantities of gas from the site, which will require greater dilution than under normal conditions.

The two main components of landfill gas, carbon dioxide and methane, are odourless and do not cause an odour problem. The major contribution to landfill odour appears to come from two groups of compounds, present in landfill gas as trace components. The first group is dominated by esters and organosulphur compounds, but also includes butane-2-ol and certain specific solvents that have been deposited with the waste (Gendebien et al, 1992). These compounds are not widespread and vary in concentration. The esters also pose a significant odour nuisance, namely ethyl butanoate, and are responsible for the "sweeter" odour typical of fresher waste. The esters and organosulphurs are associated with the early decomposition phase of the deposited waste (Gendebien et al, 1992).

The second group of compounds, which include terpenes and hydrocarbons, are widespread and consistently produced by the waste degradation (Gendebien et al, 1992). This group is responsible for the less unpleasant and typical background smell that is associated with landfills (Laister et al, 2001).

4.3.4 Damage to Vegetation

The damage to vegetation by landfill gas is due to migrating gas entering the root zone and displacing the natural soil air. The infiltrating gas will usually lead to anoxic conditions, and may affect the plant by asphyxiation, by the presence of toxic gases or by changes in pH and composition of the soil solution (Neumann and Christensen, 1996).

Methane is not usually considered toxic to plants, and in fact low methane concentrations (< 5%) have been reported to be beneficial to plants, while very high concentrations (45%) may partly damage some plants (Neumann and Christensen, 1996). Methane may be oxidised by microbes in the landfill soil cover, leading to a depletion of oxygen, increased carbon dioxide concentrations, and possibly to increased temperatures in the soil, thereby enhancing asphyxiation (Neumann and Christensen, 1996).

The natural carbon dioxide levels in soil may be as high as 3%, due to the degradation of organic matter in the soil and respiration processes. Growth for some species may be inhibited above this level, although many species may function normally up to levels of 5% CO_2 (Neumann and Christensen, 1996). At higher levels phytotoxic effects may appear. Gendebien et al (1992) reports substantial variation among plant species as far as CO_2 tolerance is concerned.

Vegetation damage from landfill gas includes chlorosis (leaves appear yellow-green), defoliation, dwarf growth, surfacial root development, branch die-back and plant death (Couth, 2001). Land adjacent to the landfill and capped areas of a landfill may be susceptible to the adverse impact of landfill gas in cover soils.

Landfill gas emissions may contain acidic gases (sulphur compounds, NO_X, HCl) and volatile organic compounds which may potentially harm fauna and flora, although asphyxiation is usually considered to be a much more dominating aspect.

4.3.5 Effect on Groundwater Quality

The production of landfill gas leads to a build up of gas pressure within the waste body, which may result in pressure-driven gas migration. This is particularly applicable to capped sites, where gases migrate into surrounding strata due to the impermeable cover layer (Kerfoot, 1996). The migrating gas will eventually be vented to the atmosphere, but the gas may contact the groundwater as it travels, which may lead to groundwater pollution. The degree to which landfill gas will affect the groundwater quality depends primarily on the proximity of the groundwater to the landfill site, and the quantity of pollutants generated in the fill (Gendebien et al, 1992). The potential for groundwater pollution is related to the geological and hydrological site characteristics.

The extent to which the gases produced in landfills will affect the groundwater quality is varied. Carbon dioxide is highly soluble in water, and is the primary groundwater pollutant. The other gases present in the landfill gas are relatively insoluble in water. Carbon dioxide that comes into contact with groundwater dissolves until it reaches an equilibrium state, and unless there are secondary reactions, the pH value drops to 4.3 (Gendebien et al, 1992). The resulting acid solution is highly aggressive and saturated with carbon dioxide (>20 ppm), which accelerates the corrosion of iron and steel and promotes the dissolution of lead (Gendebien et al, 1992).

4.3.6 Global Landfill Effects

The concerns related to landfill gases are not only localised, but evolve also at the macro-scale because of their impact on air-quality. Both carbon dioxide and methane are greenhouse gases. When these gases are dispersed in the atmosphere, they allow short wave (ultra-violet) radiation from the sun to penetrate the earth, warming it. The incoming short-wave radiation is subsequently reflected off the surface as long-wave (infrared) radiation, and trapped by the greenhouse gases, preventing the heat from being radiated back into space. This gain in heat causes the temperature in the atmosphere to rise. This phenomenon is referred to as global warming or the 'greenhouse effect'.

Greenhouse gases are classified according to their Global Warming Potential (GWP), which gives carbon dioxide, the most common greenhouse gas, a GWP of 1. Methane is a significant greenhouse gas with a GWP of 20-25 (Gendebien et al, 1992, Couth, 2001; Thorneloe, 1996; Morris, 1999). Although carbon dioxide constitutes nearly half of the gas produced in the landfill, it is not classified as a greenhouse gas because it is produced from mainly vegetable matter that would produce carbon dioxide if left to degrade naturally, i.e. it is part of the carbon cycle.

Landfill biodegradation processes release CFC's (chlorofluorocarbons) and HCFC's (Chlorodifluoromethane), which are ozone depleting chemicals. The impacts of landfill gas on the ozone layer are not considered significant however, and it is the formation of greenhouse gases that is the main global effect (Couth, 2001).

4.4 MONITORING LANDFILL GAS

The ongoing decomposition of waste in a landfill produces potentially hazardous landfill gas from the time the landfill first accepts waste until many years after the completion of the site. It is thus necessary to design a suitable monitoring procedure within the management of the landfill site, during both the operations of the site and a certain time after its closure. A monitoring procedure includes a specific program of field tests and sampling, or alternatively limited field testing in combination with a predictive mathematical computer model (Gendebien et al, 1992).

Table 4.4 Reasons and requirements for monitoring landfill gas emissions (adapted from IWM, 1998)

ARGUMENT	RATIONALE
Why monitor landfill gas emissions?	• To ascertain risk to public and environment • To verify efficiency of gas control measures • To trace trends in gas generation and migration • To obtain representative soil/gas samples at required depths in surrounding strata • To comply with the regulations
Where should landfill gas emissions be monitored?	• Inside the site to identify both the quantity and quality of gas being produced • Outside the site to establish migration of the gas according to site-specific conditions, risk assessment (the positioning of boreholes outside the site must take into account a variety of factors, including geology, housing, services etc.)
How are the emissions to be monitored	• By use of appropriate equipment and procedures
When should the emissions be monitored	• As required by relevant legislation codes of practice • As dictated by the most recent risk assessment (frequency should not be a fixed parameter) • As determined by routine review of acquired monitoring data

A typical program for monitoring gas emissions follows a systematic approach, which allows the most effective use of resources in relation to risk (IWM, 1998). Table 4.4 outlines the reasoning for and approach to establishing a monitoring program.

4.4.1 Monitoring Structures

Monitoring structures provide a means of monitoring and sampling gaseous emissions generated by the waste in a landfill. The type and extent of the monitoring structures required will depend on the site monitoring program and site-specific characteristics. Monitoring structures may be at the surface, at shallow and greater depths, immediately adjacent to the site or at some distance from the site (IWM, 1998). All structures are usually sealed from the atmosphere to prevent dilution by air.

Monitoring structures may be separated into surface, shallow and deep structures. Surface monitoring structures are typically enclosure chambers that measure an increase in gas concentration over time to obtain a gas flux over a known area. The techniques for measuring surface emissions are discussed further in section 4.5. Shallow structures include shallow probes and trial pits. Deep structures include gas monitoring boreholes and gas extraction wells. Shallow and deep monitoring structures are discussed below

- *Shallow monitoring structures* – Shallow gas probes are generally perforated galvanised steel or plastic pipes, typically 12 – 25 mm in diameter, and may be installed directly into soft strata to a depth of several metres without the use of sophisticated equipment. In practice, shallow probes are usually placed to a depth of 2- 4 metres. The probes are usually placed by percussive technique and thus the adjacent soil/waste may compress, resulting in relatively long equilibration times between the gas in the probe and the soil/waste.

  Trial pits are sometimes excavated and probes placed in the backfilled material. They serve a similar purpose to shallow gas probes, except that it may take longer for pre-excavation gas atmospheres, moisture regimes and temperatures to be established around the sampling point. An advantage of trial pits, especially those opened up in the waste body, is that they allow for the examination of ground conditions and/or shallow waste deposits, perched and/or ground water leachate levels and other localised characteristics (IWM, 1998).

- *Deep monitoring structures* – Gas monitoring boreholes are the most common method of monitoring gaseous emissions when detailed information on gas concentrations at depth are required. Boreholes generally consist of a 90 – 160 mm diameter perforated (or slotted) HDPE (High-Density Polyethylene) pipe placed into a 150 – 350 mm hole drilled into the soil/waste strata. Gas monitoring boreholes are often placed in the strata adjacent to operational or closed sites, to determine whether potentially dangerous off-site gas migration is occurring. Local geology dictates the required depth of the boreholes. Boreholes placed on site are driven to at least the depth of the waste body. In addition to providing information on gas concentrations, on site boreholes provide valuable information with regards to leachate levels and flow paths within the waste body.

Gas wells are placed in the waste body to extract landfill gas from the fill, and are of similar design as a borehole. They may be used, in addition to extracting gas, to monitor gas concentrations, gas temperatures and pressures, and the extent of waste degradation. Gas extraction systems are discussed further in section 4.7.

4.5 Monitoring Surface Emissions

Landfill gases migrating through the cover soil to the atmosphere are termed surface emissions. The problems of greenhouse gas emissions accumulating in the atmosphere, as discussed in section 4.3.6, are the biggest concern with regards surface emissions. Monitoring these emissions allows the operator to apply appropriate engineering solutions (e.g. gas extraction systems) to reduce and/or eliminate the emissions if they are deemed to be a potential environmental hazard.

There is limited legislation in South Africa with respect to monitoring surface emissions, though gas and air quality monitoring systems are required if, in the Site Investigation and the Risk Assessment, landfill gas migration and accumulation are found to represent a potential safety hazard or odour problem (DWAF, 1998). Further to this, monitoring systems are also required if the site is within 250 metres of residential or other structures. The Unites States have developed arguably the strictest legislative requirements in the world with regards air quality via the *Compilation of Air Pollutant Emission Factors (AP-42)* document (US EPA, 1995). This document has been published periodically by the U.S. Environmental Protection Agency (EPA) since 1972. The document provides emission factors, which relate the quantity of pollutants emitted by a source. They can be used to estimate area-wide emissions, emissions for a specific facility (e.g. a landfill site) and to evaluate emissions relative to ambient air quality (US EPA, 1997). The calculated emission quantities are then compared with the standards given in the Clean Air Act (CAA), with sites not meeting these standards requiring gas control systems.

Methods of determining surface emission rates from a landfill site are available (generally based on the AP-42 method), however they are rough estimates based only on waste volumes, and therefore do not take into account site specific factors. Soil moisture, microbial populations (particularly methanotrophs) and permeability to gas flow, as well as gas transport processes and vegetative transport, are important influences and controls on gas emission levels and should be examined as part of any field measurement study (Livingstone and Hutchinson, 1995). Several techniques exist to measure surface emission rates, however due to the spatial variability and complexity of landfill gas emissions, no single technique exists to measure net emissions precisely (Morris, 1999).

The most common technique for determining surface emission rates is the use of enclosure chambers, which can measure methane fluxes from small areas of the landfill surface, of scales typically less than $1m^2$. Advantages of this method include an appropriate scale for concurrent measurement of controlling variables (e.g. temperature, moisture), ability to determine the heterogeneity of surface emissions, and ready comparison with other results since this relatively simple technique has been widely deployed in non-landfill settings for a variety of gases (Bogner et al, 1997). There are two enclosure methods that are generally used, namely the *dynamic flux chamber* and the *static accumulation chamber*, which are discussed in Sections 4.5.1 and 4.5.2.

4.5.1 The Dynamic Flux Chamber

The principal of this technique is that a known area on the surface of the landfill is covered by a box (or similar), into which a controlled flow of clean, dry sweep air is introduced at a rate significantly exceeding the gaseous release rate from the surface. This sweep air mixes with the landfill gases emanating from the surface and transports these gases through an exit port (Reinhart et al, 1992; Frechen, 1995). Determining the flow rate of gas from the landfill surface involves the combined use of the flux chamber and a gas-sampling probe. A whole landfill gas sample may be taken from the probe, allowing for the direct analysis of methane and other non-methane organic compounds that might have been diluted to below traceable levels by the sweep air. With the values of the sweep air flow rate and composition, as well as the composition of the whole landfill gas sample known, a mass balance can be developed around the chamber to calculate total gas flow rates. Equation 4.1 (Reinhart et al, 1992) illustrates the mass balance, using methane as the gaseous emission of interest.

$$V(dC_e/dt) = Q_iC_i - Q_eC_L + Q_iC_L \qquad \textbf{EQ 4.1}$$

Where:
Q = flow rate (volume/time)
C = methane concentration (vol./vol.)
i, e, L = inlet, exit and landfill respectively
t = time
V = chamber volume

Since the sweep air is high purity zero air, the inlet methane concentration (C_i) is zero. The landfill gas flow rate is also much lower than the inlet gas flow rate, and thus it can be assumed that Q_i is approximately equal to Q_e. The simplified mass balance may then be solved for C_e, yielding Equation 4.2.

$$C_e = (Q_LC_L/Q_i)[1 - \exp(-t/T)] \qquad \textbf{EQ 4.2}$$

Where:
$T = V/Q_i$ (chamber residence time)

The inlet flow rate and chamber residence time is fixed for given operating conditions and chamber configurations, while the time and exit concentrations are measured during a sampling event. The concentration of methane in the landfill is known (determined from samples taken from the shallow probe). Equation 4.2 may then be solved for the flow rate from the landfill surface, Q_L.

Reinhart et al (1992) tested this dynamic flux chamber method in order to validate on-site measurements. The testing procedure included the use of a ‘test bed’, which yields a known flux of gas through an artificially created landfill surface. Tests were conducted to evaluate mixing efficiencies and optimum operating parameters (sweep air flow rate and velocity, chamber soil penetration, chamber pressure, wind speed). The result of the laboratory testing showed that accurate measurement of surface emissions can be achieved provided that soil disturbance is avoided. Optimum operating parameters were also determined, however they are related to a particular chamber design and should be determined for different designs.

4.5.2 Static Accumulation Chamber

The static accumulation chamber is similar in design to the dynamic flux chamber, however instead of using sweep air to determine surface emissions; the net uptake of a given gas through the area covered by the chamber is measured as a concentration change of the given gas against time. The assumption for this method of analysis is that, for each measurement series, the increase in concentration of a given gas in the chamber's atmosphere is linearly proportional to the gas emission flux across the surface as shown in Equation 4.3 (Morris, 1999).

$$\phi = \frac{V_c}{A_c} \cdot \frac{dC}{dt} \cdot \frac{P.MW}{R.T} \qquad \textbf{EQ 4.3}$$

Where:

ϕ = the gas emission flux ($g.min^{-1}.m^{-2}$)
V_c = volume of chamber (m^3)
A_c = area of soil surface enclosed by chamber (m^2)
DC/dt = time rate of change of gas concentration in V_c ($ml.l^{-1}.min^{-1}$)
P = atmospheric pressure (atm)
MW = Molecular weight of gas of interest (g)
R = universal gas constant ($0.082.l.atm.mol^{-1}.K^{-1}$)
T = internal chamber temperature (K)

Static accumulation chambers are placed on the capped area of the landfill, sealed to the ground surface, and concentrations of methane (and/or carbon dioxide) within the box are measured over short time intervals for a period up to two hours (termed a sampling run) (Attenborough et al, 1997). The data is then processed to produce a graph of concentration versus time. The best-fit slope of the graph represents the methane flux for the area covered by the box (Morris, 1999;

Attenborough, 1997). A correlation coefficient (R^2) is usually given for the best-fit line, with acceptance of the data dependant on this value. Generally, data that has a correlation coefficient less than 0.8 is not accepted (Attenborough, 1997)

Morris (1999) validated the static accumulation chamber method using a test bed (as in section 4.5.1). The results of the laboratory validation indicated that this method produces reasonable results provided that sampling runs are kept sufficiently long. Attenborough (1997) tested the reproducibility of the method, with results indicating that the method is reproducible within the bounds of reasonable error.

4.6 INSTRUMENTATION

There are a number of techniques available for detecting and quantifying landfill gas, with both portable and laboratory based instruments able to measure gas composition, concentration of major and minor gas constituents, pressure, temperature, flow and/or velocity, moisture content and calorific value. The choice of parameters and instruments will depend on the purpose and circumstances of the monitoring.

Routine monitoring at most landfill sites requires that the concentrations of methane, carbon dioxide and oxygen are regularly determined. Infra-red, catalytic oxidation (pellistor), thermal conductivity, flame ionisation, semi-conductor, paramagnetic and electrochemical gas detectors can be used (IWM, 1998). The most reliable results may be obtained from properly designed infra-red absorption based instruments. Where more detailed information on the composition of landfill gas is required, instruments equipped with flame ionisation detectors and/or photo ionisation sensors can be used. These sensors can detect the majority of organic materials, and are highly sensitive, operating typically in the 1 – 1000 parts per million (by volume) range.

Monitoring of landfill gas often requires detailed analysis of gas samples in order to identify and quantify individual components. In particular, this is applicable to ambient air-quality monitoring where identification of possible toxic trace elements is required. Gas Chromatography (GC) is a technique for the identification and quantification of individual components in a landfill gas sample (IWM, 1998). This technique involves injecting a gas sample into a gas stream (termed a carrier gas, which is usually helium or nitrogen). The separation of the individual compounds occurs because each compound has a different affinity for the material packed into a column (stationary phase) and the carrier gas (IWM, 1998; Gendebien et al, 1992). Each component will leave the column at a specific time (retention time) and this time will be a constant for a given set of conditions (carrier gas and flow, temperature, type of column etc.) (IWM, 1998). As each compound leaves the column it passes through a detector, with the detector response related to the concentration of the compound. The detector response can be compared to known concentration standards and hence the concentration of the individual compounds can be determined. The Gas Chromatograph is in most cases a laboratory instrument because of the need for a continuous gas supply and clean and stabilised operating conditions. The gas samples collected on site therefore have to be transported to the laboratory in sealed containers. The most common containers include vinyl, Teflon, rubber and Tedlar bags, glass vials and stainless steel tubes.

Landfill gas flows may be measured using instruments that read differential pressures (orifice plate, Pitot tube), vortex shedding devices, positive displacement meters, mass flow transducers and vane and hot-wire anemometers. Hand-held or fixed manometers can be used to measure gas pressures. The approximate calorific value of landfill gas may be measured indirectly through the methane content or directly by a calorimeter. Moisture content can be measured by a hygrometer or by passing a known volume of gas through a known amount of dessicant and calculating moisture content from the difference in mass of the dessicant before and after this process (IWM, 1998).

4.7 LANDFILL GAS CONTROL AND EXTRACTION

The migration of landfill gas into the surrounding environment through the surface of the landfill and adjacent gas permeable pathways is the factor most in need of control. The gas control systems commonly used to prevent this migration include impervious barriers, passive venting and active gas pumping. The majority of newly engineered landfills have barrier systems installed to prevent leachate migration into the environment, thereby ensuring that gaseous emissions are also contained. Passive venting techniques consist of simple venting trenches backfilled with coarse material to create a zone of relatively high gas permeability to be preferentially used by the gas (Gendebien et al, 1992).

Commonly, vent trenches are sealed in a row and the gas is collected with a series of vent stacks. The use of venting trenches is generally limited to relatively shallow landfills however.

The active pumping of gas from the landfill is a more sophisticated, but more efficient, system of controlling gas. These systems involve the extraction of gas from the waste body under a slight vacuum by use of a pumping station containing an extraction unit. Gas control systems are a requirement in South Africa in areas where high gas generation rates may pose an environmental risk. The development of attenuation landfills in South Africa before the enforced legislative requirements has resulted in very few landfills having barrier systems to prevent off-site migration of landfill gas, and highlighted the need for active gas extraction as the only feasible method to control emissions. In addition to preventing gas migration, active gas extraction via vertically driven wells in the waste body facilitates the collection of leachate, which would have otherwise migrated into the surrounding environment. The active extraction of gas from the waste body is discussed further in section 4.7.1 below.

4.7.1 Active Gas Extraction

The most common form of gas extraction is via vertical extraction wells. The wells are typically 90 – 150 mm diameter high-density polyethylene (HDPE) pipes, although other materials such as polyvinylchloride (PVC), polyethylene (PE) and fiber-reinforced plastic are sometimes used. In order to place the extraction pipes into the waste body (or surrounding strata), a hole is formed in the waste by drilling. There are a number of different drilling techniques, which vary according to the type of drill-bit used. In general, the drill is mounted on a motor truck which incorporates the drilling platform, heavy duty hydraulic jacks and a diesel driven hydraulic pump (Gendebien et al, 1992). This drill rig can accommodate several drill bits, which may include telescopic spindles, hollow bore augers, reverse circulation and conventional circulation drills and down the hole hammers (Gendebien, et al, 1992). Depending on the system used, drill rigs can form holes of diameters ranging from 200 to 1200 mm in diameter, with depths ranging from 12 to 460 metres (Gendebien et al, 1992). Plate 4.1 shows a typical drilling rig and auger drill bit. This drilling technique was used in a gas extraction project recently undertaken at the Mariannhill Landfill Site in Kwa-Zulu Natal, South Africa.

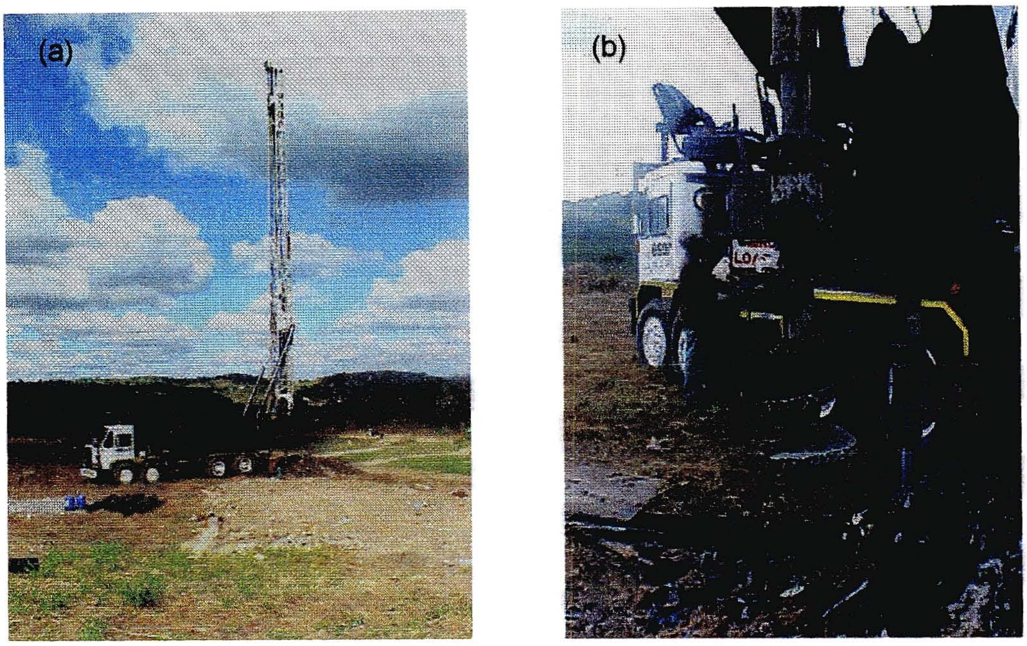


Plate 4.1 Typical drilling rig (a) and an auger drill bit (b)

The diameter and depth of the drilled hole depends on the purpose of the extraction well. Where gas extraction is required to prevent off-site migration, wells are located on the perimeter of the site (termed 'curtain' wells), with local geology dictating the required depths. The depth of extraction wells placed in the waste body for either exploitation or flaring are usually between 50% and 90% of the refuse depth.

The typical landfill gas extraction well consists of a pipe perforated/slotted (between 10 and 20 % of the pipe area) in its lower part, which is placed in the drilled hole, backfilled with gravel and sealed off against the inflow of atmospheric air around the upper, non-perforated part of the pipe (Gendebien et al, 1992; Lombard et al, 1998). The diameters of the boreholes are typically between 250 and 300 mm. The slotted pipe diameters are typically between 125 and 150 mm (Couth, 2001). The wells are fitted with telescopic parts and slip joints where large settlements are expected. Each slotted pipe has a well head that is connected to the gas collection header (extraction pipework) (Gendebien et al, 1992). The well head is fitted with a valve, which is used to control the vacuum and throttle the well output. The well head also has fittings for flow measurement and gas sampling. Figure 4.4 shows a typical well design.

As is shown in Figure 4.4, gas well designs often incorporate a leachate extraction system. Leachate level control is vital for the efficiency of a gas abstraction system, and is usually controlled in the form of pneumatic ejector pumps, shaft driven sump pumps, submersible electric pumps or eductor pumps (Leach, 1996).

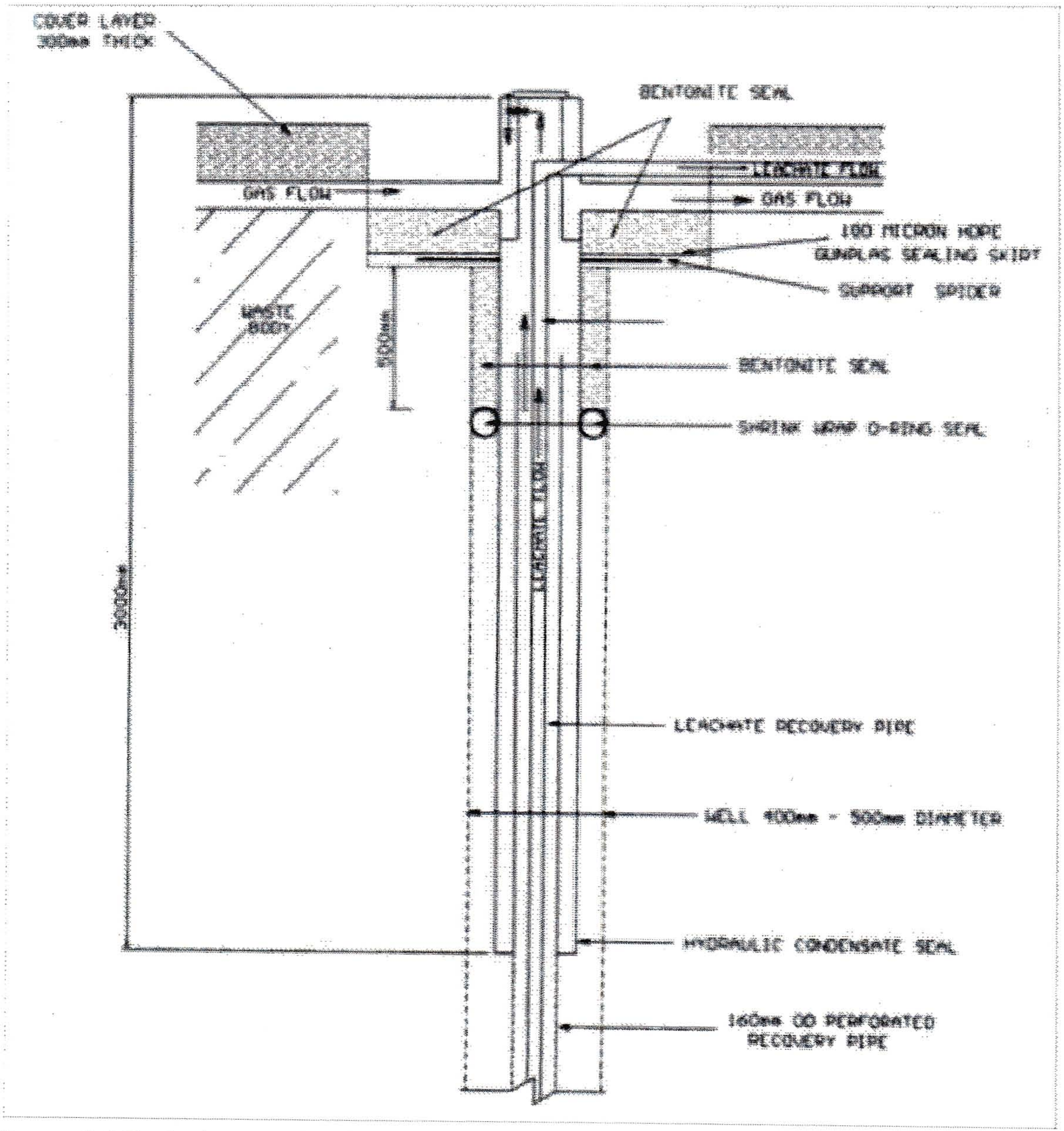


Figure 4.4 Typical gas extraction well design (Bowers, 2001)

The radius of influence of the wells, which refers to that portion of the landfill where a pressure reduction is induced by pumping from the extraction well is dependant on a number of factors (Gendebien et al, 1992). The most notable factors being the depth of the waste, surface seal and gas extraction pressure (Couth, 2001). The spacing of the wells depends on their function, with perimeter wells (used to control gas migration) being more closely placed than central wells. Research has shown a radius of influence of central wells from 25m to 45m (40 to 90 m well spacing) (Lofy, 1996a; Lofy 1996b; Fernandez, 1995; Leach, 1996). Central wells in the United Kingdom are typically spaced at 50m (Couth, 2001)

The extent of the vacuum at the extraction wellhead can vary according to the desired quantity and quality of landfill gas and to different site-specific situations (Cossu et al, 1996a). These are related to such factors as the height of the abstraction well, the characteristics of daily cover, the in-situ waste quality and the top cover design (Cossu et al, 1996a). A low permeability top cover design means that higher suction pressures can be applied to the wellheads, while poor top cover designs (high permeability) may lead to air ingress into the fill, resulting in poorer quality gas and inhibition of the anaerobic ecosystem. The pressures at the well head are maintained in the 5 to 40 mbar range, depending on the factors previously discussed (Couth, 2001; Cossu et al, 1996a). The vacuum necessary for gas extraction and transportation is created by means of a blower. The types of blowers specifically used in the landfill context include radial, rotary and lateral canal blowers (Cossu et al, 1996a).

The extraction pipework (also known as gas collection headers) used to transport the gas collected from the vertical wells to a landfill gas utilisation plant are generally HDPE pipes placed either above or below the landfill surface. The extraction pipes are designed to reduce pressure losses and differences in suction pressure between wells (Couth, 2001). The landfill gas abstracted from the landfill is usually water saturated, as temperatures are lower at the landfill surface than within the landfill themselves (causing water vapour in the gas to condense in the gas collection headers) (Gendebien et al, 1992). The extraction pipe therefore has to be designed with a slope (between 1:50 and 1:20) to allow condensate to flow either back into the vertical wells or into condensate traps placed at low points in the extraction pipework. The extraction pipework should also allow for differential movement of the wells (due to settlement effects). Extraction pipes are sized on the basis of the specific flow rate and permissible pressure losses in the extraction pipeline. The gas flow and friction losses in pipes are modeled using the Darcy formula (Couth, 2001). Gas extraction pipework in practice is usually designed one size greater than the theoretical diameter, to allow for condensate movement (Couth, 2001).

There are several options for the treatment and/or exploitation of landfill gas once it has been collected. These include (Gendebien et al, 1992):

- Venting (no recovery, potential odour and explosion hazards, greenhouse effect)
- Flaring (no recovery, less potential odour and explosion hazards)
- Direct burning (heat production)
- Engine fuel (mechanical or electrical power with or without heat recovery)
- Turbine fuel (electrical power with or without heat recovery)
- Vehicle fuel (mechanical power)
- Injection to the natural gas grid
- Production of chemicals

Landfill gas collected from South African landfills is generally flared, as the cost of upgrading the gas to produce fuel or natural gas is not feasible in most cases. It has been shown that landfill gas collection systems can be 70% effective in the collection of landfill gas, however it still leaves 30% of landfill gas that may be emitted to the atmosphere (Couth, 2001).

4.8 MODELLING LANDFILL GAS PRODUCTION

The development of landfill gas (LFG) models that are able to predict the yield and production rate of biogas generated is necessary in terms of evaluating potential gas migration and related problems and for the installation of a gas management system. Landfill gas models are classified according to the availability of data and the state of knowledge of the system (Cossu et al, 1996b). Theoretically, a complete biogas model should include three sub-models (Cossu et al, 1996b):

- Stoichiometric submodel – This gives the maximum theoretical yield of biogas from the anaerobic degradation of the organic waste fraction. Some models proposed in the literature are simply stoichiometric and only provide information on LFG yields.
- Kinetic submodel – This is a dynamic model, which predicts the temporal evolution of LFG generation rates. It can be either an empirical model, based on a more or less simple equation of a defined order; or a deterministic model, based on a set of equations describing the degradation of the different biodegradable MSW fractions; or an ecological model, which describes the dynamic of microbial populations and substrate in the landfill.
- Diffusion submodel – This is a dynamic model, which describes the time and place variation of pressure and gas composition within the landfill body. LFG emission rates can be obtained, and the effectiveness of the gas extraction system can be verified.

This thesis is focused on generation models, and hence only aspects relating to stoichiometry and kinetics of LFG will be described further.

4.8.1 Estimation of Landfill Gas Yields

The total amount of gas produced is often calculated from measured or estimated refuse analyses. The carbon content of the waste is generally used (Ehrig, 1996). The total gas production rate can be calculated directly from Equation 4.4 below, under the assumption that the carbon is totally biologically converted into biogas (CH_4 and CO_2) (Cossu et al, 1996b; Ehrig, 1996):

$$G_e = 1.868.C\ (CH_4 + CO_2) \qquad \textbf{EQ 4.4}$$

Where: G_e = total gas production (m^3 (STP)/ton_{MSW})
C = carbon content

The value 1.868 is a conversion factor from solid carbon to gaseous carbon and STP is standard temperature and pressure. The relationship between methane and carbon dioxide depends on the composition of the degraded organics (Ehrig, 1996). For this reason, in practical calculation, the evaluation of the maximum theoretical LFG yield is often carried out using Equation 4.4, and assuming a predefined ratio of $CH_4/CO_2 = 0.55 - 0.6$ (Cossu et al, 1996b).

Equation 4.4 simplifies the gas yield somewhat, in that it is based on the amount of organic matter in the waste without considering its effective biodegradability (Cossu et al, 1996b). Pfeffer (1974) and Andreottola and Cossu (1988) suggest that the organic carbon is roughly 50% on a dry basis of MSW organic matter, and only 50% of this amount is biodegradable (Cossu et al, 1996b). Other authors (e.g. Tchobanoglous et al, 1993; Hoeks, 1983) have also estimated the amount of organic carbon, suggesting values of 200–250 kg/ton$_{MSW}$. Andreottola and Cossu (1988) provided a formula to evaluate the total biodegradable organic carbon present in a mass of waste by accounting for separate organic components (e.g. food waste, yard waste wood). Each waste component and its related biodegradable fraction of organic carbon are summed to yield the total biodegradable organic carbon. The moisture content (which affects biodegradability) of each component is also taken into account in the expression. Tabasaran (1982) suggested that the fraction of biodegradable carbon that may be converted to landfill gas depends on the temperature in the landfill, and provided a formula to correct for temperature effects. The temperature, however, primarily affects generation rates, which are strictly associated with the biological activity within the landfill (Cossu et al, 1996b). Equation 4.5 below provides the LFG specific yield, and is an expression that represents the common theoretical basis for the majority of LFG generation models (Cossu et al, 1996b).

$$Y_{LFG} = \sum_{i=1}^{n} 1.867\, OC_i\, (fb)_i . (1 - u_i) . p_i \qquad \textbf{EQ 4.5}$$

Where: Y_{LFG} = yield of landfill gas (litres gas/kg MSW)

OC_i = biodegradable organic carbon in the dry *i* th component of waste (kg biodegradable carbon/kg wet MWS)

$(f_b)_i$ = biodegradable fraction of OC_i (kg biodegradable carbon/kg carbon)

u_i = moisture content of the *i*th component of waste (kg H_20/kg wet *i* component)

p_i = wet weight of the *i*th component of waste (kg *i* component/kg MSW)

Although Equation 4.5 provides a theoretical LFG yield, it is often difficult to determine actual values for the input parameters. Several authors (Cossu et al; 1996; Tchobanoglous et al, 1993; Andreottola and Cossu, 1988) have determined typical values for these parameters, allowing the model user to predict approximate gas yields.

4.8.2 Landfill Gas Generation Rates

In modelling biogas production, it is as important to determine the rate and duration of the gas production, as it is to determine the maximum yield. The general equation that rules biogas production is given by Equation 4.6 (Cossu et al, 1996):

$$\frac{dC}{dt} = f\left(t, C^n\right) \qquad \textbf{Eq. 4.6}$$

Where: C = amount of methane or biodegradable organics
t = time

Equation 4.6 can express either the rate of substrate degradation or the rate of gas production. The greatest absolute value exponent *n* of the independent variable in Equation 4.6 is called the order of the model (Cossu et al, 1996). Zero order models imply that the methane generation rate is independent of the amount of substrate remaining or the amount of gas produced. The majority of LFG production models follow first order kinetics, which means that the limiting factor is the remaining amount of substrate or the amount of biogas already produced (Cossu et al, 1996). It is known that many factors (e.g. moisture and nutrient availability, temperature) affect the generation of biogas, however the use of a first order kinetic model with respect to substrate is most common.

Each waste component has a different rate of producing gas from its fraction of biodegradable carbon, and therefore it is common in first order models to incorporate two or three substrate classes distinguished by different decay rate constants, in what are termed multi-phase models. The classes may include –

waste components that are slowly and readily biodegradable; and waste components that are slowly, moderately and highly biodegradable carbon. The readily biodegradable class is represented by food wastes, the moderately biodegradable class by yard waste, and the slowly biodegradable class by paper, cardboard, wood and textiles (Cossu et al, 1996).

A comparison of existing models to observed landfill gas yields by Coops et al (1995) has shown that there is very little difference in the mean relative errors between first order, multi–phase first order and second order models. Table 4.5 lists the mean relative errors associated with each type of model.

Table 4.5 Mean relative errors of landfill gas models (adapted from Coops et al, 1995)

Model	Mean Relative Error (%)
Zero-order	44
First-order	22
Multi-phase	18
Second Order	22

The time span over which gaseous emissions are released is another important result from gas models. Information concerning generation time may be satisfactorily provided by the half time ($t_{1/2}$), the time over which the gas generation equals half of the estimated yield (Cossu et al, 1996). Several authors have given average generation times (Bridgewater and Lidgren, 1981; Ham and Barlatz, 1989; Richards, 1989) and average half times (Augenstein and Pacey, 1991).

As suggested in section 4.8.1, the accuracy of LFG generation models is often dictated by the accuracy of the input parameters. The difficulty in determining these input values coupled with the fact that assumed values are not always relevant to a specific site often means that results obtained from LFG models are estimates.

CHAPTER 5
EXPERIMENTAL WORK

5.1 INTRODUCTION

The characterisation of landfill emissions involved experimental work both in the field and in the laboratory. The field work for this dissertation was conducted at the Mariannhill and Bisasar Road Landfill Sites in the Durban Unicity, which is situated on the east coast of South Africa (Figure 5.1). The boundaries of this region were established in 1996, and resulted in the Ethekweni Municipality (previously Durban City Council) acquiring responsibility for waste disposal operations in the new area (Strachan et al, 1999). Three engineered general waste landfill sites currently operate under the waste disposal unit of the Ethekweni Municipality, Durban Solid Waste (DSW) - the Bisasar Road Landfill Site, the Mariannhill Site Landfill and the La Mercy Landfill Site. Figure 5.2 shows the DMA region and the location of the various landfills.

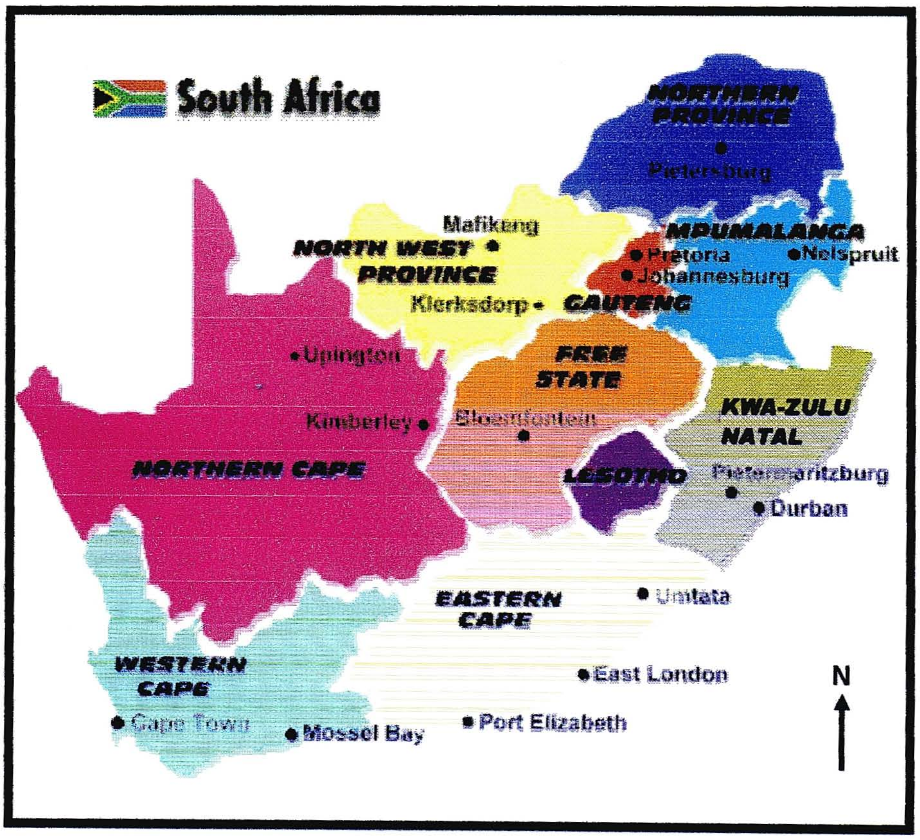


Figure 5.1 Map of South Africa, showing the location of Kwa-Zulu Natal (Mercer C, 1997)

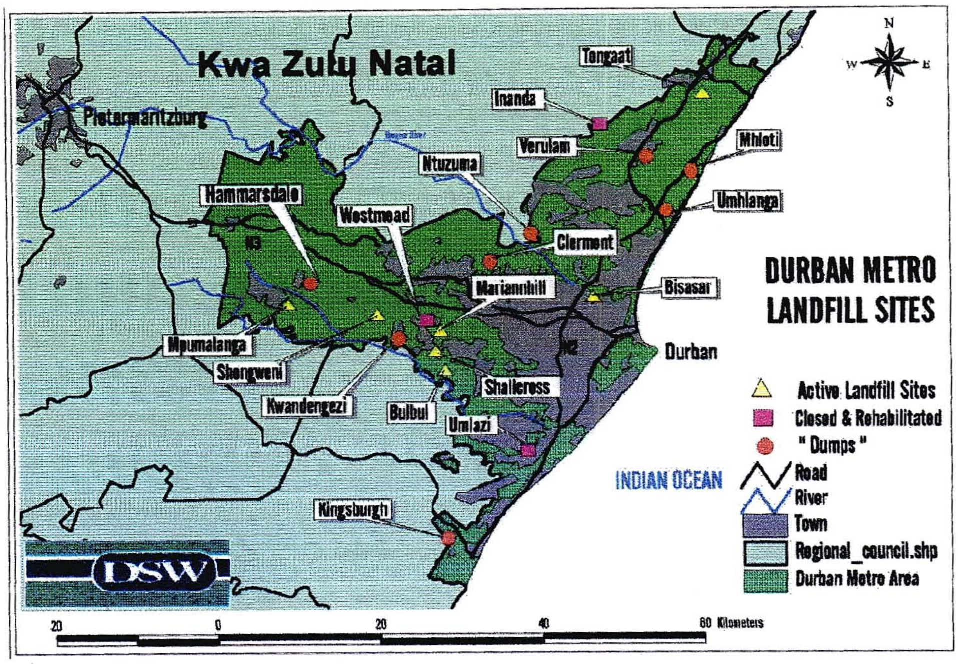


Figure 5.2 Map of the DMA showing the location of the various landfills (Courtesy DSW)

5.2 OVERVIEW OF THE RESEARCH

Figure 5.3 presents an overview of the work conducted for this research. Landfill emissions were characterised at the Bisasar Road and Mariannhill landfill Sites. The initial stages of the research included a comprehensive desktop study of the two sites. The study focused on landfill management techniques, landfill and waste characteristics, incoming waste volumes, waste composition, and historic data on leachate and landfill gas emissions. Following the study, experimental work in the field was undertaken, focusing on the characterisation of leachate and landfill gas.

Leachate samples were regularly collected from a lined landfill cell at the Bisasar Road landfill (Randles Cell) and two lined cells at the Mariannhill Landfill (Cell 1 and Cell 2). The samples were analysed for typical physical and chemical constituents found in leachates. Landfill gas emissions were monitored by means of shallow probes placed in various areas of the Bisasar Road landfill site and in Cell 1 and Cell 3 at the Mariannhill landfill site. Gas emissions at the Mariannhill landfill site could also be monitored via gas extraction wells placed in Cells 1 and 2. A validation of a method for measuring surface emissions was also investigated.

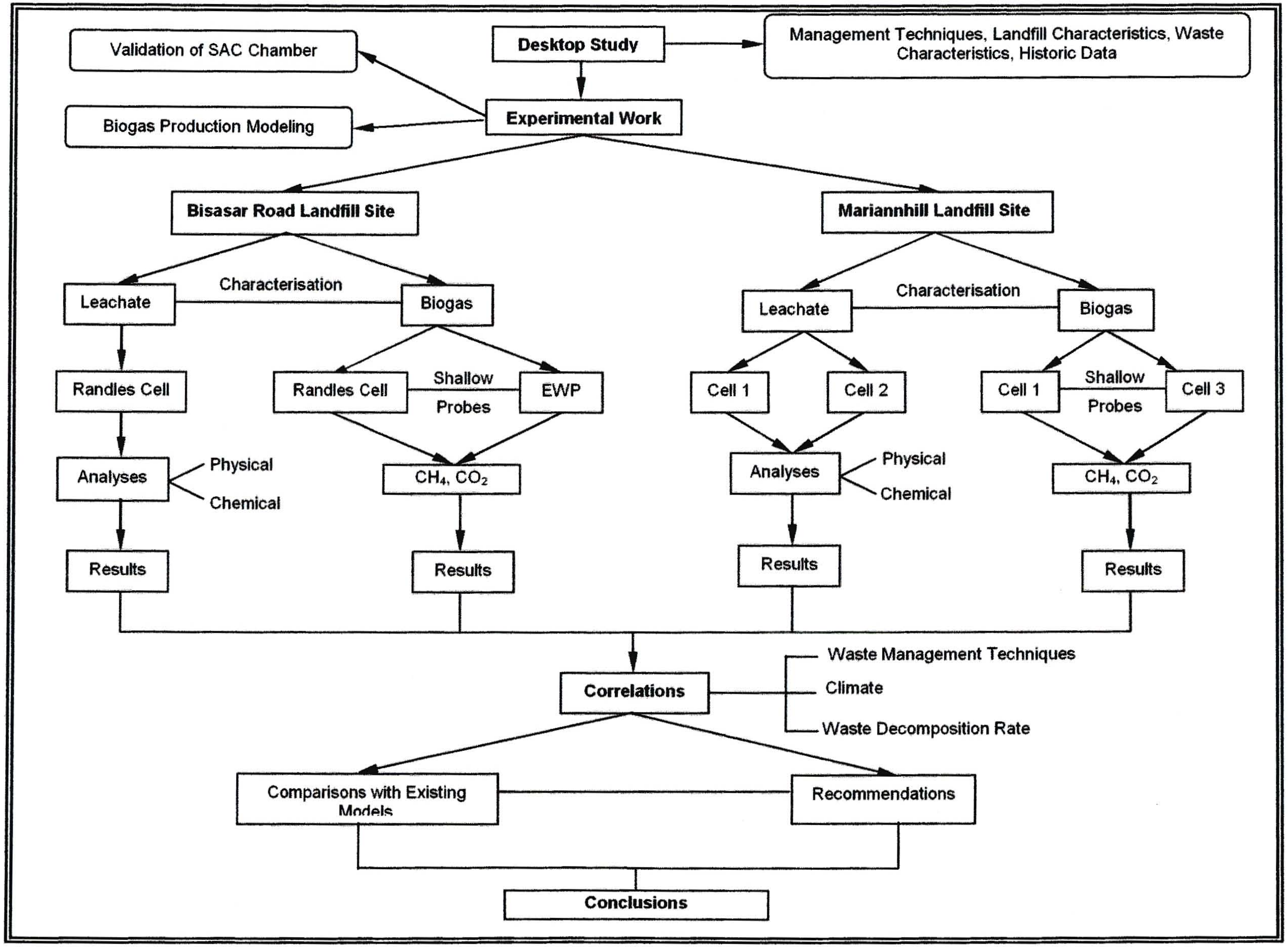


Figure 5.3 Overview of the research

Two landfill gas prediction models, the Physical-Chemical/Biochemical model (Muntoni et al, 1995; Cossu et al, 1996) and the LandGEM computer model (EPA, 1997) were comprehensively studied. They were both applied to Cells 1 and 2 to predict the approximate rate and volume of gas. Comparisons were then made between the results of the two models and literature. Comparisons were also made between the models predictions and the actual volume of gas being extracted from the two cells. The Physical-Chemical/Biochemical model is available in a mathematical format. In order to provide an 'easy to use' tool for estimating gas emissions, the model was programmed in Microsoft Excel^{TM}.

From the results of the emissions characterisation and the modeled biogas emissions, correlations were made with respect to climatic conditions, waste degradation rates and waste management techniques. Conclusions could then be drawn regarding the rate of waste decomposition and landfilling techniques, in particular with respect to the effectiveness of cellular landfill management.

5.3 THE BISASAR ROAD LANDFILL SITE

The Bisasar Road landfill site was originally established in May 1980, approximately eight kilometres north of the Durban central business district (CBD). It is currently one of the busiest sites in the country, receiving an average of 3000 tons of solid waste per day (Strachan, 2000). The landfill has a total capacity of approximately 21 million cubic metres, and has a remaining airspace capacity of approximately twelve million cubic metres. It is expected to serve the DMA for a further eighteen years.

The site consists of an unlined waste body over which a newly engineered landfill is being developed. The implementation of the Minimum Requirements (DWAF, 1998) highlighted the need for containment and treatment of landfill emissions. The site has been developed both as an attenuation landfill in areas where the waste body has not been sealed off from the environment, and as a containment landfill where fresh waste is to be deposited on virgin soils. At present, the site has three distinct areas that have been given the names the "Randles Cell", "Existing Waste Plateau (EWP)" and "Old Existing Waste (OEW)". Plate 5.1 is an aerial view of the Bisasar Road Landfill Site, showing these three areas.

Plate 5.1 Aerial view of the Bisasar Road Landfill Site

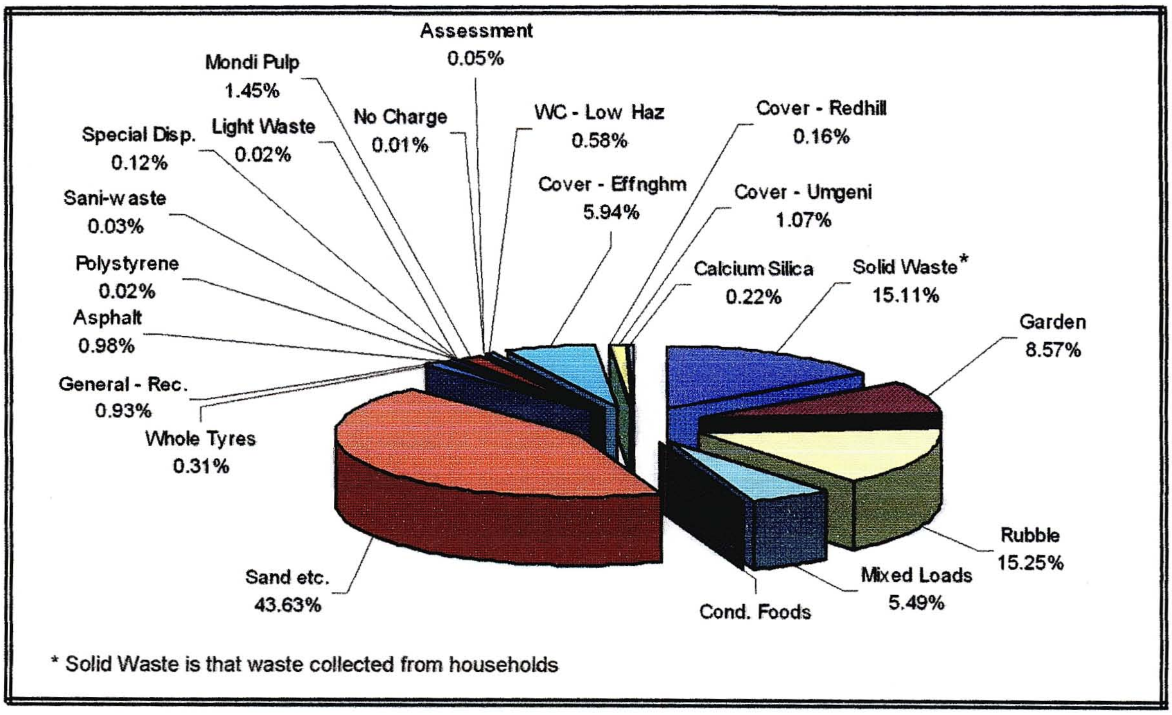
The Randles Cell is a newly constructed containment landfill opened in January 1999 (discussed further in section 5.2.1). The EWP is a central, unlined waste body that has been built up to a plateau, resulting in the creation of two new valleys, which now flank the plateau. The OEW is the oldest area of the site, consisting of waste approximately 10 – 20 years old. This area is unlined and is equipped with a gas extraction system. Leachate is extracted through eductor systems in the gas wells, and through deep-seated cut-off drains immediately down slope of the site (Strachan, 2000).

The Bisasar Road landfill is a GLB^{+} site (a large landfill in a water surplus area that accepts general waste), receiving Municipal Solid Waste (MSW) from Durban and surrounding areas. A detailed breakdown of the typical waste stream received at the landfill site is given in Figure 5.4. Weighbridge tonnages for each fraction were averaged over a seven-year period and converted to their relative percentages. Landfill management strategies include the compaction of fresh waste via landfill compactors, separate dumping of construction and biodegradable wastes and the covering of fresh waste at the end of each day with sand or a suitably inert material such as paper pulp. The layer of cover varies between 100 and 150 mm. A waste compaction ranging between 1.0 and 1.4 tons/m^3 is achieved (Strachan, 2002).

The site produces approximately 200 000 litres of leachate per day, which is discharged to sewer.

5.3.1 The Randles Cell

The Randles cell is a fully lined containment landfill. It covers an area of approximately 36000 m^2 and is located in the south east of the landfill site. The cell is situated in a valley between virgin soil slopes and the EWP. The cell was originally lined along the base and part of the way up the virgin slopes. A subsequent extension to the lining system has meant that the entire virgin slope and the side slope of the EWP will be sealed off from the waste in the cell. Plate 5.2 shows the Randles cell viewed from the east during the first stage construction



* Solid Waste is that waste collected from households

Figure 5.4 Percentage breakdown of the typical waste stream entering the Bisasar Road Landfill Site (average from 1994 - 2001) (Weighbridge data courtesy DSW).

of the liner.

The Randles Cell lining system comprises (from top layer to bottom layer):

- 37.5 to 50 mm crushed stone leachate collection and drainage layer
- Cement stabilised sand protection layers
- 100 KN/m^2 Geogrid placed on slopes only
- 300 g/ m^2 non-woven protection geofabric
- 2 mm HDPE (High Density Polyethylene) geomembrane layer
- Cement stabilised sand protection layers
- Liner formation layer consisting of compacted in-situ material

The leachate produced drains down towards the northern part of the cell where it is discharged into a leachate sump, and then flows into the sewer line.

The cell began receiving waste in January 1999. Waste was placed for approximately eight months, after which landfill operations moved to another area of the site. Landfilling operations in the cell recommenced in February 2000, and at present the cell remains in operation. It receives all wastes except construction waste.

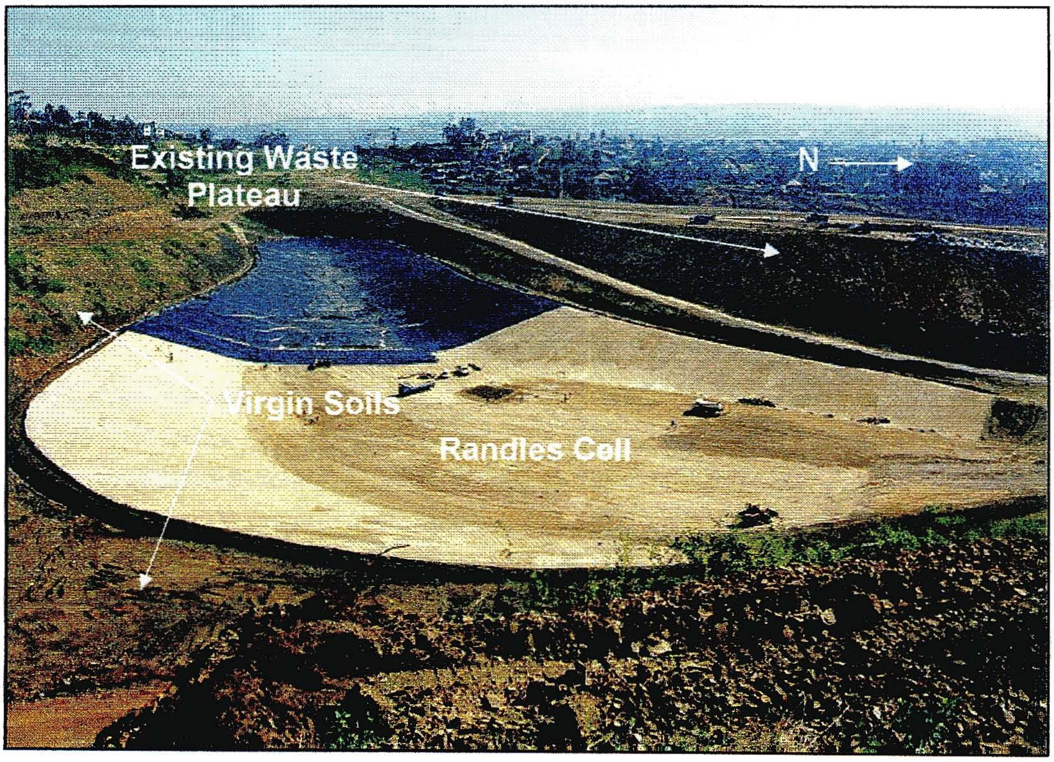


Plate 5.2 The Randles Cell

5.4 THE MARIANNHILL LANDFILL SITE

The Mariannhill landfill Site is situated approximately twenty-five kilometers west of Durban City, and is a typical 'new-generation' GLB$^+$ landfill. The site was opened in July 1997 and receives approximately 400 tons of solid waste per day. The landfill was arguably located to textbook standards being well-screened from the public eye by the natural topography, and the established growth of numerous large trees in the peripheral buffer zone (Strachan et al, 1999). The site serves the disposal requirements of the Inner West City Council (IWCC), and is expected to be in operation for another 16 years.

The Mariannhill Landfill has been developed as a series of small containment cells within the overall landfill footprint. The first cell (Cell 1) was opened in July 1997, reaching completion in March 1999. The second cell (Cell 2) was subsequently opened, reaching completion in December 2000. The third cell (Cell 3) was opened and is currently in operation. The construction of a fourth cell has also begun. The site is not ideally suited in terms of the availability of cover material as it is bounded by steep side slopes and with shallow colluvial soils overlying hard rock sandstone of the Natal Group (Strachan, 2000). The design of the lining system for the three cells has been the same. The location of the site on a sandstone geological formation has necessitated a more stringent liner system, similar to that required for a hazardous waste site (type H:h). The liner system consists both of a flexible membrane liner and of natural clay. The various layers of the liner are (from top to bottom):

- 37.5 to 50 mm crushed stone leachate collection and drainage layer
- Cement stabilised sand protection layers
- FPP (Flexible Polypropylene) geomembrane layer
- Primary clay liner
- Leachate detection layer consisting of 37 to 50 mm crushed stone
- Secondary clay liner
- Compacted in-situ soil.

The three cells have separate leachate collection systems, allowing each leachate to drain to a sump down slope of the landfill. The combined leachate from the three cells overflows from the sump into a collection tank, which then discharges to the sewer line.

Approximately 15 000 litres per day is currently being discharged. Plate 5.3 is an aerial view of the Mariannhill Landfill Site showing the location of the three cells.

The site receives all MSW, and the fresh waste is covered daily with sand, either excavated from areas around the site or brought in as waste. The layer of cover varies between 100 and 150 mm. Landfill management techniques are the same as at the Bisasar Road Landfill Site. The waste is compacted to a density of 1.0 – 1.4 tons/m^3 (Strachan, 2002). A breakdown of the typical waste stream entering the Mariannhill Landfill Site is shown in Figure 5.5. The weighbridge tonnages from the opening of the site to December 2000 were used to determine the waste composition, as described in Section 5.3.

Plate 5.3 Aerial view of the Mariannhill Landfill Site, showing the location of the three cells (Courtesy DSW)

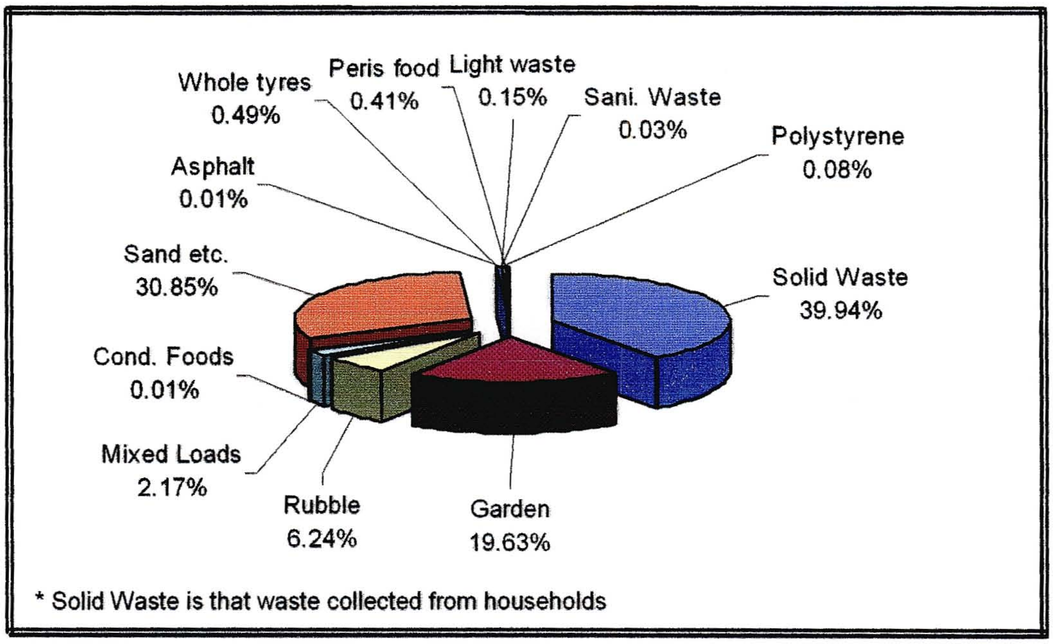


Figure 5.5 Percentage breakdown of the typical waste stream entering the Mariannhill Landfill Site (average from July 1997 – December 1999) (Weighbridge data courtesy DSW).

5.5 LEACHATE SAMPLING

Leachate was sampled directly from the discharge pipes from the Randles Cell, Cell 1 and Cell 2 that flow into the leachate sumps. The sampling procedure was as follows:

- The grid covering the sump was removed
- A clean, plastic bucket (25 litre capacity) was lowered into the sump just below the discharge pipe and leachate was collected
- The leachate was swirled around in the bucket and returned to the sump
- The bucket, having been rinsed with the leachate to be sampled was again lowered into the sump and leachate collected
- A clean, plastic sampling bottle (1000 ml) was then filled with leachate from the bucket
- The leachate was swirled around in the bottle and returned to the sump
- The bottle was then refilled and excess leachate was returned to the drain
- Leachate samples in the bottles were then taken directly to the laboratory and stored in the fridge at 4°C to prevent the loss of volatile components in the leachate.

Chemical Analyses were initially conducted by the Echalaz & Ozborne (Pty) Ltd. Laboratories (in Durban) and by the Durban Metro Wastewater Services (DMWS), and subsequently at the University of Natal wastewater testing laboratory in the School of Civil Engineering, Surveying and Construction. All leachate samples were tested in accordance with the *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al, 1989).

5.5.1 Randles Cell Sampling

Leachate from the Randles cell was sampled on a weekly basis from February to December 1999. After critically analysing the first eleven months of leachate data, it was evident that there were no large variations in the leachate parameters from week to week. Samples were therefore collected on a two-weekly basis until May 2000. There was a subsequent interruption of three months in the sampling routine until the opening of the wastewater laboratory at the University of Natal in September 2000. The resources available at the wastewater laboratory allowed for more frequent leachate analysis, hence samples were collected on a weekly basis until August 2001.

5.5.2 Mariannhill Cell 1 and Cell 2 Sampling

Strachan (2000) undertook an extensive leachate treatability trial on the Mariannhill Landfill Site leachates. Samples for the trials were taken from the collection tank downstream of the leachate sump (Section 5.4). The samples collected and analysed from October 1998 to April 1999 were from Cell 1. The characterisation of this leachate was necessary for the trial (analyses done by Echalaz & Ozborne Pty (Ltd) and DMWS), and hence a large database on the quality of this particular leachate was available.

In October 2000, the leachate sampling from the Cell 1 and Cell 2 discharge pipes commenced. The samples were collected on a weekly basis until the beginning of August 2001.

5.6 LEACHATE CHARACTERISATION SUITE

The analysis suite to characterise the three leachates was chosen based on typical constituents found in leachates. Table 5.1 reports the suite of analyses.

Table 5.1 General suite of analyses for which the leachate samples were tested

Chemical Oxygen Demand (COD)* (mg/l)	Iron (mg/l)
Biochemical Oxygen Demand (BOD)* (mg/l)	Nickel (mg/l)
Alkalinity (as $CaCO_3$)* (mg/l)	Zinc (mg/l)
Chlorides* (mg/l)	Cadmium (mg/l)
Conductivity (mS/m)	Lead (mg/l)
Ammonia* (mg/l)	Mercury (:/l)
Nitrites (mg/l)	Arsenic (mg/l)
Nitrates (mg/l)	Total Solids* (mg/l)
Tot Kjedahl Nitrogen (mg/l)	Volatile Solids* (mg/l)
Sulphates (mg/l)	Total Suspended Solids* (mg/l)
Ortho-Phosphates (mg/l)	Volatile Suspended Solids* (mg/l)
Sodium (mg/l)	Total Dissolved Solids (mg/l)
Manganese (mg/l)	Volatile Fatty Acids (as Acetic Acid) (mg/l)

* Constituents analysed at the University of Natal laboratory

The testing methods for the analysis of the leachates were standard as found in Clesceri et al (1989). The detailed methods of determining the constituents reported in Table 5.1 are given in Appendix A.

5.7 LANDFILL GAS SAMPLING

An investigation into landfill gas emissions was undertaken at both the Mariannhill and Bisasar Road Landfill Sites. Monitoring structures included shallow probes placed in waste of different ages, and gas extraction wells. Shallow probes were placed in the Randles Cell and the EWP at the Bisasar Road landfill and in Cell 1 and Cell 3 at the Mariannhill landfill. The shallow probes were placed to a depth of two metres in all cells except the Randles Cell, where they were placed to a depth of one metre. The probes were slotted, 20 mm Outer Diameter (OD) PVC pipes fitted with removable end caps to prevent air ingress. Figure 5.6 is a schematic diagram of a typical sampling point. A landfill gas extraction project was undertaken at the Mariannhill landfill site, which provided deeper monitoring structures (extraction wells) (further discussed in Section 5.7.2).

The probes were initially placed at the Bisasar Road Landfill Site using a Dynamic Cone Penetrometer (DCP). It consists of a standard metal rod (20 mm diameter) fitted with a 25 mm driving cone, which is driven into the ground by repeated blows from a drop-hammer. The slotted PVC pipes could then be placed into the formed hole and sealed with clay. This technique was chosen because it is relatively simple and economical, however it proved to be highly affected by the presence of tyres and construction waste. This made the formation of the holes difficult and time consuming. For this reason, a two metre long 'steel nail' with a diameter of 60 mm was constructed. The holes could then be formed by driving the nail into the landfill surface by an on-site excavator. This method proved to be considerably faster and safer.

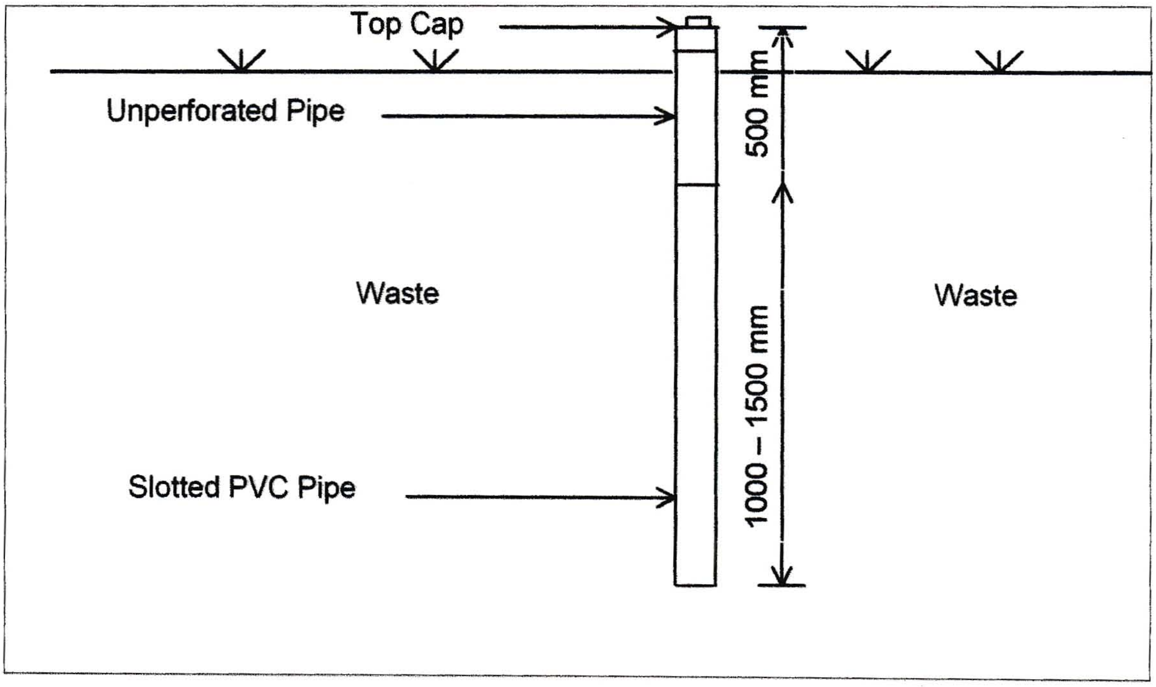


Figure 5.6 Schematic of a typical sampling point

5.7.1 Probe Placements at the Bisasar Road Landfill Site

At the start of the research (In August 1999) (Bowers, 1999), twenty 2 m deep probes were placed in the EWP in a quasi-regular grid pattern. At the time of the probe placements, the uppermost layer of the plateau was approximately one year old. The distances between probes ranged from fifteen to forty metres, in order to uniformly cover the plateau. These probes were sampled twice weekly during September and October 1999.

The placement of the shallow probes in the Randles cell was more difficult, because ongoing landfill operations meant that 'permanent' sampling probes were impossible to set-up. Four probes were initially placed to a depth of 1m at the base of the cell, where the waste was approximately nine months old. A further nine probes were placed in the waste terrace once landfilling operations allowed. The waste in this area was approximately one month old. These probes were sampled on a daily basis for the month of October 1999. Figure 5.7 shows the positions of the probes in the EWP and Randles cell respectively.

5.7.2 Probe placements at the Mariannhill Landfill Site

Twenty-two 2 m deep probes were placed in Cell 1 in April 2000 using the 'steel nail' technique. The probes were placed in a grid-like pattern, with a radius of influence of five metres (approximately ten metres apart). The top of the waste body was approximately one year old. Biogas was initially sampled three times per week, however it became apparent that less frequent sampling would be sufficient, and further sampling was performed on a weekly basis. The probes in the cell were sampled for twelve months. Probes were not placed in Cell 2 due to landfilling operations

A gas extraction system was put in place in Cells 1 and 2 and was in operation in July 2001. The system consisted of six extraction wells (three in Cell 1 and three in Cell 2) and a flare (GEO – FLARE, MODEL GFE – 500) capable of burning between 100 and 500 Normal m^3/hour (Nm^3/hr) of landfill gas. The holes into which the wells were placed were formed by an auger. Each well is made from slotted (10% open area) HDPE pipes and have a diameter of 160 mm. The wells were placed approximately 70 m apart, and the depths of the wells range between 13 and 17 metres. The methane concentrations in the gas wells are sampled on a daily basis by the landfill staff.

The shallow probes in Cell 1 were monitored twice following the installation of the extraction system to establish what effect the extraction system had on the gas composition in the probes.

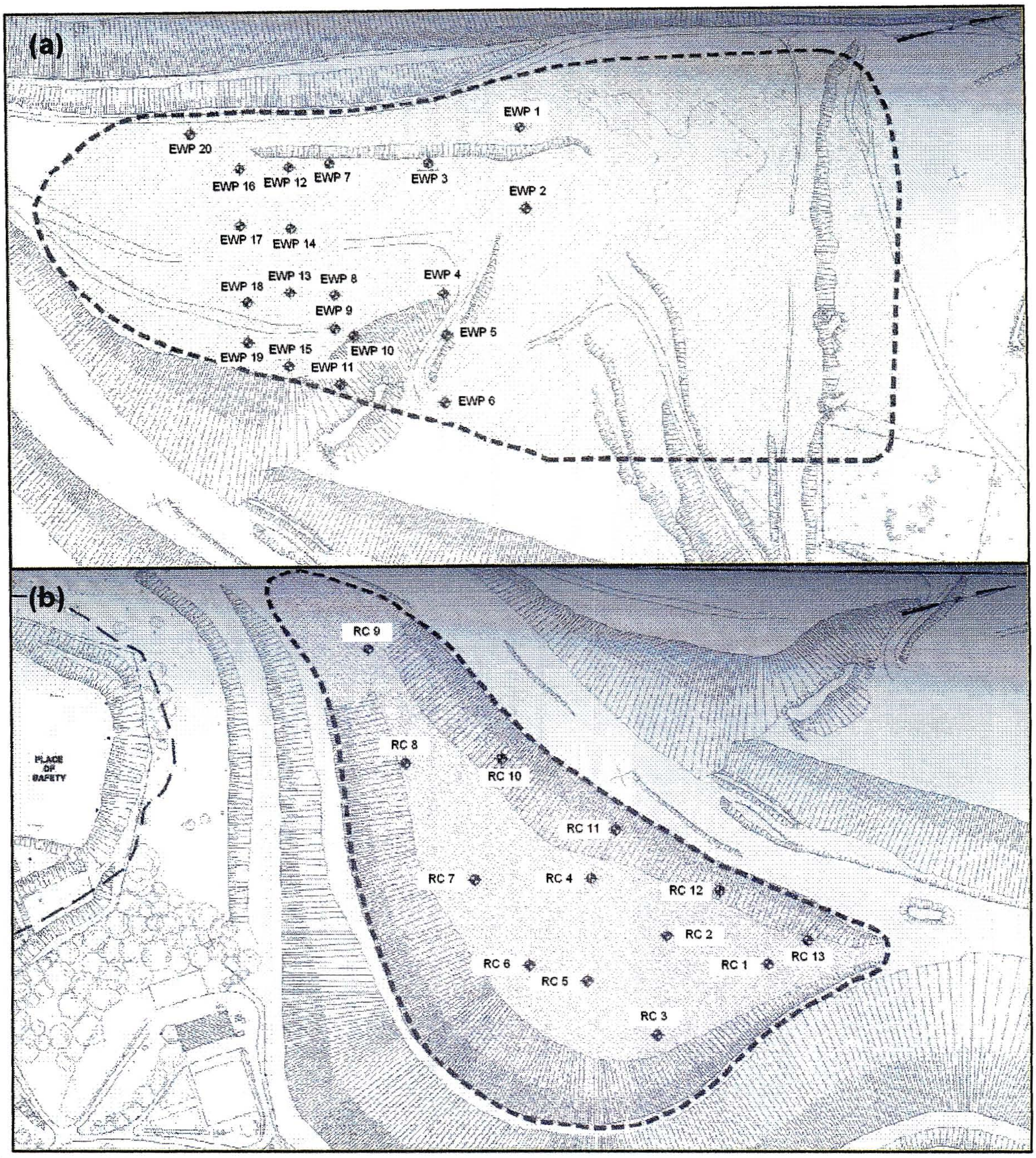


Figure 5.7 Location of the shallow probes in (a) The EWP and (b) The Randles Cell at the Bisasar Road Landfill Site

Ten probes were placed in Cell 3 in September 2001. They were sampled on a weekly basis until November 2001. The waste into which the probes were placed was between four and six months old at the time of the probe placements.

Figure 5.8 illustrates the positions of the shallow probes in Cell 1 and the gas extraction wells in Cells 1 and 2. Figure 5.9 illustrates the positions of the shallow probes in Cell 3.

5.7.3 Determining Landfill Gas Composition

A portable gas analyser (Geotechnical Instruments GA 94) was used to determine the composition of landfill gas in the shallow probes and the gas extraction wells. An integral pump draws landfill gas (biogas) through a rubber-tipped plastic sampling tube and an in-line water trap (fitted with a replaceable filter) into a sample chamber. An infra-red beam is projected, via sapphire windows, through the gas sample. Three detectors sense the beam: one for Methane, one for Carbon Dioxide and one for compensation. A microprocessor calculates the amount of infra-red light absorbed at different wavelengths and determines the various gas concentration levels present. Readings are shown on a liquid crystal display as a percentage of gas concentration by volume - Methane concentrations may also be expressed in terms of a percentage of the lower explosive limit.

The oxygen concentration is measured by the Galvanic Cell Principle. The electrochemical sensors generate an electric current in the presence of a detected gas and can provide fast, stable response signals (IWM, 1998). Plate 5.4 shows the GA 94 and a typical sampling point.

The GA 94 was calibrated regularly (monthly) at the Bisasar Road Landfill site using a gas mixture of methane and carbon dioxide of known concentrations. Geotechnical Instruments UK (Pty) Ltd. serviced the gas analyser during the research period to ensure that it remained in good working condition.

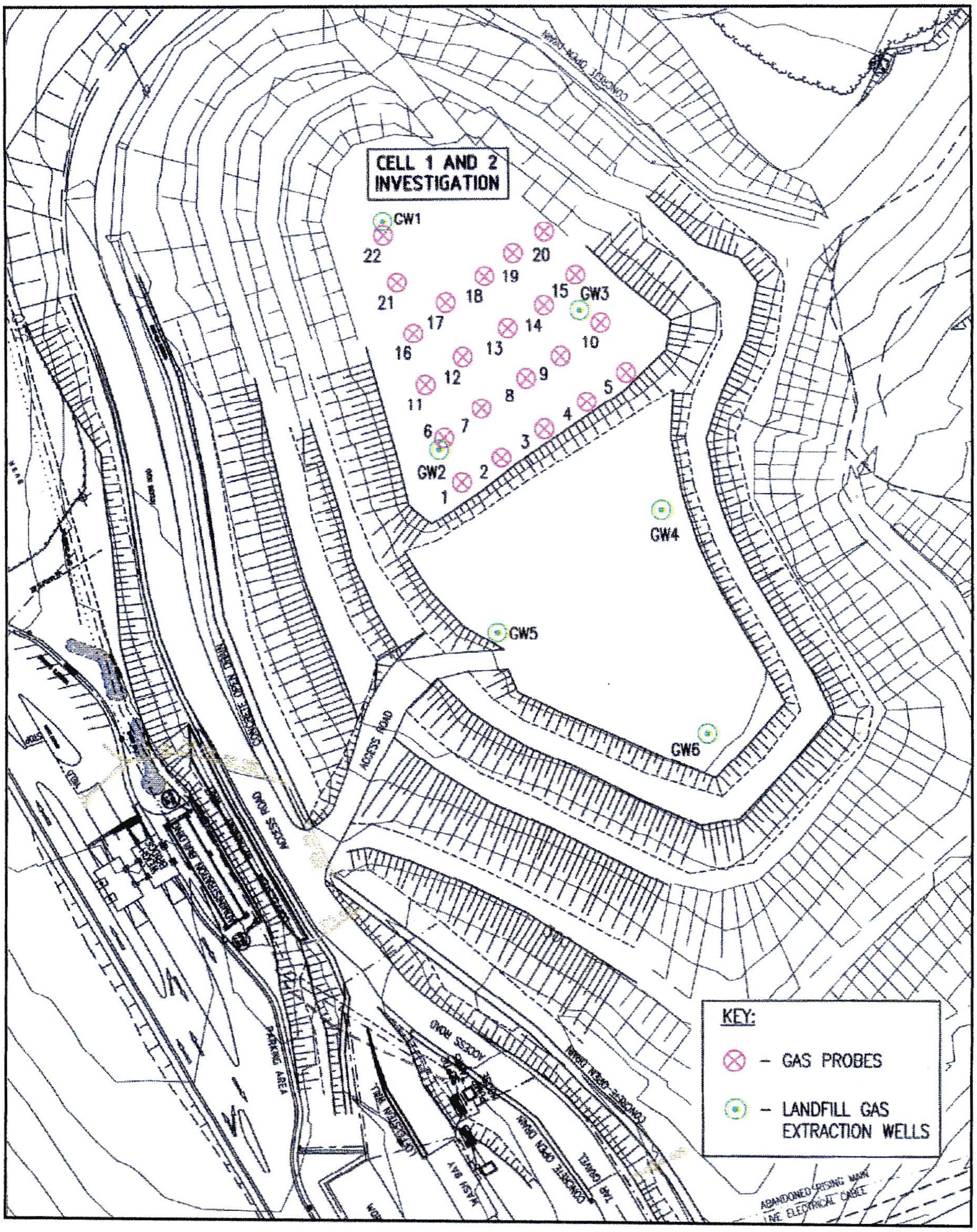


Figure 5.8 Location of the shallow probes in Cell 1 and the gas extraction wells in Cells 1 and 2 at the Mariannhill landfill site

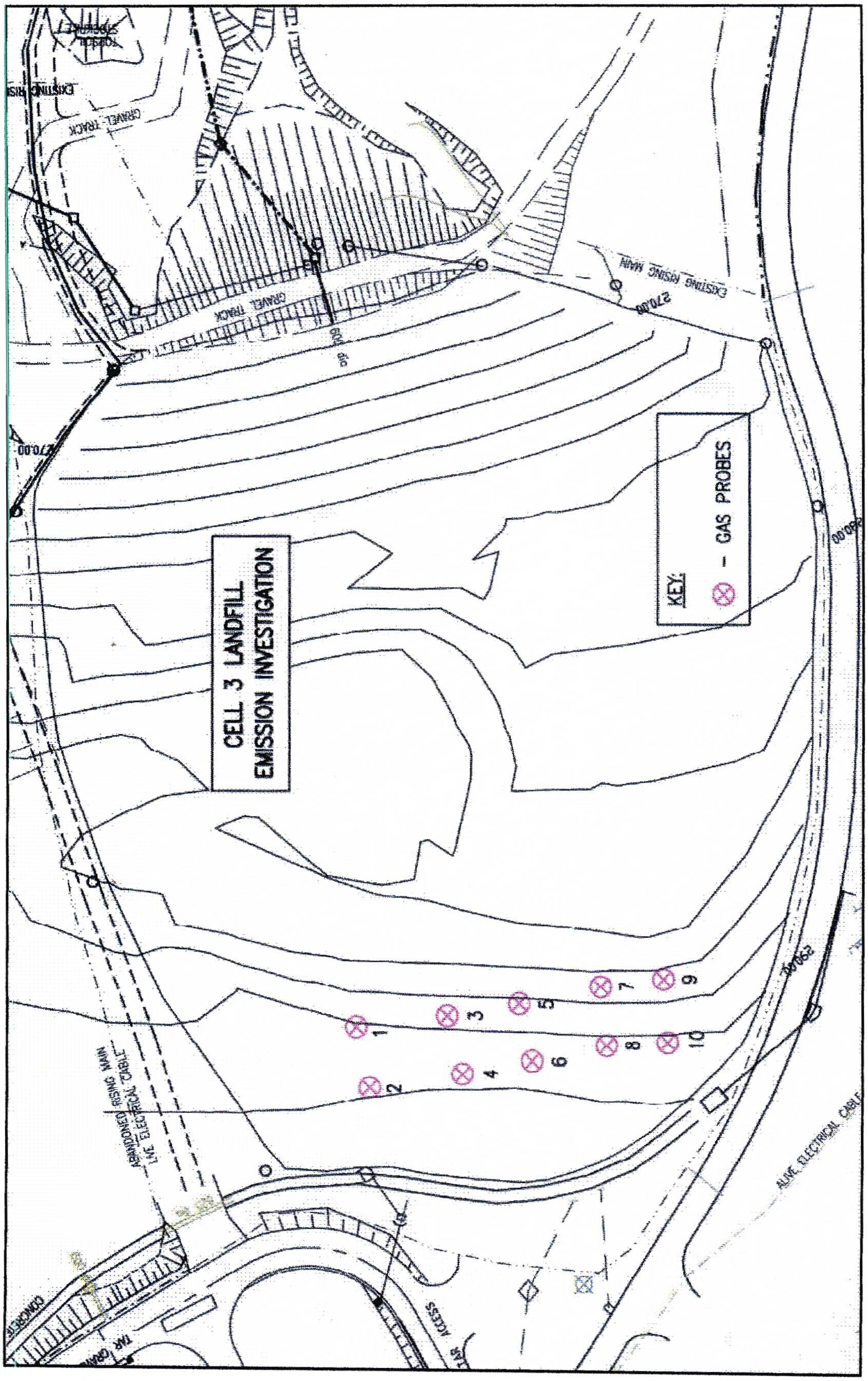


Figure 5.8 Location of the shallow probes in Cell 3 at the Mariannhill landfill site

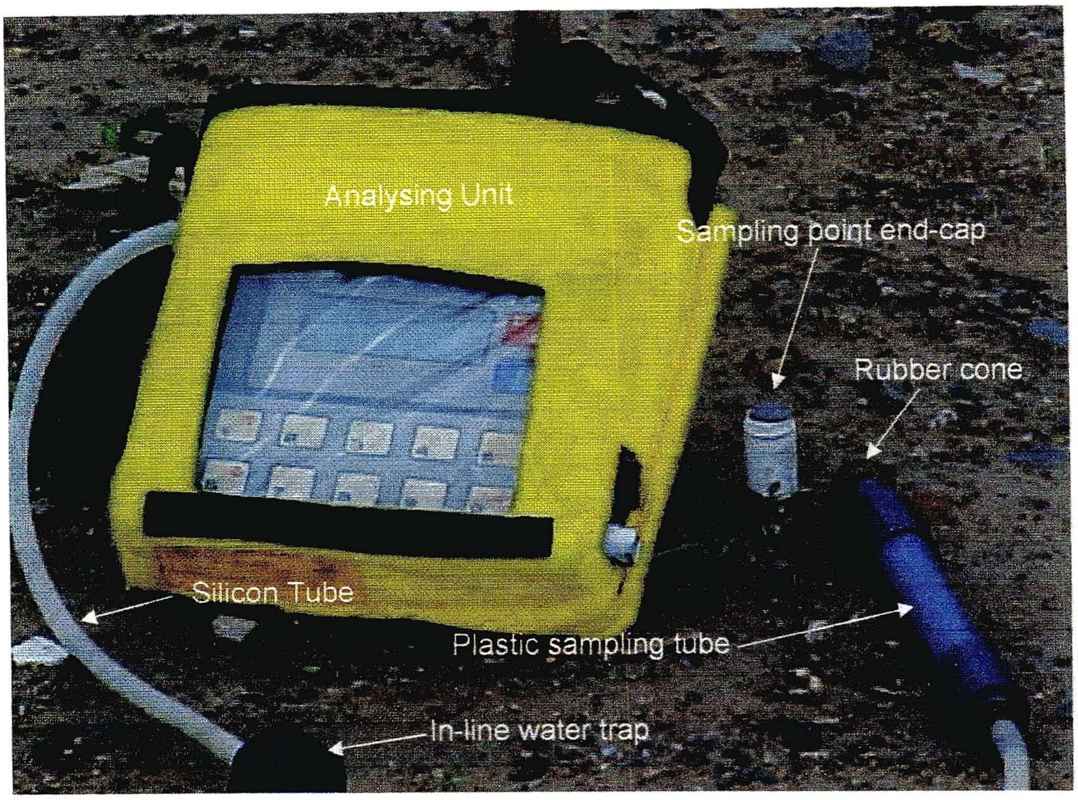


Plate 5.4 The GA 94 and a typical sampling point

A description of the sampling procedure at each shallow probe sampling point and gas extraction well is given below.

- Air was drawn through the analyser to purge the system of any biogas.
- The cap on the shallow probe/valve on the extraction well was removed/opened.
- The rubber cone on the end of the plastic sampling tube was placed firmly over the sampling point and the pump immediately switched on.
- Once the concentrations of methane, carbon dioxide and oxygen had stabilised, the pump was switched off. The readings were considered to be stable when the concentrations of the three gases did not change by more than 0.2 % (by volume in air) over a period of at least thirty seconds.
- The concentration readings were stored in the analyser.

The vacuum applied to the shallow probe by the integral pump was not considered sufficient to draw air into the probe through the landfill surface.

5.8 ESTIMATING LANDFILL GAS YIELDS USING PREDICTIVE MODELS

Two models were used to estimate the yield of landfill gas from Cells 1 and 2 at the Mariannhill Landfill Site. The first model is based on work done by Muntoni et al (1995) and Cossu et al (1996), which involved predicting the amount of carbon in the waste that may be converted to biogas. The second model was the LandGEM computer model (EPA, 1997).

5.8.1 The Chemical-physical/Biochemical Model (Muntoni et al, 1995; Cossu et al, 1996)

The production of biogas is considered in two sub-models in this multi-phase modeling method, as proposed by Muntoni et al (1995). The first sub-model describes the influence of several chemical-physical parameters (content of biodegradable organic carbon, moisture content, temperature, density and particle size) on the conversion of organic carbon to biogas. The second sub-model describes the kinetics of biogas production considering the biodegradation rates of three categories of organic matter, viz. easily biodegradable, biodegradable and slowly biodegradable matter. The results from the chemical-physical sub-model provides the input for the biochemical sub-model and allows the forecast of specific and absolute biogas production for individual cells and for the landfill as a whole.

The chemical-physical submodel calculates for each cell and for each waste component (e.g. putrescibles, cardboard, garden refuse) the quantity of biodegradable carbon based on the composition and the chemical-physical characteristics of the waste. Equation 5.2 describes the relationship between these characteristics.

$$(CO_b)_{i,j} = [C_i \, (f_b)_i \, (1 - u_i) \, p_i]_j \qquad \textbf{EQ 5.2}$$

Where:

i = 1..n index of waste component

j = 1...n index of cell

$(CO_b)_{i,j}$ = Amount of organic carbon that may be converted to biogas (kg_C/kg_{MSW})

C_i = Biodegradable organic carbon in waste mass ($kg_C/kg_{kg\ dry\ component}$)

$(f_b)_i$ = Biodegradable fraction of organic carbon ($kg_{biodegradable\ C}/kg_C$)

u_i = Water content of the waste component ($kg_{H2O}/kg_{waste\ component}$)

p_i = Humid weight ($kg_{waste\ component}/kg_{MSW}$)

Determining site-specific values for the waste component characteristics (C_i, u,) and the ratio of biodegradable carbon to total carbon (f_b) is difficult in practice. The parameter values used for the purpose of this research were derived from the literature and from analyses of the general waste stream in the DMA and the composition of the waste received at the landfill site (as recorded at the weighbridge).

The biodegradable organic carbon inside cell j is given by the sum of the biodegradable organic carbon for each waste fraction, as shown in Equation 5.3.

$$(CO_b)_j = \sum_{i=1}^{n} (CO_b)_{i,j} = \sum_{i=1}^{n} C_i . f_b . (1 - u_i) . p_i \qquad \textbf{EQ 5.3}$$

The biodegradable organic fractions in MSW usually have sufficient moisture to prevent inhibition of bacterial activity. The moisture content however is generally smaller than the field capacity, depending on the degree of compaction. It is assumed in the model that the biodegradation rate is a maximum if the waste is saturated. Under normal conditions, the waste is unsaturated and the lack of moisture is the limiting factor. A corrective factor is therefore introduced in the model, as shown in Equation 5.4.

$$\alpha = \left(\frac{I_{s.l.}}{I_{s.l.max}} \right) \qquad \textbf{EQ 5.4}$$

Where:

$I_{s.l.}$ = Solid-liquid interface (m^2)

$I_{s.l.max}$ = Solid-liquid interface at saturation conditions (m^2)

It is difficult to estimate $I_{s.l.}$ for a such a heterogeneous material as waste, but α can be estimated using Equation 5.5 (Halvadakis, 1983).

$$\alpha = \left(\frac{u}{u_s}\right) \quad \textbf{EQ 5.5}$$

Where:
α = Landfill moisture coefficient
u = Moisture content (%)
u_s = Saturation moisture content (%)

Determining in-situ values for the moisture content and the saturation moisture content of the waste body was beyond the scope of this research. Both Cells 1 and 2 have been producing leachate consistently for more than two years. It has therefore been assumed that the waste has reached field capacity and is nearing saturation. A value of 0.8 was chosen for α (it is assumed that the waste body is 80% saturated).

A further corrective factor (β) is applied to account for the reactive surface area of the solid fraction, which depends on the density and waste particle size. Determining the ratio of reactive to maximum reactive surface is difficult in practice, and hence a value of 0.9 is assumed.

The amount of carbon that may be converted to biogas is also an increasing function of temperature. Tabasaran (1982) provides a correlation, which is shown in Equation 5.6.

$$CO_e = CO_b\,(0.28 + 0.014\,T) \quad \textbf{EQ 5.6}$$

Where:

CO_e = Amount of biodegradable carbon that may be converted to biogas ($kg_C/kg_{wet\ MSW}$)

CO_b = Amount of biodegradable carbon available in the waste ($kg_C/kg_{wet\ MSW}$)
T = Temperature (^0C)

The output of the chemical-physical sub-model is thus given by a mass of biodegradable carbon that may be converted to biogas for each MSW component and for each cell.

The biochemical sub-model is based on a first-order kinetic model, which describes the rate of substrate (biodegradable carbon) consumption, as is shown in Equation 5.7. Each waste type has an associated biodegradation rate. This model assumes that there are three general fractions of biodegradable matter in the waste mass into which the various waste types fall, viz. easily biodegradable, biodegradable and slowly biodegradable matter. Each waste component must therefore be placed into one of three fractions of biodegradable matter. If more than one waste type is considered as easily biodegradable, the masses of biodegradable carbon are added. The same approach applies for the other two fractions.

$$\frac{d.(CO_g(t))}{(CO_e)_{h,j} - (CO_g(t))_{h,j}} = k_h\ .dt \qquad \textbf{EQ 5.7}$$

Where:

h = 1,..,3 general biodegradable fraction index
j = 1,..,n Cell number index
$(CO_g)_{i,j}$ = Carbon converted to biogas ($kg_c/kg_{wet\ MSW}$)
$(CO_b)_{i,j}$ = Carbon available for conversion to biogas at time t = 0 ($kg_c/kg_{wet\ MSW}$)
k_h = Biodegradability coefficient for the h^{th} waste fraction ($year^{-1}$)
t = Time (years)

k_h is a global reaction coefficient representing both the hydrolysis reaction and the biochemical transformations that lead to the production of biogas. It can be estimated for different fractions as a function of their half-life ($t_{1/2}$), as is shown in Equation 5.8.

$$k_h = \ln 2/(t_{1/2}) \qquad \textbf{EQ 5.8}$$

The corrective factor for the moisture conditions in the landfill, $\forall$, and the correction for the effective reactive surface area (β), are applied to k_h at this stage, to yield an 'effective' reaction coefficient $K_{he/}$. Values for k_h were obtained from the literature. Equation 5.9 shows the application of the factors.

$$K_{he}\,(yr^{-1}) = \alpha.\beta.K_h \qquad \textbf{EQ 5.9}$$

As discussed in Section 4.8.1, 1.868 m^3 of biogas can be produced from the biodegradation of one kilogram of organic carbon. The cumulative biogas production at time t is given by Equation 5.10.

$$G_t = \sum\nolimits_{h,j} 1.186(CO_e)_{h,j}(1 - e^{-K_{he,j}t}) \qquad \textbf{EQ 5.10}$$

The specific gas production is given by Equation 5.11.

$$g = -\,dG/dt = \sum\nolimits_{h,j} 1.868(CO_e)_{h,j}K_{he,j}e^{-K_{he,j}t} \qquad \textbf{EQ 5.11}$$

The fundamental inputs for this model are the mass of waste in the cell/landfill under consideration and the quantitative composition of the waste body, as these dictate the amount of biodegradable carbon available for conversion to biogas. The weighbridge at the Mariannhill Landfill site provided the individual masses of all the waste components received at the landfill. The relative contribution of each waste component to the total mass of waste (humid weight (p_i)) was determined from the comprehensive analysis and processing of the weighbridge data.

A Waste Stream Analysis (WSA) of the DMA was used in combination with the weighbridge data to determine the waste composition in the instances when the data was not specific enough. The WSA was performed by SKC Engineers and involved the collection of solid waste samples from ten different types of housing developments in the DMA (DMWS, 1998). Samples of the waste produced from each development were hand-sorted into components, namely: soft plastics, hard plastics, glass, tin/aluminum, cardboard, paper, putrescibles and other waste. The daily mass of waste generated at each development and the mass of each of the components are presented in the WSA report (DMWS, 1998) for the six regions in the DMA (Inner West, North, North Central, Outer West, South and South Central). The WSA data was analysed and processed to yield the relative contribution of each waste component to the total mass of waste generated by each region. The WSA provides a more accurate insight into the composition of the waste brought to the landfill site via curbside collection vehicles.

The WSA for the Inner West region was considered most representative of the waste body, as this is the predominant area served by the Mariannhill Landfill Site. The WSA data is presented in Appendix C1. Figure 5.10 presents a summary of the model.

In the instances where model parameter values could not be determined from actual data, the chosen literature values were critically analysed and adapted for the climatic conditions prevalent in Kwa-Zulu Natal. An insight into the various waste component characteristics could be gained from the weighbridge data and waste stream analysis. The characterisation of leachate and biogas emissions during the research provided knowledge on the effects of the sub-tropical climate on waste degradation rates, which relate directly to the production of biogas.

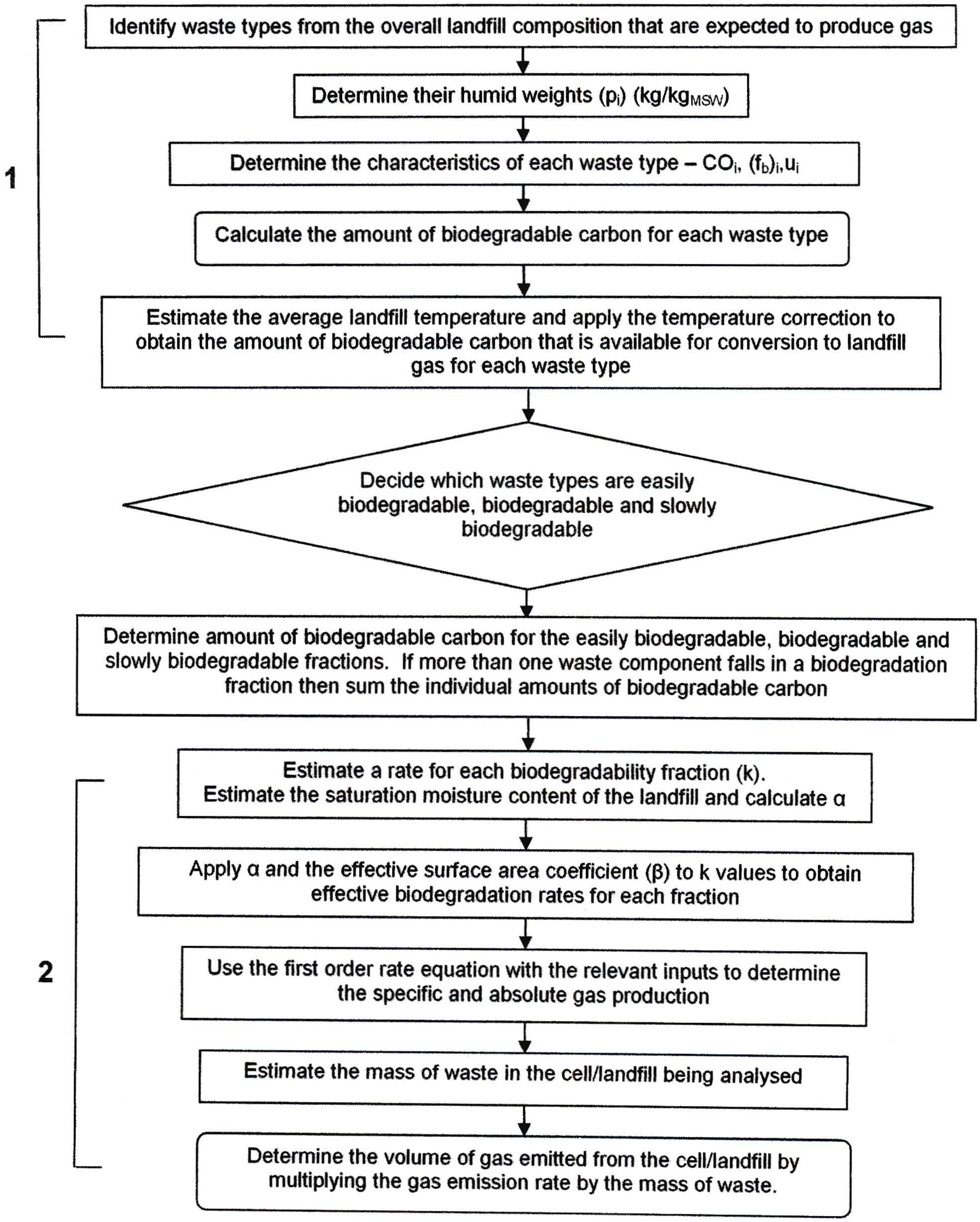


Figure 5.10 Overview of the model, showing the progression from 1) The Chemical-Physical Model to 2) The Biochemical Model.

5.8.2 Programming of the Chemical-Physical/Biochemical Model in Microsoft Excel™

As part of this research project, the Chemical-Physical/Biochemical model, which is available in the format presented in Section 5.8.1, was programmed in Microsoft Excel™ using the Visual Basic™ programming language in order to make it more accessible to landfill managers. The programmed model and users manual is presented in Appendix D. The program provides a clear, simple interface, which in conjunction with the users manual can be used to predict landfill gas emissions for individual cells or for a landfill as a whole.

The program develops in four environments, which are clearly integrated in a main menu screen, as described below:

- *Instructions Environment* – the program presents a general overview of the model and its objectives. A series of pop-up menus guides the user through the general process that the model follows.

- *Inputs Environment* – the second part of the program requires the user to input all the model parameters. Firstly, the user must have knowledge of the waste composition in the landfill. This data can be estimated from a WSA or obtained from weighbridge records. The gas producing waste components must be identified and their relative masses calculated (humid weight). The user must then decide which components are easily biodegradable, biodegradable and slowly biodegradable. The model allows a maximum of four different waste components per biodegradation fraction.

  The name of each component must then be entered for the easily biodegradable category. The parameter values (humid weight, carbon content, biodegradable fraction of carbon, moisture content) for the respective components must then be entered. Once all the inputs for the easily biodegradable fraction have been entered, the model asks the user for the general characteristics of the fraction. These include the biodegradation half time (in years), the landfill moisture coefficient (α) and the effective surface area reaction coefficient (β). The program then calculates the biodegradation constant (k) and the effective biodegradation constant (k_e)

The biodegradable and slowly biodegradable fractions follow the same sequence as for the easily biodegradable category.

Once the parameters related to the various waste components have been entered, the user returns to the main menu. The next step requires the user to enter the waste volumes in the cell/ landfill being analysed in six monthly intervals.

The user returns to the main menu, where the program requires that the average landfill temperature be entered. Following this, the key inputs may be inspected, and manually change if necessary. The inputs may also be set to zero if the user wishes to restart the model.

- *View Inputs* – All the input parameters are neatly presented, allowing for a final inspection of the entered data.

- *View Outputs* – The program runs the model using the inputs, and presents 3 graphical results – the specific gas production, cumulative gas production and the total gas emissions from the cell/landfill in question. Tabulated results for the total gas emissions are also presented.

The model is user-friendly, and additional software other than Microsoft Excel™ is not required. Parameter values can be easily updated; thereby allowing the landfill manager to update predicted emissions as more waste is placed in the cell/landfill. The users manual provides typical parameter values for a variety of wastes, which may be used if site-specific data is not available.

5.8.3 The Landfill Gas Emissions Model (LandGEM)

This landfill gas model was developed by the US EPA to estimate uncontrolled emissions of the various compounds present in landfill gas. The model was developed as part of the US EPA's AP-42 document (US EPA. 1995), which provides methodologies to estimate potential emissions from various sources, either through the use of emission factors where data is unavailable, or through models where some data is available.

The model provides estimates of landfill gas generation based on a theoretical first-order kinetic model of methane production. Unlike the multi-phase model described in Section 5.9.1, one global generation constant is used to model the biodegradation of all waste fractions. Equation 5.12 is the LandGEm model equation.

$$Q_{CH4} = L_0 . R . (e^{-kc} - e^{-kt}) \qquad \textbf{EQ 5.12}$$

Where:

Q_{CH4} = Methane generation rate at time t (m^3/yr)
L_0 = Methane generation potential, (m^3_{CH4}/Mg refuse)
R = Average annual refuse acceptance rate during active life (Mg/yr)
k = Methane generation constant (yr^{-1})
c = Time since landfill closure, yrs (c = 0 for active landfills)
t = Time since the initial refuse placement (yrs)

Site-specific information is generally available for variables R, c and t. The values for L_0 and k must be estimated. The potential methane generation capacity depends primarily on the organic content of the waste, and can vary widely depending on the waste composition in the landfill (US EPA, 1997).

The landfill model includes both regulatory default values and recommended default values for L_0 and k. The regulatory defaults were developed for regulatory compliance purposes and to provide conservative default values on a national basis in the US (US EPA, 1997). As a result, the default values may not be representative of specific landfills. The recommended default values are based on 'best fit' empirical data for 21 landfills. The predicted methane emissions however ranged from 38 to 492 percent of actual emissions, so there is considerable variability among landfills and considerable uncertainty in this estimation method

(US EPA, 1997). The use of site specific data rather than either set of landfill model defaults are therefore preferred for more accurate emission rates. A value for the methane generation potential (L_0) can be chosen from the literature (e.g. Gendebien et al, 1992) and then the methane generation rate (k) can be calculated using the EPA Reference Method 2E (US EPA, 1991).

Reference method 2E provides a standard testing procedure for determining optimum operating conditions for gas extraction systems in the United States. The method includes the use of pressure and monitoring probes around extraction wells to determine an approximate radius of influence of each well. The pressure probes are also used to monitor gas quality, the results of which may be used to determine the suction head that must be applied to the system by the blower to prevent air ingress into the fill. If the average well depth, average stabilised radius of influence and average stabilised flow rate of the extraction system is known, then together with the density of refuse, the fraction of decomposable refuse and the methane generation potential, a k value may be calculated. The formula that the LandGEM model uses to calculate the k value is given by Equation 5.13.

$$ke^{-k}A_{avg} - \left(5.256\times10^{5}\right)\frac{Q}{2.f.L_0R^2.\pi.D.\rho} = 0 \quad \textbf{EQ 5.13}$$

Where:

k = Methane generation constant (year^{-1})
A_{avg} = Average age of the waste (year)
Q = Average stabilised flow rate (m^3/min)
f = Fraction of decomposable waste
L_0 = Methane generation potential (m^3/ton)
R = Average stabilised radius of influence (m)
D = Average depth of the wells (m)
ρ = Density of the refuse (ton/m^3)

The value for k in Equation 5.13 is solved by iteration. The LandGEM model allows the user to input the relevant information and then solves for k.

The recommended default values for the methane generation rate (k) are 0.04/yr for areas receiving more than 635 mm (25 inches) in a year, and 0.02/yr for areas receiving less than 635 mm in a year. A default value of 100 m^3/ton refuse is given. It is recommended because it provided better agreement of emissions derived from measured data to predicted emissions (US EPA, 1997).

Carbon dioxide and Non-Methane Organic Compounds (NMOC), which are expected to be emitted from landfills based on test data compiled in the U.S. Environmental Protection Agency's (EPA's) compilation of air pollutant emission factors, AP-42 (EPA, 1997) can also be determined. The model allows the user to choose the ratio of methane:carbon dioxide:NMOC ratios in the gas. Site-specific data can therefore be used if an analysis of the gas generated on site has been performed.

The model outputs are user-specified and can be set to give a graphical or tabulated output of predicted yearly emission for 200 years after the first waste was placed for carbon dioxide and methane. The user can also obtain the predicted emission rate of any specified NMOC in the model's database.

5.9 SURFACE EMISSIONS MEASUREMENT

A surface emission inventory was conducted at the Mariannhill landfill site on Cells 1 and 2. The initial objective of determining the rate (flux) of gas passing through the landfill surface in cells 1 and 2 was to evaluate the effectiveness of a gas extraction system in reducing net emissions to the atmosphere. The intention was to determine the surface emissions rates before and after the installation of the gas extraction system in Cells 1 and 2. A Static Accumulation Chamber (SAC) was used to determine the surface emissions due to its relatively simple design and ease of use (as described in section 4.5.2).

The SAC was constructed as a cylinder from 2mm stainless steel. The base of the chamber was 700mm in diameter and it had a wall height of 200 mm, as shown in Plate 5.5. This gave the chamber a volume of 0.077 m^3 and base area of 0.385 m^2. A rubber septum was fitted to the top of the chamber to allow gas samples to be extracted via a syringe. The dimensions were chosen to enclose a sufficiently large volume, thereby preventing the excessive build up of gas in the chamber.

The SAC method requires that gas samples be drawn from the chamber at regular time intervals (a sampling run), and subsequently analysed. A sampling run included taking 7 samples from the chamber, which were drawn after 0, 1, 2, 4, 8, 16, and 32 minutes. The procedure followed during a sampling run is described below:

- The SAC was placed onto the landfill surface and sealed at the edges (using wet clay) to prevent atmospheric dilution inside the chamber.
- The first gas sample was drawn from the centrally located septum on the SAC using a 10ml gas tight SGE Removable Leur/Needle syringe. The syringe was pumped at least twice before withdrawal of a sample to ensure good mixing of the internal chamber atmosphere.
- The sample was inserted into a 2ml pre-evacuated glass sample vial (with a teflon seal and red rubber septum) for GC analysis. The vials were overpressurised with 3ml of sample.

This procedure was followed for the remaining samples in the run

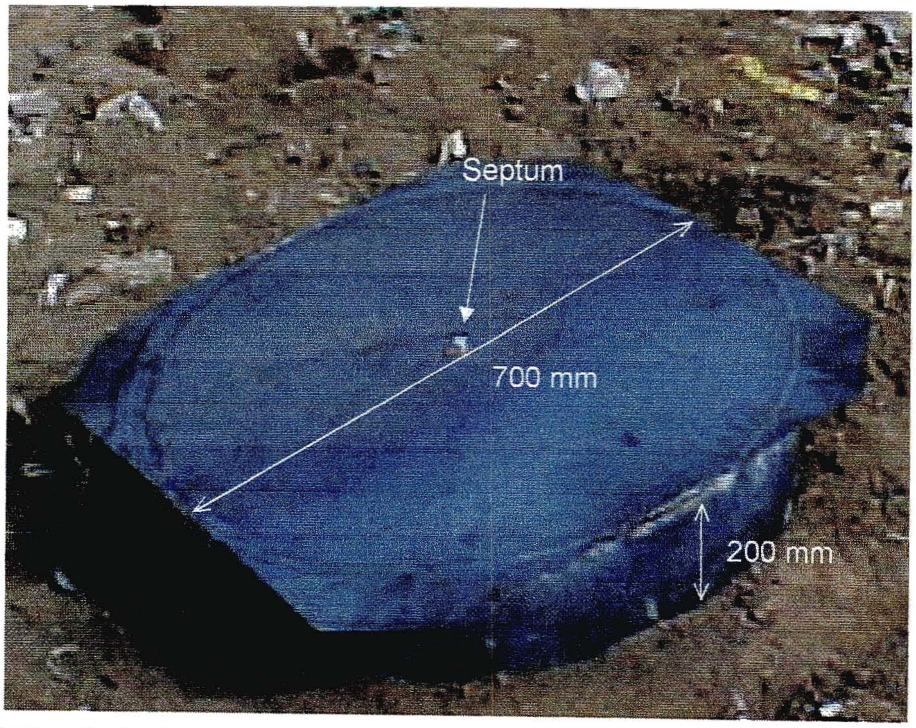


Plate 5.5 The Static Accumulation Chamber

The sampling runs were set at a maximum time of 32 minutes because, according to an extensive study performed by Morris (1999), the accuracy of the method does not increase significantly beyond this time. The GC analysis was performed at the school of Chemical Engineering at the University of Natal using a GOW-MAC Gas Chromatograph with packing type Hayesp D (Plate 5.6). The carrier gas was helium. The GC yields the percentage concentrations of air (oxygen and nitrogen), methane and carbon dioxide. The retention times for the three gases were 1.4, 2.8 and 6.6 minutes respectively.

The gas fluxes for each sampling run were calculated using Equation 4.3. The gas concentrations obtained from the GC analysis were plotted against time so that the dC/dt term could be calculated (Appendix E1).

5.9.1 Measuring On-site Surface Emissions

Prior to the installation of the gas extraction system in Cells 1 and 2, a sampling campaign of the surface emissions from the two cells was undertaken. Thirty-eight areas on the plateau and side slopes of both cells were sampled using the SAC technique over a one-week period.

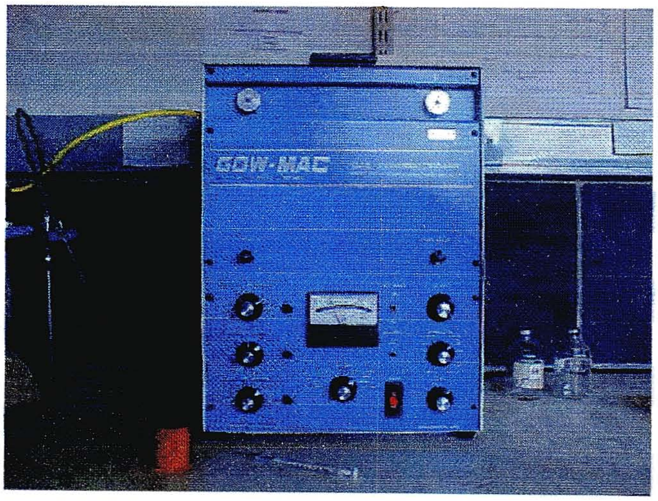


Plate 5.6 GOW-MAC Gas Chromatograph used for analysis of samples

Upon testing of the samples collected during the sampling runs, no gas was detected in any of the glass vials. It was therefore decided to 'calibrate' the flux box (i.e. determine optimum working parameters and evaluate the accuracy of the SAC method) in a laboratory using a specially constructed test bed before embarking on any further sampling campaigns. The time required designing the test bed and calibrating the flux box meant that the gas extraction system was already in place, and hence the initial objective could not be met.

5.9.2 Design of the Test Bed

A test bed was constructed to ensure a well-regulated gas emission through a soil surface, and to simulate, as closely as possible, actual field emissions of landfill gas. A square bed, 1200 x 1200 mm, was constructed from 20-mm pine, with an overall height of 250 mm. The length of the sides were chosen to be sufficiently larger than the diameter of the chamber so that the effects of gas flow at the boundary of the bed could be ignored (Morris, 1999).

A layer of 19mm gravel and five layers of geofabric (needle punched Kaymat geotextile Grade U39) were placed on the test bed base to a height of 75mm, above which a false floor was placed. The false floor had 169 (13 x 13) 6mm drilled holes at 75 mm spacing. A gas inlet hole was drilled into one side of the test bed, approximately 40mm above the base of the bed (the centre of gravel layer). A gas cylinder fitted with a regulator and rotameter delivered gas to the bed via a 12mm fibre-reinforced gas delivery pipe connected to the inlet hole. Only carbon dioxide was used as the test gas because it was considered to dangerous to have a carbon dioxide/methane mixture indoors. The layers of geofabric were placed to allow gas to build up in the gravel layer, thereby ensuring uniform vertical flow through the perforated false floor.

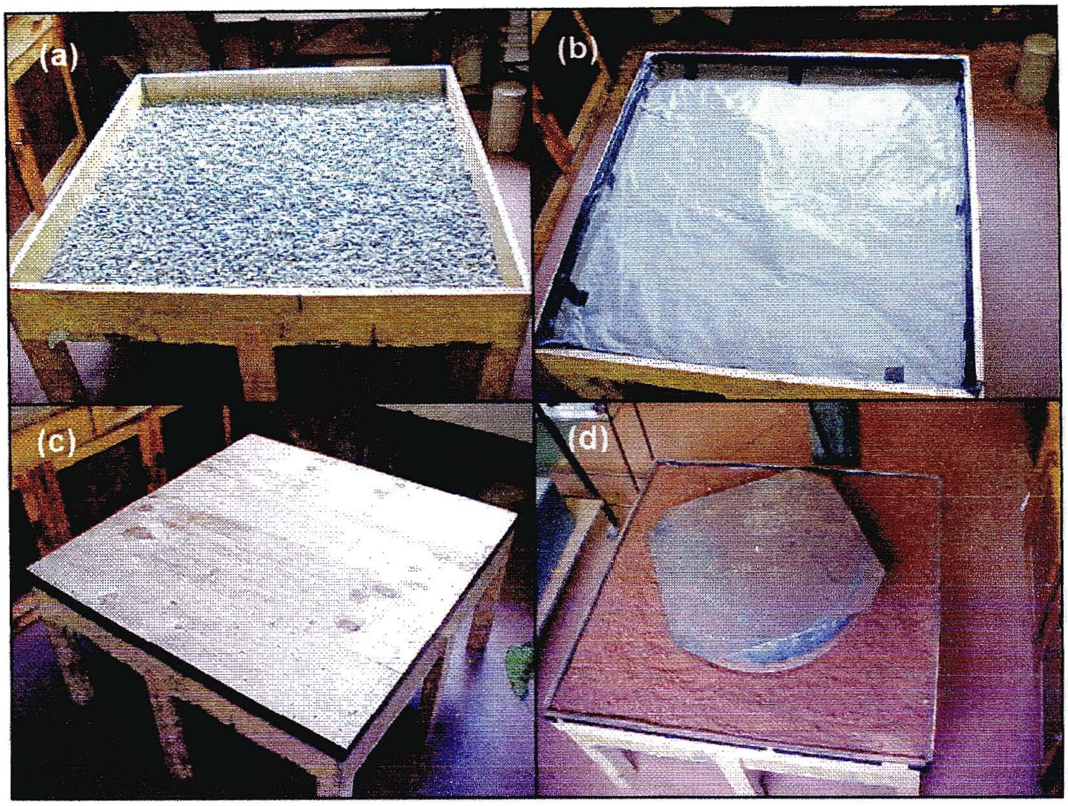


Plate 5.7 The various stages in the construction of the test bed: (a) The gravel layer (b) The bidim layers (c) The false floor with 169 holes (d) Completed test bed

Another layer of geofabric and approximately 120 mm of uniformly graded Berea Red Sand with negligible moisture content was placed on the false floor. The soil layer was uniformly compacted in four 30-mm layers over which a 6-kg concrete cylinder was rolled. The reasonable assumption that the flow of gas up through the sand was identical to the flow of gas distributed through the false floor could therefore be made, as no restrictions to gas flow had been imposed (Morris, 1999). Plate 5.7 shows the test bed in the various stages of construction.

The flow of gas into the bed was regulated upstream with a pressure regulator and rotameter. The flow of gas to the test bed remained constant provided that the rotameter remained at same level. Figure 5.11 is a schematic layout of the test bed system.

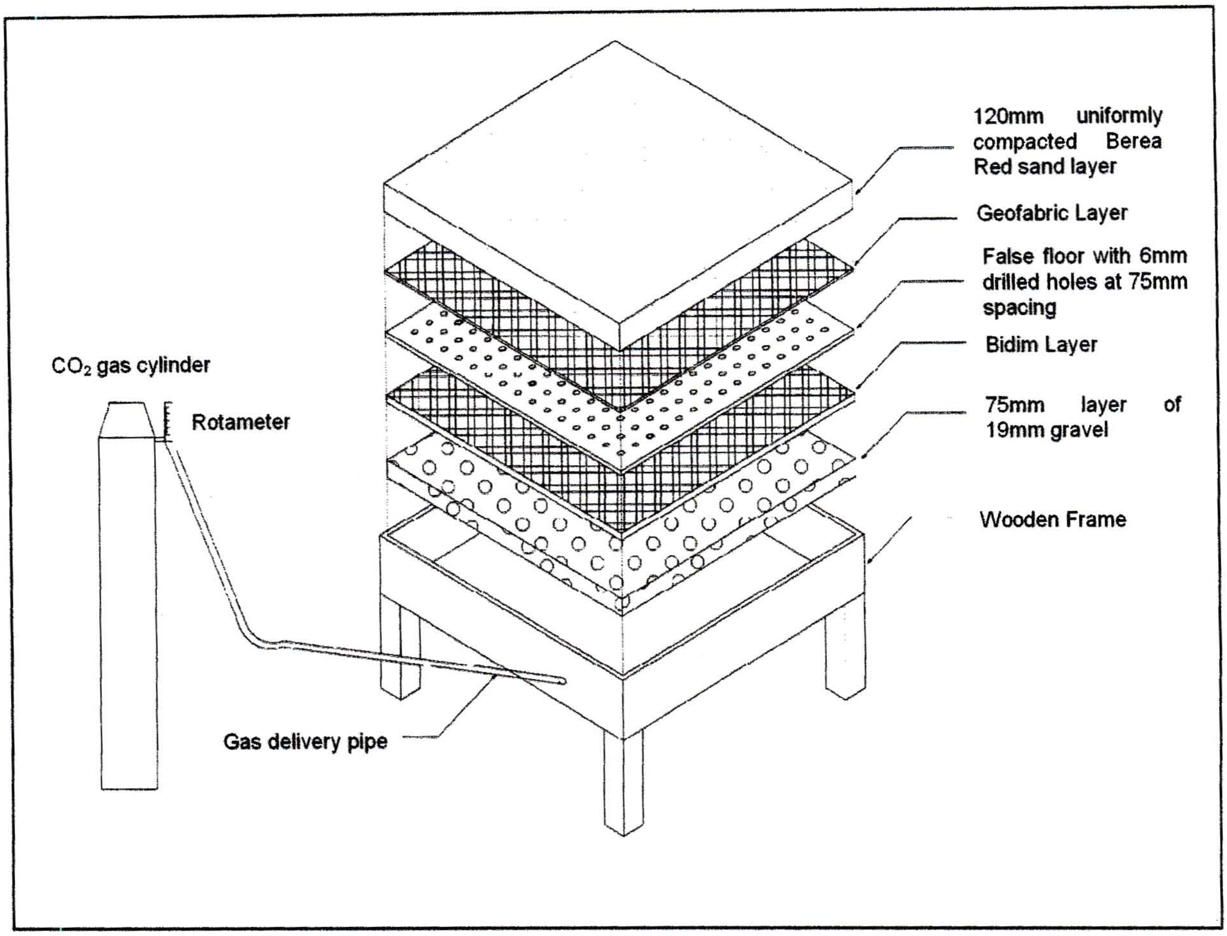


Figure 5.11 Schematic layout of the test bed

The gas flow from the cylinder to the bed was set at two different rates, namely 2 and 5 litres per minute (Lpm), which resulted in gas fluxes of 2.498 and 6.243 $g.m^{-2}.min$. These rates were based on Bogner et al (1997), who cited a number of references concerning field emissions measurement, showing that typical methane fluxes range between 0 and 1.38 $g.m^{-2}.min$. A slightly higher flux was chosen to ensure that sufficient gas would pass through the bed, and that it would be detected in the SAC.

Twenty-one laboratory tests were performed using the test bed. Fourteen runs were performed at a flux of 2498 $mg/min.m^2$ and six runs at a flux of 6243 $mg/min.m^2$

CHAPTER 6

LEACHATE CHARACTERISATION RESULTS

6.1 INTRODUCTION

This chapter presents the results of the leachate analyses for the Randles Cell, Mariannhill Cell 1 and Mariannhill Cell 2. Accuracy and precision of the chemical analyses performed by the Echalaz and Ozborne (Pty) Ltd. laboratories and Durban Metro Wastewater Services could not be established. Accuracy and precision of the chemical analyses performed at the University of Natal are presented in Appendix A1. Where trends in leachate constituents have been presented graphically, the corresponding tabulated data is presented in Appendix A2.

The prevailing climatic conditions have a significant effect on the composition of leachate (Robinson et al, 1998). The volume of leachate that is produced is primarily dependent on the amount of rainfall (particularly for uncapped landfills). A warm, wet climate facilitates biological decomposition processes in the landfill, which in turn directly influences the pollutant load of a leachate. The characterisation of the three leachates analysed in this research therefore incorporates rainfall data in order to determine, qualitatively, the extent to which the climate affects the change in leachate composition with landfill age.

Durban has a humid, sub-tropical climate with warm, wet summers and mild, relatively dry winters. The mean annual temperature is 20.^{0}C and the annual range is 8.0^{0}C (Durban Metro, 1999). Highest mean temperatures are experienced in February and lowest mean temperatures in July. The annual rainfall is often in excess of 1000 mm, with a mean annual rainfall of 1009 mm (Durban Metro, 1999). Two climatic seasons may be identified, a 'wet season' running from October to March, and a 'dry season' running from April to September. The highest cumulative rainfall for six consecutive months is considered as the 'wet season' and vice-versa for the 'dry season'. Figure 6.1 presents the monthly rainfall from January 1997 to July 2001. The wet and dry 'seasons', and the average temperature and humidity for each month is also shown. The climatic data was obtained from a weather station located at the Durban International Airport, and is presented courtesy of the South African Weather Service. The tabulated climatic data is presented in Appendix A1.

The average temperature over the period shown in Figure 6.1 was 23.1^{0}C and the average humidity was 80.8 %.

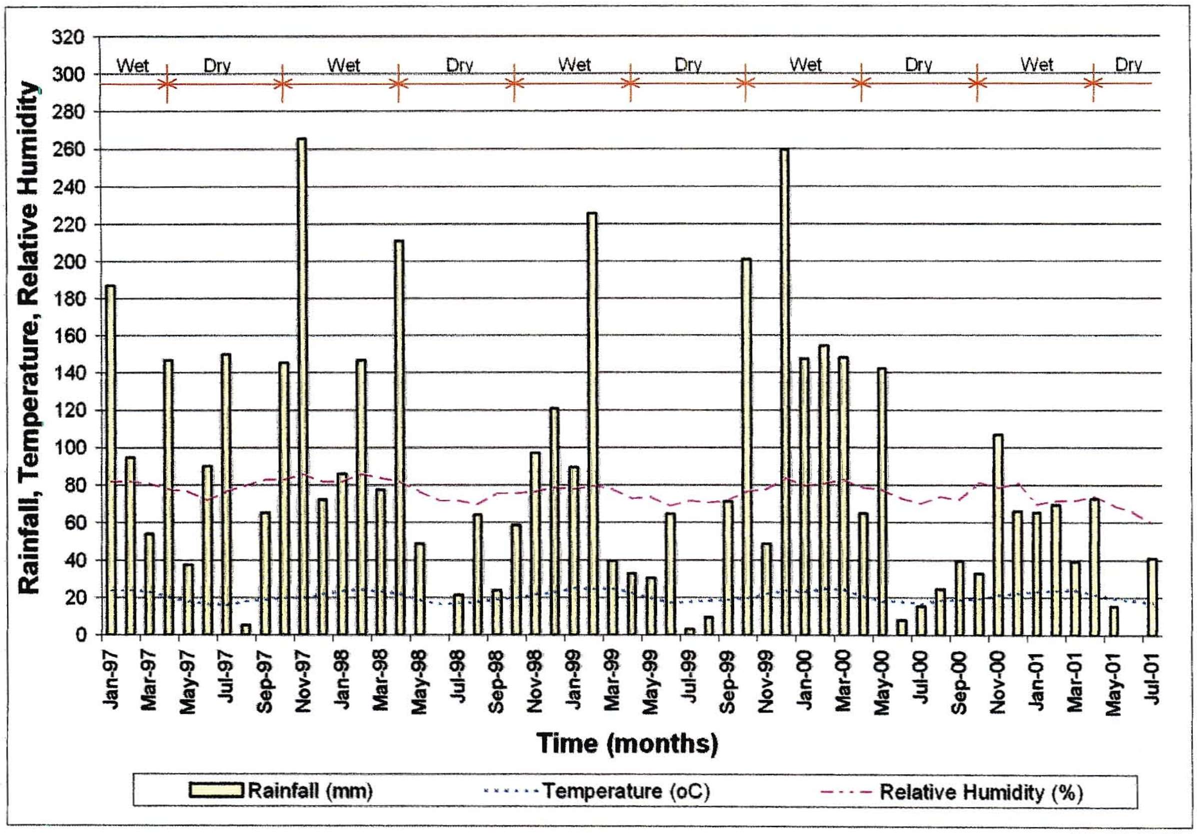


Figure 6.1 Monthly rainfall, temperature and humidity for Durban over the leachate sampling periods (Courtesy of the South African Weather Service)

6.2 RANDLES CELL LEACHATE CHARACTERISATION (Bisasar Road Landfill Site)

6.2.1 pH Analyses

Figure 6.2 shows the variation of the leachate pH with time. As it can be seen from the figure, the leachate consistently remained in the range of pH 7 – 8, with only the first sample analysed having a pH typical of an acetogenic ('young') phase. Within three months after disposal operations began, the leachate had reached a relatively stable, neutral pH value, typical of an early methanogenic phase (Robinson, 1993; Qasim and Chiang, 1994; Ehrig 1989).

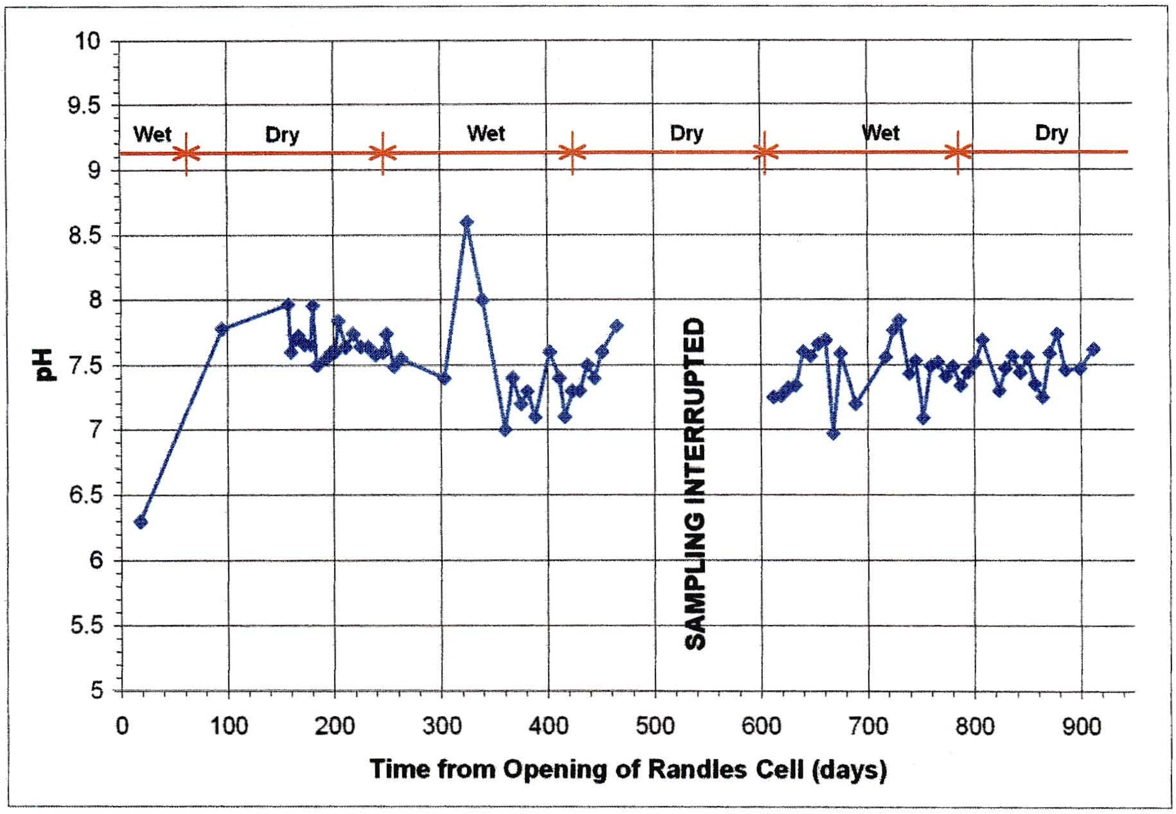


Figure 6.2 Variation of the pH with time for the Randles Cell leachate

6.2.2 COD Analyses

Figure 6.3 shows the variation of the COD with time. The COD generally ranged between 2000 and 4000 mg/l during the first eight months of disposal operations. These concentrations are typical of a methanogenic leachate (Ehrig, 1989; Robinson, 1993). Only the first sample has a typical acetogenic COD concentration (Ehrig, 1989), with the second sample showing a methanogenic concentration approximately three months after the first waste was placed.

After the first eight months (approximately 240 days), the COD showed a fairly dramatic drop to below 1000 mg/l. This was possibly due to leachate dilution during the first wet season after disposal operations commenced. The wet 'season' that coincided with the drop in COD concentrations was from October 1999 to March 2000. Referring to Figure 6.1, this 'season' was particularly wet, with 957.7 mm of rain falling. This was 42% higher than the expected average of 675 mm. It seems reasonable at this stage of the cell's life that the effects of the wet season are represented in the leachate characteristics relatively quickly, since the landfill cell had a relatively small volume of waste at this stage. It is probable that the landfill was relatively shallow, resulting in short hydraulic retention times for percolating rainwater.

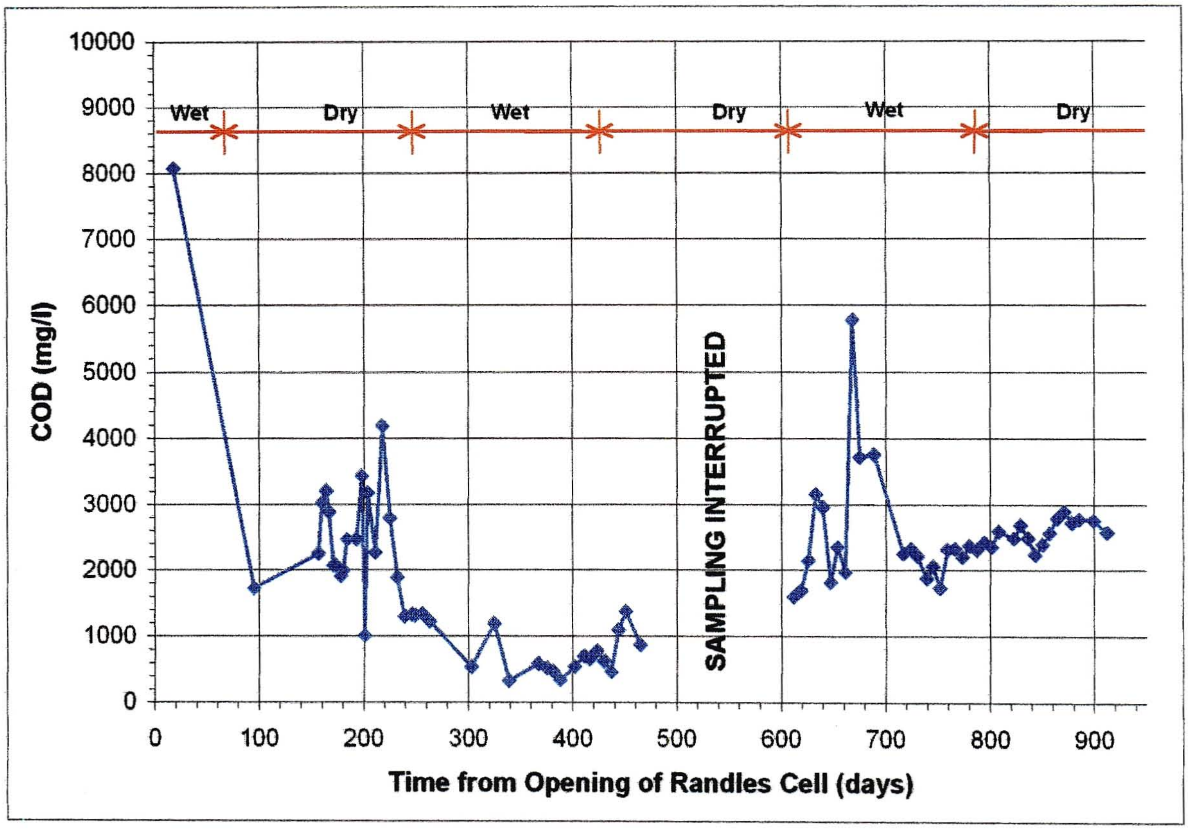


Figure 6.3 Variation of the COD with time for the Randles Cell leachate

After approximately 20 months (600 days), there was a general increase in COD concentrations to between 2000 and 4000 mg/l (only one sample had COD greater than 4000 mg/l), which is again typical of a methanogenic leachate. The general trend of the COD concentration after 20 months appears to be increasing. The possible reasons for this are:

- The effects of the wet and dry seasons (and therefore leachate dilution) are less pronounced at this later stage because of the increased volume and depth of the waste, which may result in lower hydraulic conductivities and longer hydraulic retention times for percolating rainwater. The lower hydraulic conductivities result from of a more compact waste body, which is caused by settlement due to increased overburden and biological decomposition. The effects of the dry season could possibly have increased the pollutant load of the leachate, and hence the COD (opposite of the dilution effect). This may only have affected the leachate characteristics after the dry season due to the increased hydraulic retention times (i.e. there was a lag period before the effects of the dry season took affect).

- Ongoing landfill operations and the continued placement of fresh waste resulted in the simultaneous production of young, acetogenic leachates with higher organic pollutant loads

6.2.3 Chlorides Analyses

Figure 6.4 shows the variation of the chloride concentration with time. Chloride is an important parameter in gauging dilution effects in a landfill. Chlorides are readily soluble in water and persist in the landfill, since it is not converted during biological stabilisation of the waste body. A reduction in the chloride concentration in a leachate is usually attributed to a dilution or 'washout' effect (Robinson, 1993). As is shown in Figure 6.4, the initial concentrations of chlorides (up to day 303) ranged between 1000 and 2500 mg/l. The general increase from day 95 (1st sample) to day 218 (16th sample) was most likely due to the chlorides in the freshly deposited waste solubilising in the percolating leachate. It may also have been due to the first dry 'season', where lower volumes of infiltrating water resulted in a leachate with a more concentrated chloride content.

Establishing whether there was a dilution effect due to the second wet 'season' (as suggested in Section 5.2.2) was not possible due to an interruption in the analyses of the chlorides over this period. Three samples were taken in the beginning of this 'season'; with the first two showing no signs of dilution (day 256 and day 263). The third sample however (day 303), had the lowest chloride concentration of all the samples. This may have been an indication of a dilution effect, however it cannot be considered conclusive.

The general trend of the chlorides concentration upon resumption of the analyses (on day 619) was to increase. The concentrations range between 2000 and 3500 mg/l. The general increase may be due to the continued placement of fresh waste (and hence the continued solubilisation of chlorides). The previous dry season may also have had a delayed concentration effect on the leachate composition, as with the COD concentrations.

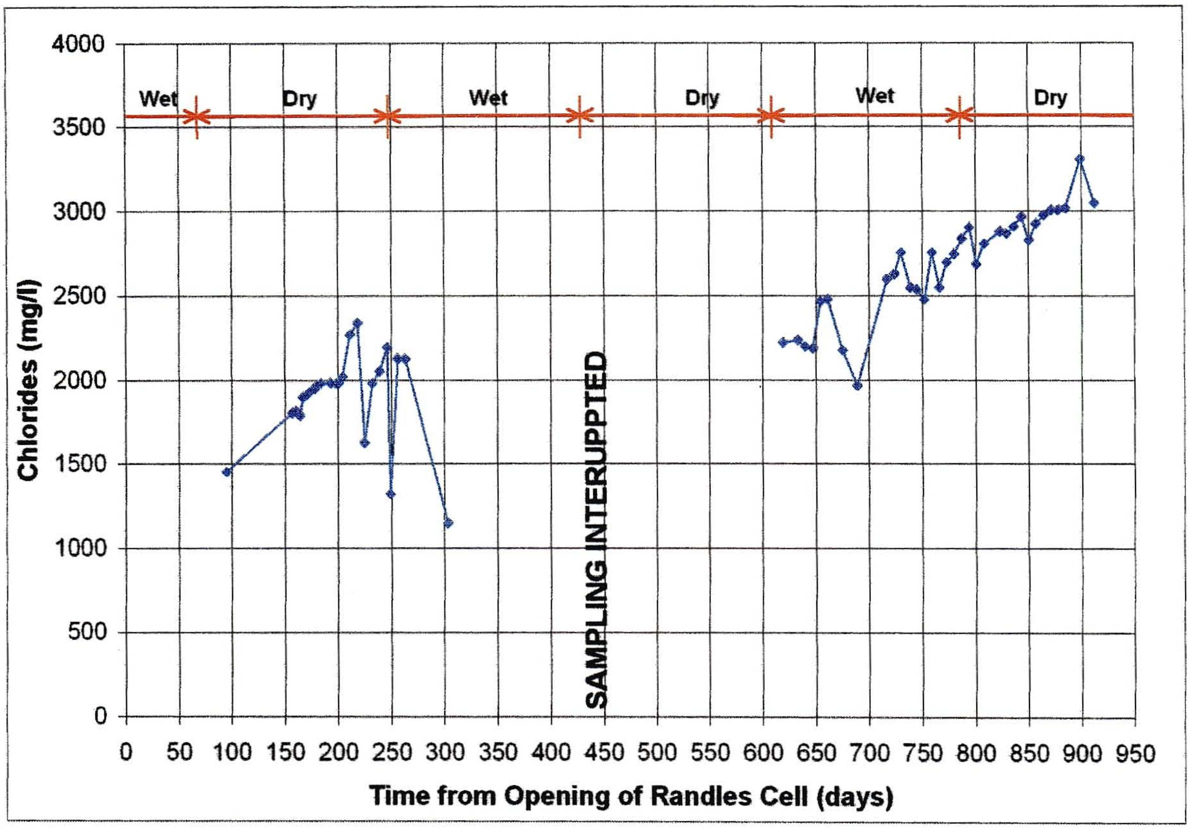


Figure 6.4 Variation of the chlorides concentration with time for the Randles Cell Leachate

6.2.4 Alkalinity Analyses

Figure 6.5 shows the variation of the leachate alkalinity (measured as calcium carbonate) with time. The first two samples showed relatively low alkalinity concentrations. Within six months the alkalinity increased to between 5000 and 6000 mg/l. This was most likely caused by the lixiviation of easily soluble inorganic ions (e.g. sodium, calcium, magnesium, chloride) from the waste body, forming carbonates and bicarbonates. The relatively high alkalinity concentrations may have provided a strong buffer, resulting in a relatively stable pH (as shown in Section 6.2.1).

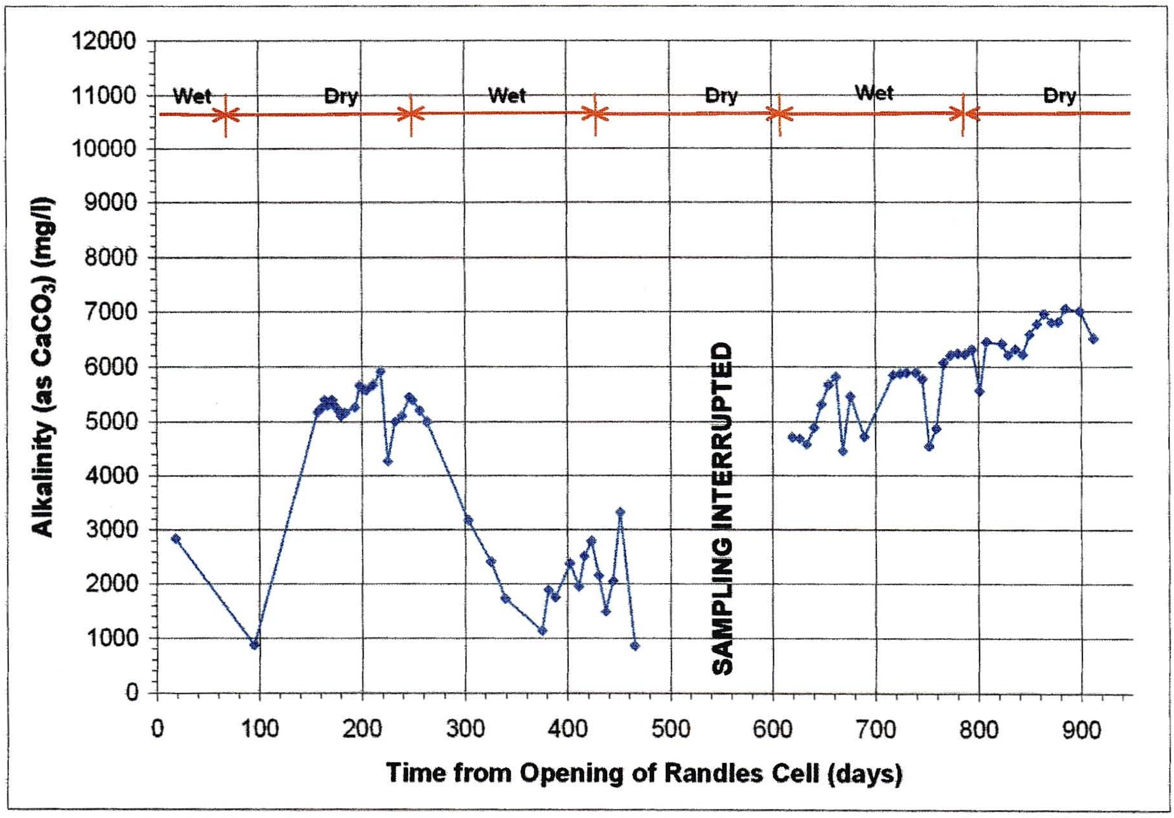


Figure 6.5 Variation of the alkalinity concentration with time for the Randles Cell leachate

The subsequent drop in alkalinity concentrations after approximately 300 days was possibly due to leachate dilution during the first wet season after disposal operations commenced.

After approximately 600 days, the alkalinity concentrations were typical of a fully methanogenic leachate. The trend in the alkalinity concentrations after this time is to increase. This is most likely due to the continued lixiviation of readily soluble material made available by the ongoing deposition of fresh waste.

6.2.5 Ammoniacal-Nitrogen Analyses

Figure 6.6 shows the variation of ammoniacal nitrogen in the leachate with time. The ammoniacal-nitrogen concentrations in the early samples, apart from the first two samples, are typically acetogenic, ranging between 500 and 800 mg/l). Andreottola and Cannas (1992) report a range of 500 – 1000 mg/l for an acetogenic leachate. The overall concentrations are extremely erratic however, with particularly low values from day 303 to day 444, coinciding with the low COD values over the same sampling period. This may also be due to a dilution effect caused by the wet 'season'.

The trend, after the relatively low values, was for the concentration to increase, reaching 1000 mg/l after 30 months. These concentrations are typical of early methanogenic conditions. Strachan et al (1999) report average ammoniacal-nitrogen concentrations for a relatively old, methanogenic leachate produced at the Bisasar Road landfill site (from the Old Existing Waste body, Section 5.3) of 1300 mg/l.

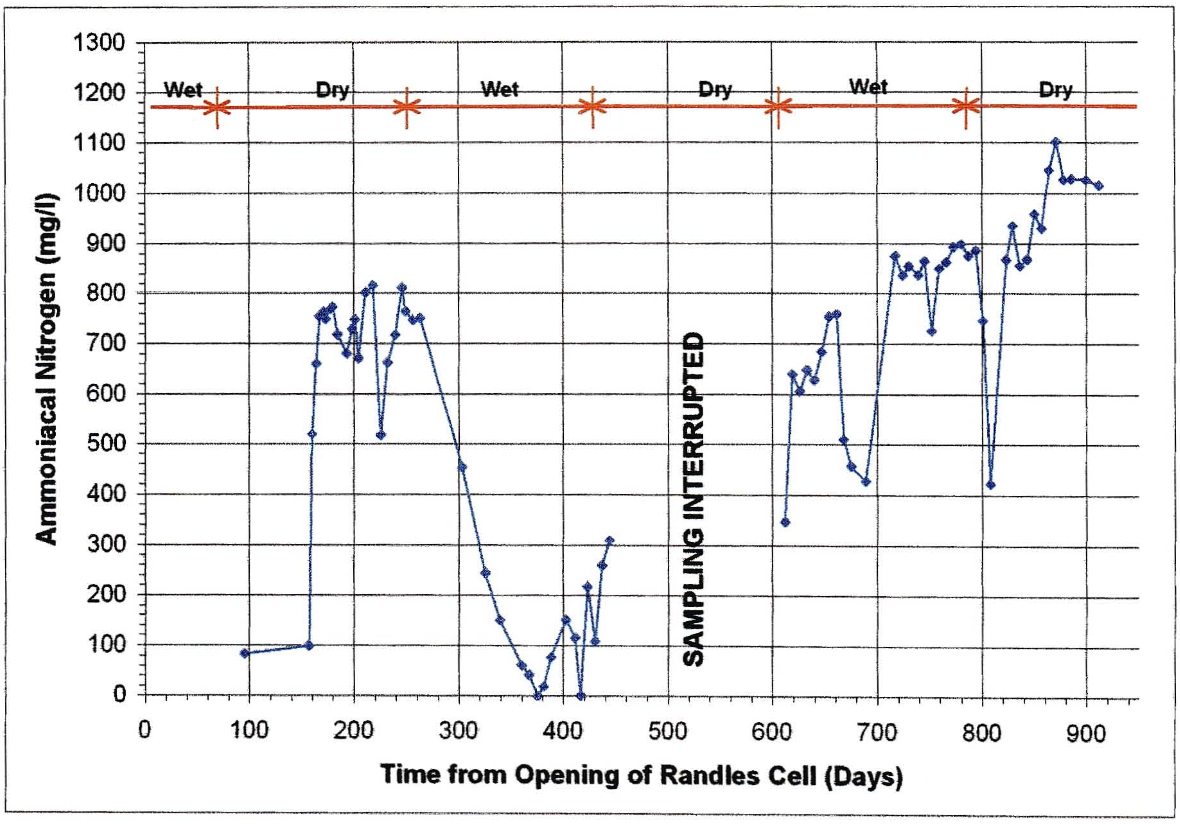


Figure 6.6 Variation of ammoniacal-nitrogen with time for the Randles Cell Leachate

6.2.6 BOD Analyses

Figure 6.7 shows the variation of the BOD with time. BOD analyses where conducted sporadically over the sampling period. Regular analyses were conducted for the first nine months of disposal operations, and again after 20 months. The BOD concentrations in the first nine months (Figure 6.7 (a)) generally ranged between 100 and 800 mg/l, which are typically methanogenic. Robinson (1993) reports a range of 100 – 1800 mg/l, and Ehrig (1989) reports a range of 20 – 550 mg/l for methanogenic leachates.

The BOD concentrations after twenty months (Figure 6.7 (b)) range between 300 and 450 mg/l. These are typical concentrations found in older methanogenic leachates.

The BOD/COD ratio may be used to evaluate the decomposition phase and relative biodegradability of a leachate. Figure 6.8 shows the variation of the BOD/COD ratio with time. The general trend of this ratio for the first nine months of waste disposal was increasing (Figure 6.8 (a)). Andreottola and Cannas (1992) report ratios of approximately 0.7 for acetogenic leachates. As can be seen from Figure 6.8, the trend is tending towards a value of 0.5.

After twenty months, the ratios range between 0.12 and 0.18. This is typical of an older, methanogenic leachate.

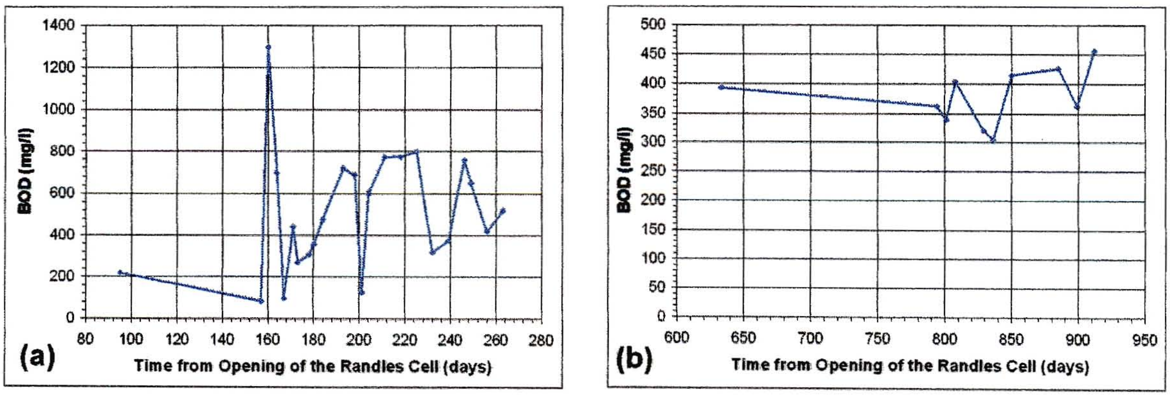


Figure 6.7 Variation of the BOD in the Randles Cell with time for (a) the first 9 months (Bowers, 1999) and (b) after 20 months

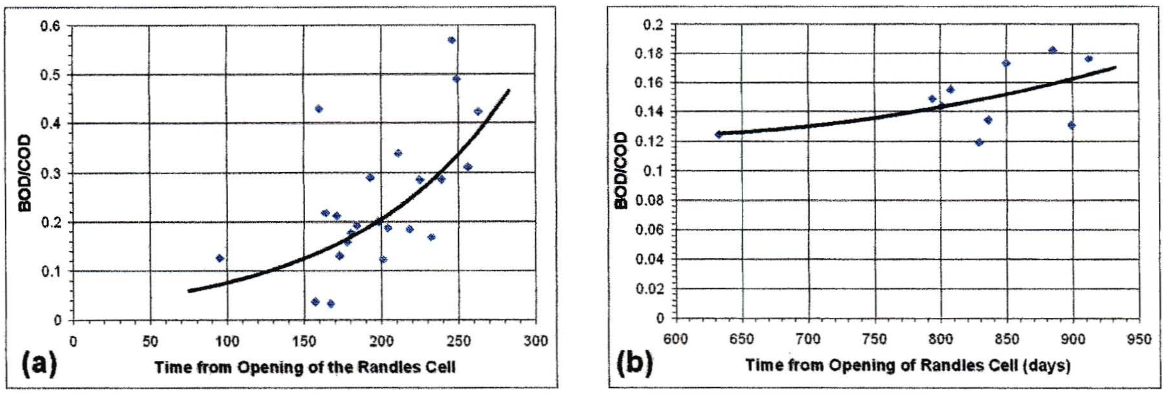


Figure 6.8 Variation of the BOD/COD ratio with time for (a) the first 9 months (Bowers, 1999) and (b) after 20 months

6.2.7 Solids Analyses

Figure 6.9 shows the variation of the Total Solids (TS) and Volatile Solids (VS) with time. The TS concentration over the first nine months varied (apart from the first sample) between 7000 and 9000 mg/l. The TS concentrations dropped after approximately 14 months, again indicating a dilution effect due to the wet 'season'. After approximately twenty months, the TS concentrations rose to the initial range of values reported. There is an increasing trend of TS concentrations after 20 months, with concentrations after 30 months reaching 10600 mg/l. Trois (1996) reported typical TS concentrations of 12000 mg/l in relatively old leachate (waste between five and fifteen years old) extracted from the Old Existing Waste area (Section, 5.3) at the same site.

The concentration of VS over the first nine months ranged between 1500 and 2500 mg/l. VS were again analysed after twenty months, with the results showing similar values as for the first nine months. There is an increasing trend in the VS (as for the TS) after twenty months, with concentrations reaching 3500 mg/l after 30 months. Trois (1996) reported typical VS concentrations from the Old Existing Waste Area of 4000 mg/l.

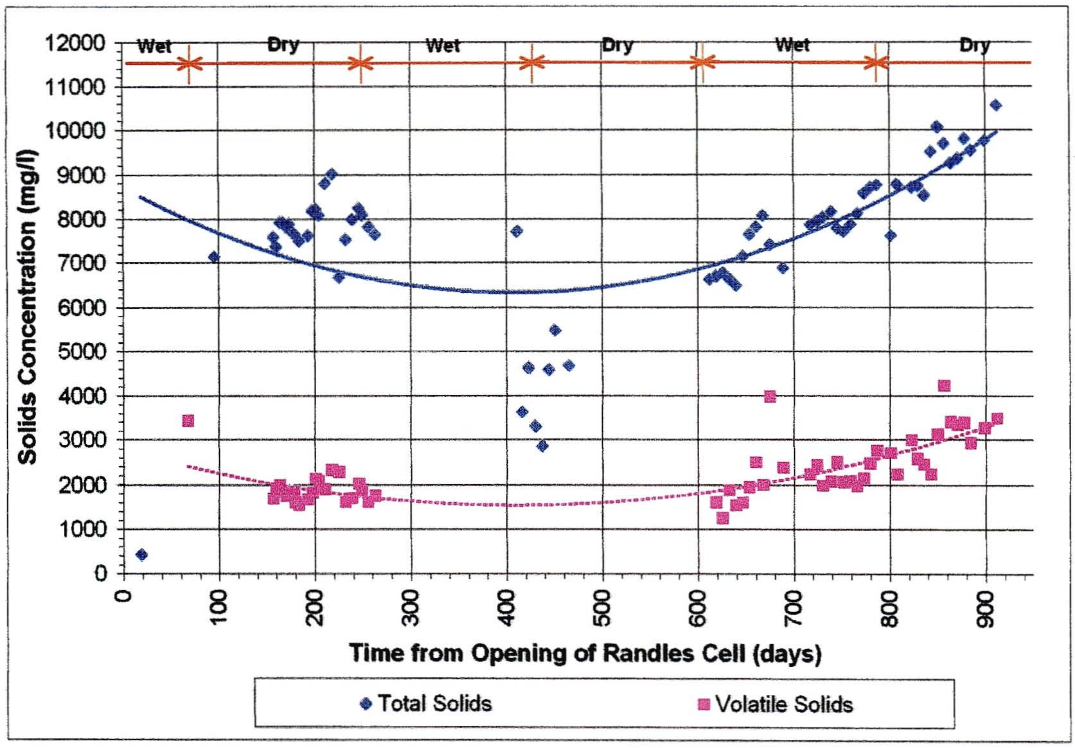


Figure 6.9 Variation of the Total Solids (TS) and Volatile Solids (VS) with time for the Randles Cell leachate

Figure 6.10 shows the variation of the Total Suspended Solids (TSS) and the Volatile Suspended Solids (VSS). The concentrations of TSS and VSS remained within the range 0 – 140 mg/l for the first thirty months of disposal operations, with the majority of samples having values less than 80 mg/l. These values are generally lower than those reported by Qasim and Chiang (1994) (100 – 1000 mg/l).

The Total Dissolved Solids (TDS) in a leachate sample can be calculated as the TSS subtracted from the TS. Since the TS concentrations are considerably higher than the TSS concentrations, the TDS trend follows a similar trend to the TS. In the first nine months, the TDS concentrations generally ranged between 7000 and 9000 mg/l, which is lower than values quoted by Qasim and Chiang (1994) (10000 – 140000 mg/l for the first year of waste disposal). The TDS concentrations after thirty months were approximately 10000 mg/l.

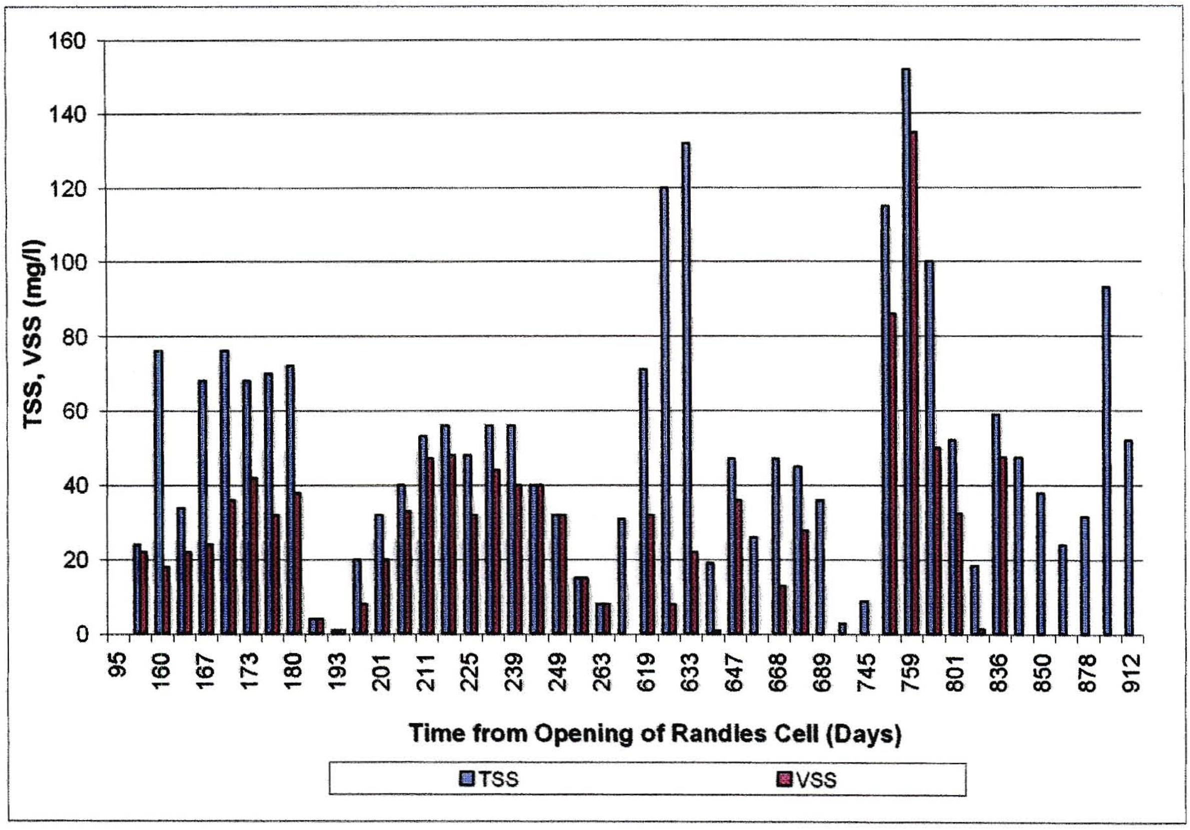


Figure 6.10 Variation of the Total Suspended Solids (TSS) and the Volatile Suspended Solids for the Randles Cell leachate

The Fixed Solids (FS) can be determined by subtracting the VS from the TS. The volatile fraction of the TS may be used to estimate the amount organic matter (and therefore the extent of the bacterial population). The FS generally represent the mineral (inorganic) content of the leachate. When determining the VS concentration, the leachate sample is heated at approximately 550 ^{0}C. At this temperature, all organic matter is volatilised (VS), while the inorganic matter (FS) remain as ash. The ratio of VS to FS may therefore be used as an indication of the relative amount of organic matter in the leachate. Figure 6.11 shows the variation of the VS/FS ratio with time.

The ratio over the first 300 days lies in the range of 0.2 to 0.4. After 600 days, the ratio generally lies in the range of 0.2 – 0.6 (only two samples showed particularly high ratios). The general trend in the ratio appears to be increasing. Qasim and Chiang (1994) report ratios at the start of landfilling between 1.3 and 2, which gradually decreases as the organic matter in the waste is converted to landfill gas.

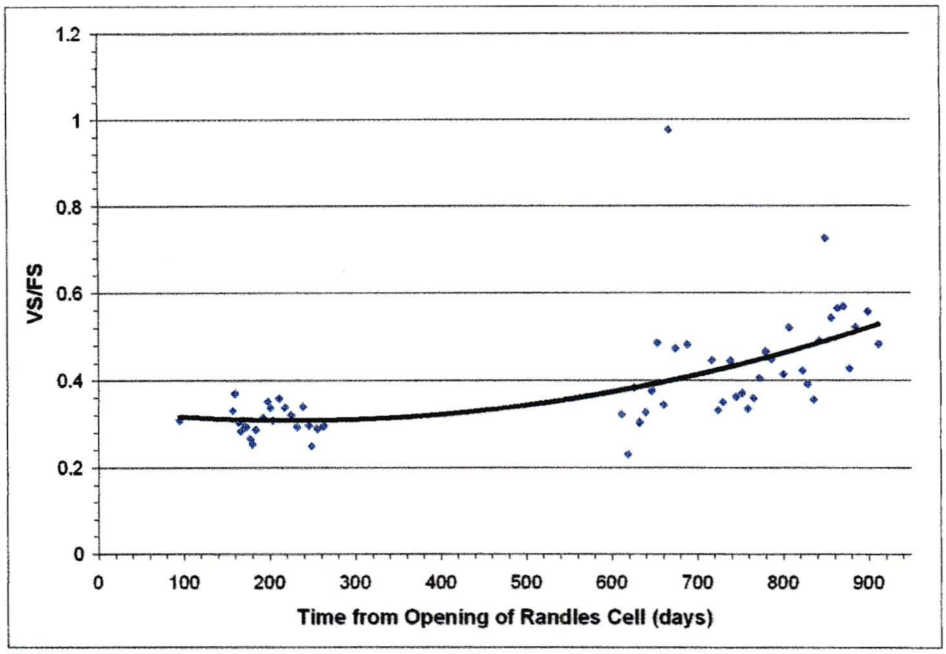


Figure 6.12 Variation of the Volatile Solids to Fixed Solids ratio with time for the Randles Cell leachate

The ratios for the Randles Cell leachate are considerably lower than the literature values and suggest a low proportion of organic matter (and therefore a relatively small bacterial population) is present in the leachate. The general increase in the ratio could be attributed to the ongoing deposition of waste, which continually makes organic matter available.

6.2.8 Volatile Fatty Acids, Sulphates and Phosphates Analyses

The leachate sampled over the first nine months had a considerably larger analysis suite than in the months following. This Section and Section 6.2.9 presents the results of the chemical analyses for the parameters that were only analysed over the first nine months after the opening of the cell. Table 6.1 presents the results of the Volatile Fatty Acids (VFA), sulphate and phosphate chemical analyses.

Table 6.1 The concentrations of sulphates, ortho-phosphates and VFA in the Randles Cell leachate for the first 9 months of disposal operations (Bowers, 1999)

Sampling Date	Time from opening of Cell (days)	Sulphates (mg/l)	Ortho-Phosphates (mg/l)	VFA (as acetic acid) (mg/l)
28/4/99	95	12	0.1	392
29/6/99	157	9.1	29	1400
2/7/1999	160	<1	5.1	3054
6/7/1999	164	18	4.7	1620
9/7/1999	167	<1	29	6054
13/7/99	171	<5	30	1836
15/7/99	173	<5	30	3276
20/7/99	178	<5	31	2004
22/7/99	180	<5	31	3096
26/7/99	184	6.6	31	2436
5/8/1999	193	2.5	31	2640
10/8/1999	198	6.6	29	3228
13/8/99	201	27	29	2088
16/8/99	204	<1	7.4	1668
23/8/99	211	<1	7.4	2640
30/8/99	218	5.8	6.5	1710
6/9/1999	225	11	0.7	1140
13/9/99	232	<1	2	2442
20/9/99	239	1.6	3.3	1626
27/9/99	246	<1	5.7	1812
30/9/99	249	<5	14	2038
7/10/1999	256	27	6.7	2328
14/10/99	263	44	6.5	1446

The concentration of sulphates in the leachate samples is generally lower than the literature suggests. Qasim and Chiang (1994) report values between 50 and 1000 mg/l. Andreottola and Cannas (1992) report values between 10 and 1200 mg/l. The relatively low sulphate concentrations in the leachate indicate that there may have been a reduction to sulphides.

The phosphate concentrations were in the typical ranges reported by Andreottola and Cannas (1992) (0.3 – 25 mg/l); Ehrig (1989) (0.1 – 30 mg/l) and Qasim and Chiang (1994) (23 – 33 mg/l).

The VFA concentrations are typical of an acetogenic leachate. Robinson (1993) reports a range of VFA for acetogenic leachates of 950 – 22500 mg/l. Although most of the VFA concentrations for the Randles Cell leachate samples fall into the lower part of the quoted range, it is important to note that the total VFA in a leachate consists of a number of acids (e.g. propionic, butyric, formic lactic, acetic). In this study, the VFA have been measured only as acetic acid (assumed to be the principal organic acid), whereas the quoted range are total VFA.

6.2.9 Heavy Metals, Metals and Conductivity Analyses

Table 6.2 presents the results of the chemical analyses for heavy metals. The concentrations of the heavy metals are generally lower than those quoted by Qasim and Chiang (1994), Robinson (1993) and Canziani and Cossu (1989). The likely reasons for the low metal concentrations are:

- The waste body that is producing the leachate does not contain large quantities of heavy metals.
- The pH of the leachate is too high to solubilise the heavy metals to the same extent as reported in the literature.

Table 6.2 The concentrations of the heavy metals in the Randles Cell leachate for the first 9 months of disposal operations (Bowers, 1999).

Sampling Date	Time From Opening Of Cell (Days)	Manganese (mg/l)	Iron (mg/l)	Nickel (mg/l)	Copper (mg/l)	Zinc (mg/l)	Cadmium (mg/l)	Lead (mg/l)
28/4/99	95	0.3	1.5	0.2	<0.1	0.2	<0.1	0.2
29/6/99	157	*	1	0.2	<0.1	0.2	<0.1	0.1
2/7/1999	160	1.5	1.4	0.3	<0.1	0.2	<0.1	0.2
6/7/99	164	1.4	1.5	0.1	<0.1	0.3	<0.1	0.7
9/7/99	167	1.1	1.3	0.2	<0.1	0.2	<0.1	<0.1
13/7/99	171	0.8	1.2	0.1	<0.1	0.4	<0.1	<0.1
15/7/99	173	0.8	1.2	0.1	<0.1	0.4	<0.1	<0.1
20/7/99	178	0.9	1.3	0.2	<0.1	0.4	<0.1	<0.1
22/7/99	180	0.9	1.3	0.2	<0.1	0.4	<0.1	<0.1
26/7/99	184	1.1	1.4	0.2	<0.1	0.2	<0.1	0.3
5/8/99	193	1.3	1.4	0.2	<0.1	0.2	<0.1	0.3
10/8/99	198	1.3	2	0.2	<0.1	0.2	<0.1	0.3
13/8/99	201	<0.1	1.2	0.2	<0.1	0.2	<0.1	0.3
16/8/99	204	1.8	2.8	0.2	>0.1	0.3	<0.1	0.2
23/8/99	211	1.5	2.7	0.2	<0.1	0.3	<0.1	0.2
30/8/99	218	1.2	<0.1	0.3	0.1	0.2	<0.1	0.4
6/9/99	225	2.9	5.4	0.2	<0.1	<0.1	<0.1	0.4
13/9/99	232	2.5	6.6	0.2	<0.1	<0.1	<0.1	0.4
20/9/99	239	1.9	6.1	0.2	0.1	0.1	<0.1	0.4
27/9/99	246	1.4	5.8	0.2	0.1	0.2	<0.1	0.4
30/9/99	249	1.5	5.3	0.2	<0.1	0.2	<0.1	0.2
7/10/99	256	0.1	2.1	0.1	<0.1	0.3	<0.1	<0.1
14/10/99	263	0.3	0.5	0.1	<0.1	0.2	<0.1	<0.1

*Sample not analysed for parameter

Table 6.3 presents the results of the chemical analyses for sodium, conductivity, arsenic and mercury.

Table 6.3 The concentrations of Sodium, Mercury, Arsenic and Conductivity for the Randles Cell leachate for the first 9 months of disposal operations (Bowers, 1999).

Sampling Date	Time From Opening Of Cell (Days)	Sodium (mg/l)	Mercury (µg/l)	Arsenic (µg/l)	Conductivity (:s/m)
9/2/99	18	164	*	*	*
28/4/99	95	914	<5	12	117
29/6/99	157	975	<0.5	<5	1312
2/7/1999	160	952	<5	<5	1097
6/7/99	164	1052	<1	11	1359
9/7/99	167	1130	<1	40	1373
13/7/99	171	1140	<1	22	1407
15/7/99	173	1165	<1	22	1402
20/7/99	178	1130	<1	18	1387
22/7/99	180	1130	<1	13	1405
26/7/99	184	534	<1	7	136
5/8/99	193	492	<1	9	135
10/8/99	198	622	<1	18	143
13/8/99	201	572	<1	6.5	145
16/8/99	204	1306	<1	11	1440
23/8/99	211	1450	<1	14	1520
30/8/99	218	1436	<1	49	1562
6/9/99	225	920	<1	44	1128
13/9/99	232	1170	<0.2	44	1350
20/9/99	239	1216	<1	50	1407
27/9/99	246	1320	<1	42	1502
30/9/99	249	1342	<1	28	1476
7/10/99	256	1260	<1	18	1402
14/10/99	263	1266	<1	24	1370

*Sample not analysed for parameter

The concentration of sodium is typically acetogenic (Robinson, 1993, reports a range of 474 – 2400 mg/l). Andreottola and Cannas (1992) suggest that high concentrations of ions (cations and anions) are present in acetogenic leachates. The relatively high conductivities are also typically acetogenic, indicating that there was a high ion concentration in the leachate in the first nine months of disposal operations.

The concentration of the metalloids mercury and arsenic are generally similar to those quoted in the literature (Qasim and Chiang, 1994; Andreottola and Cannas, 1992). The metal concentrations (heavy metals included) are generally low in comparison to those found in crude sewage, and hence do not pose a significant health risk.

6.2.10 Summary of Leachate Characteristics

From the preceding discussion of the individual leachate constituents, it is evident that the Randles Cell leachate had a highly variable composition over the sampling period. The relatively low concentrations of COD and BOD, and the neutral pH suggest that the leachate was methanogenic within nine months of the first waste being placed, however the concentration of some of the constituents suggest that the leachate was acetogenic. A possible explanation for this behaviour is given below:

- There were zones in the waste body that had already reached methanogenisis. Perched water tables may have existed in the waste body, creating zones where ideal conditions for methanogenisis existed, particularly if the cell was well drained. Percolating leachate passing through the methanogenic zones and zones where waste was relatively dry and poorly degraded may have produced a leachate with both acetogenic and methanogenic characteristics. Since all the leachate in the cell is discharged from one pipe, it will have characteristics of both the decomposition phases.
- The relatively low BOD and COD concentrations may have been a result of a waste body with a relatively low proportion of biodegradable matter. An analysis of the waste stream entering the Bisasar Road landfill (Figure 5.4) shows that the potentially biodegradable waste components (solid waste, mixed loads and garden refuse) account for approximately 29 percent of the total waste mass. Within these potentially biodegradable components, only a small proportion may consist of organic matter. This may have resulted in the relatively low concentrations of organic matter, measured as the BOD and

COD. Although the concentrations of volatile fatty acids in the first nine months were in the general range for an acetogenic leachate, they were relatively low and suggest a low proportion of organic matter. The low volatile solids to fixed solids ratios also suggest a low proportion of organic matter.

The decreases in concentration of the majority of the leachate constituents to relatively low levels, between nine and sixteen months, suggest that the leachate had become diluted. This was most likely due to the influence of the wet 'season' over this period, which had a considerably higher than average rainfall.

The leachate characteristics after 20 months were typically methanogenic. The general trend of the parameters after the aforementioned period was increasing, which was most likely due to ongoing landfill operations. The leachate characteristics may have been influenced by younger waste in the acetogenic phase.

The continued placement of fresh waste does not make it possible to determine the exact time scale involved in reaching methanogenic conditions. The heterogeneous nature of the waste body, which may result in poorly drained areas (perched leachate horizons) and preferential leachate pathways, produces a highly variable leachate, which includes both acetogenic and methanogenic characteristics. Considering the relatively low concentrations of COD and BOD and the neutral pH of the leachate however, it is apparent that parts of the waste body were methanogenic within nine months of disposal operations.

It is evident that the waste body reacts well to rainfall and climatic variations. The rainfall is sufficient to provide natural flushing of the cell, and hence, to reduce the leachate polluting potential during the wet seasons. The installation of a drainage layer throughout the base of the cell is proving to be an appropriate engineering solution in order to enhance leachate drainage.

The relatively low biodegradability of the leachate (low BOD, COD and BOD/COD ratios), particularly after twenty months, infers that biological treatment would be concerned more with the removal relatively high concentrations of ammoniacal-nitrogen than organics.

6.3 MARIANNHILL CELL 1 LEACHATE CHARACTERISATION (Mariannhill Landfill Site)

A research project on the treatability of the Mariannhill leachate was undertaken from October 1998 until December 1999 (Strachan, 2000). The research included the collection and analysis of leachate samples from a header tank, prior to discharge to sewer (Section 5.5.2). Landfill operations in Cell 1 were completed in April 1999, and then Cell 2 was opened. The leachate in the header tank after the opening of Cell 2 consisted of a mixture of both leachates (Section 5.4), and hence it is not possible to present cell-specific analytical leachate results after the closure of Cell 1. The subsequent leachate analyses that were conducted at the University of Natal from September 2000 to August 2001(Section 5.5.2) are presented in Sections 6.3.1 to 6.3.6.

Table 6.4 presents a summary of the leachate composition sampled from October 1998 to April 1999 (closure of Cell 1). Twenty-three samples were analysed over this period. The first sample was taken fifteen months after the opening of the cell. The analytical results for each leachate sample is presented in Appendix A1.

Table 6.4 Summary of the leachate composition for Mariannhill Cell 1 from October 1998 – April 1999 (adapted from Strachan, 2000)

	pH	COD (mg/l)	Ammoniacal -Nitrogen (mg/l)	Alkalinity (mg/l)	Sodium (mg/l)
Minimum	7.50	940	8	940	800
Maximum	8.80	3430	1028	6200	1730
Mean	7.91	1452	385	4380	1112
Standard Deviation	0.33	567	258	1083	244

The leachate sampled over this initial period had a relatively low average COD concentration and a slightly alkaline average pH, which are typical of a methanogenic leachate. The average concentration of ammoniacal-nitrogen was low (Andreottola and Cannas (1992) suggest values between 500 and 1000 mg/l for a relatively young leachate), and may have been because of a waste body with a small proportion of proteinous materials. The trend of the ammoniacal-nitrogen concentrations in samples 14 to 23 (presented in Appendix A2, Table A2.4) was to increase, suggesting that parts of the waste body were acetogenic. This most likely resulted in the continued release of ammonia, which is not converted in an anaerobic environment, thereby leading to an increase in ammoniacal-nitrogen concentrations in the leachate. The alkalinity and sodium concentrations are typically methanogenic. The standard deviations of the leachate data are relatively high for the COD, ammoniacal-nitrogen and alkalinity parameters however. This indicates that the leachate had a variable composition over the sampling period, suggesting that stable methanogenic conditions had not yet been reached. The waste body was most likely in the early methanogenic phase.

The leachate was sampled over only one wet 'season' (Section 6.1) and therefore the influence of rainfall events on the leachate characteristics could not be determined. The results of the leachate analyses conducted at the University of Natal are presented below. Table 6.5 presents the leachate sample numbers and dates on which each sample was collected.

6.3.1 pH and COD Analyses

Figure 6.13 shows the variation of the pH and COD for the leachate. The first sample was taken approximately 3.17 years after the opening of the cell (October 2000; 1.42 years after the closure of the cell) and the last sample was taken approximately 4.08 years after the opening of the cell (August 2001; 2.33 years after the closure of the cell).

As can be seen in Figure 6.13, the pH of the leachate over the sampling period consistently remained between 7 and 8.5. The COD concentration generally ranged between 1000 and 2000 mg/l, and only two samples had a concentration greater than 3000 mg/l. These parameter values are typical of a methanogenic leachate.

Table 6.5 Sample numbers and dates on which each sample was collected for the Cell 1 leachate.

SAMPLE NUMBER	DATE OF SAMPLING EVENT	SAMPLE NUMBER	DATE OF SAMPLING EVENT
1	4/10/2000	19	14/03/01
2	11/10/2000	20	28/03/01
3	18/10/00	21	4/4/2001
4	25/10/00	22	11/4/2001
5	1/11/2000	23	18/04/01
6	8/11/2000	24	3/5/2001
7	15/11/2000	25	9/5/2001
8	22/11/2000	26	16/05/01
9	28/11/2000	27	23/0501
10	13/12/2000	28	30/05/01
11	12/1/2001	29	6/6/2001
12	23/01/01	30	13/06/01
13	1/2/2001	31	20/06/01
14	7/2/2001	32	27/06/01
15	14/02/2001	33	4/7/2001
16	21/02/2001	34	18/07/2001
17	28/02/2001	35	1/8/2001
18	7/3/2001		

Note: Sample was collected 3.17 years after the opening of the cell. Sample 35 was collected 4.08 years after the opening of the cell.

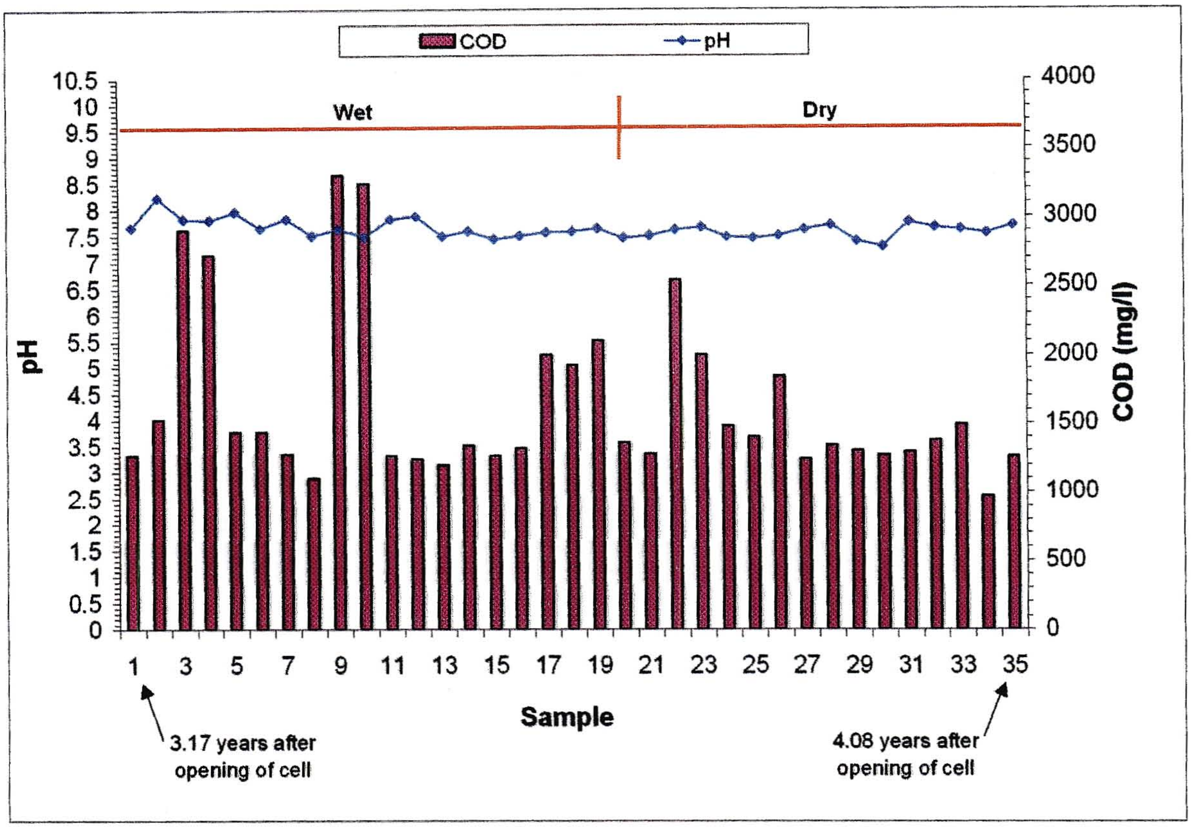


Figure 6.13 Variation of the pH for the Cell 1 leachate

Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

The range of COD concentrations was relatively narrow, and indicates that the wet and dry 'seasons' did not have a marked effect on the leachate characteristics. This second sampling campaign began more than one year after the closure of the cell when the waste body was at its maximum depth, which may have resulted in relatively low hydraulic conductivities and long hydraulic retention times for percolating rainwater (as discussed in Section 6.2.2). The cell also covers a relatively small area (particularly when compared to the Randles Cell), and therefore has a smaller rainfall catchment.

6.3.2 Ammoniacal-Nitrogen Analyses

Figure 6.14 shows the variation of ammoniacal-nitrogen in the leachate. The concentrations generally varied between 300 and 700 mg/l.

The ammoniacal-nitrogen concentrations in the leachate were generally higher than for the first sampling period (Table 6.4). This may have been a result of the continued placement of fresh waste in the cell after the initial sampling period, leading to increased concentrations of ammonia in the leachate. Although landfill operations were complete when the second sampling campaign was undertaken, the conversion of ammoniacal-nitrogen is limited in an anaerobic environment (Andreottola and Cannas, 1992), and hence it remains in the leachate in relatively high concentrations. Another possible explanation for this behaviour is that parts of the waste body may still have been in the acetogenic stage during the second sampling campaign (after the closure of the cell), which resulted in the continued release of ammonia.

As discussed in Section 6.3.1 for the COD concentrations, there does not appear to be any correlation between the wet and dry 'seasons' and the ammoniacal-nitrogen concentrations.

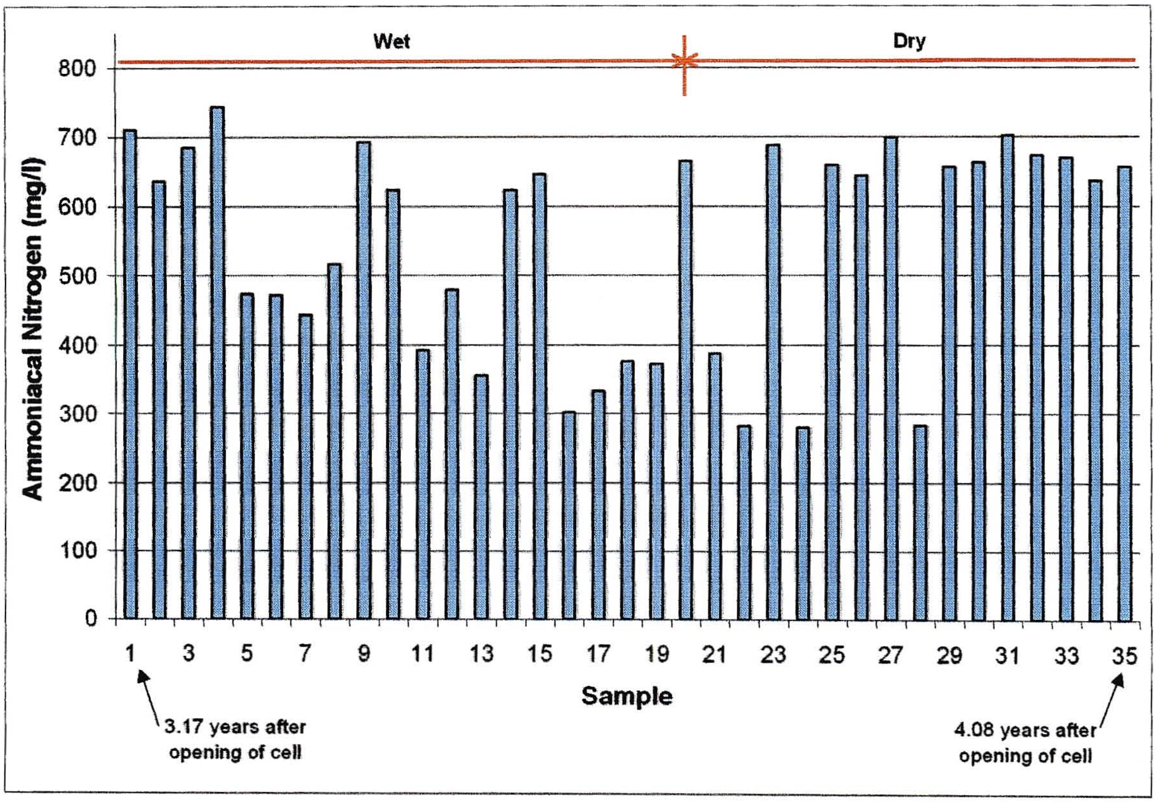


Figure 6.14 Variation of ammoniacal-nitrogen in the Cell 1 leachate

Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

6.3.3 Alkalinity and Chlorides Analyses

Figure 6.15 shows the variation of the alkalinity and chloride concentrations in the leachate. The concentration of chlorides, consistently ranging between 1600 and 2000 mg/l and the alkalinity concentrations, generally ranging between 4800 and 6200 mg/l, indicate a methanogenic leachate.

The consistent concentrations for both parameters again indicate that the rainfall seasons did not dilute or concentrate the leachate.

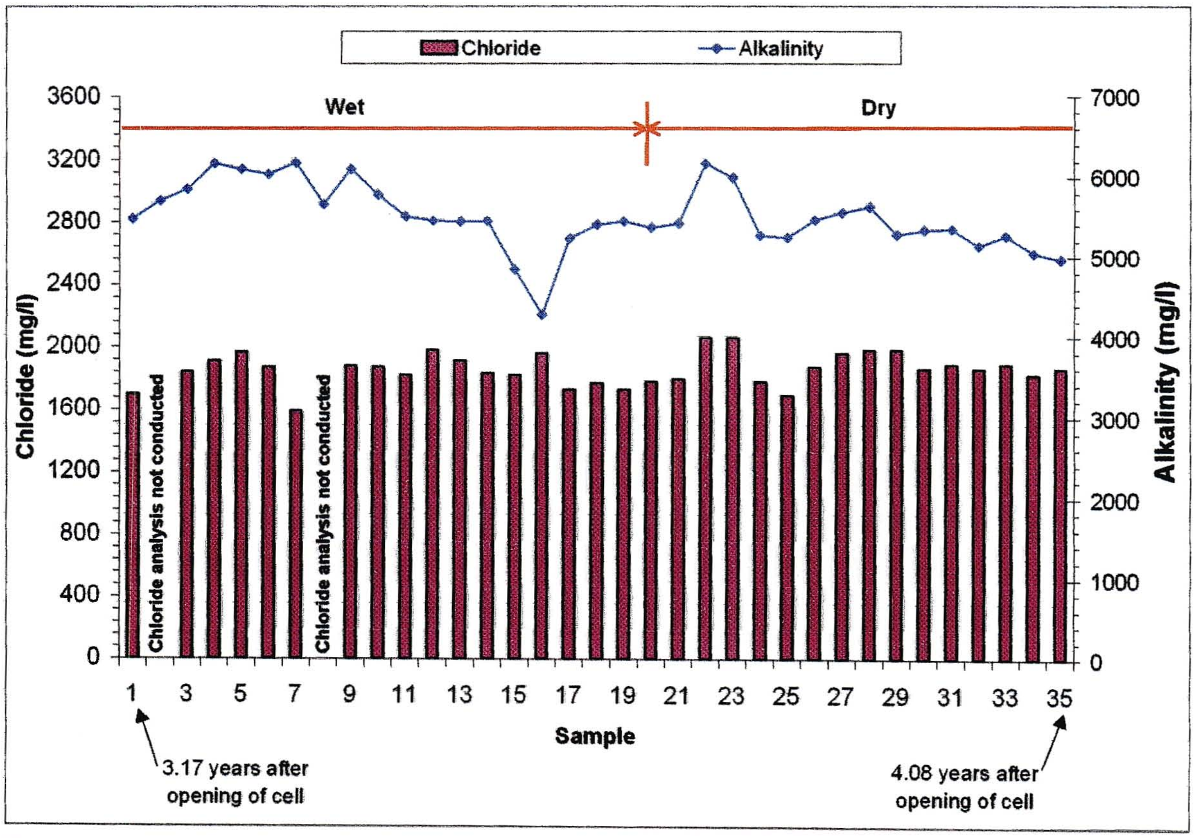


Figure 6.15 Variation of chlorides and alkalinity in the Cell 1 leachate

Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

6.3.4 BOD Analyses

BOD analyses were conducted sporadically over the sampling period. Table 6.5 presents the results of the BOD analyses and the respective BOD/COD ratios.

Table 6.6 Results of the BOD analyses

Sample Number	Sampling Date	BOD (mg/l)	BOD/COD	Season
1	18/10/00	256	0.088	Wet
21	4/4/2001	24	0.019	Dry
25	9/5/2001	68.9	0.049	Dry
26	16/05/01	83.9	0.046	Dry
27	23/0501	159	0.128	Dry
33	4/7/2001	56	0.038	Dry
34	18/07/2001	56	0.058	Dry
35	1/8/2001	125	0.099	Dry

The BOD concentrations are relatively low, and are typical of an older, methanogenic leachate. The low BOD/COD ratios suggest that the leachate had a low biodegradability.

6.3.5 Solids Analyses

Figure 6.16 shows the variation of the Total Solids and Volatile Solids (VS) in the leachate. The TS concentrations generally ranged between 6000 and 7000 mg/l over the sampling period. The VS concentrations generally ranged between 1000 and 3000 mg/l. These values are relatively low when compared to the Randles Cell solids concentrations.

Figure 6.17 shows the variation of the Total Suspended Solids and the Volatile Suspended Solids in the leachate.

The concentrations of the TSS and VSS over the sampling period were highly variable. The suspended solids concentrations were generally low, with a maximum TSS of 161 mg/l, and a maximum VSS of 113 mg/l.

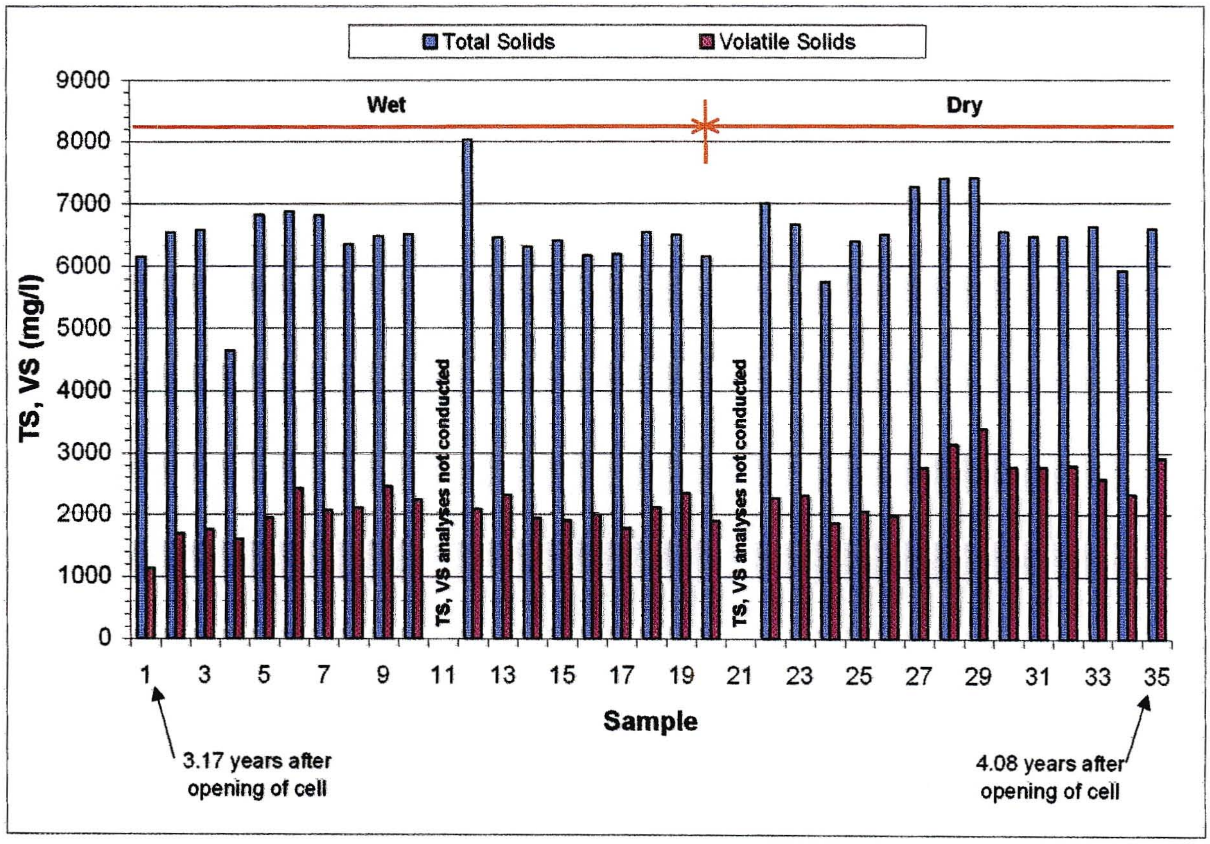


Figure 6.16 Variation of the Total Solids (TS) and Volatile Solids (VS) in the Cell 1 leachate. Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

The high variability of these parameters may be due to the testing procedure. The TSS are determined by passing a well mixed sample through an eight micron filter and then evaporating the residue on the filter paper at 100 – 105 °C. The dry residue represents the TSS. Because of this filtration process, any solids larger than eight microns will remain on the filter as TSS (this may include material such as mobilised sand that has been washed out by percolating leachate). Landfill operations do not provide for homogeneous conditions in the waste body (especially with regards to cover material) and hence some leachate samples may contain more mobilised material than others, which is reflected in turn by the variable TSS concentrations. The VSS is determined by placing the filter paper with residue into a furnace at 550°C and calculating the mass of residue (generally considered organic) that is volatilised. In the instances where relatively high concentrations of organic matter are mobilised (and therefore relatively low concentrations of inorganic matter), the VSS fraction will be relatively high and vice-versa for relatively low concentrations of organic matter.

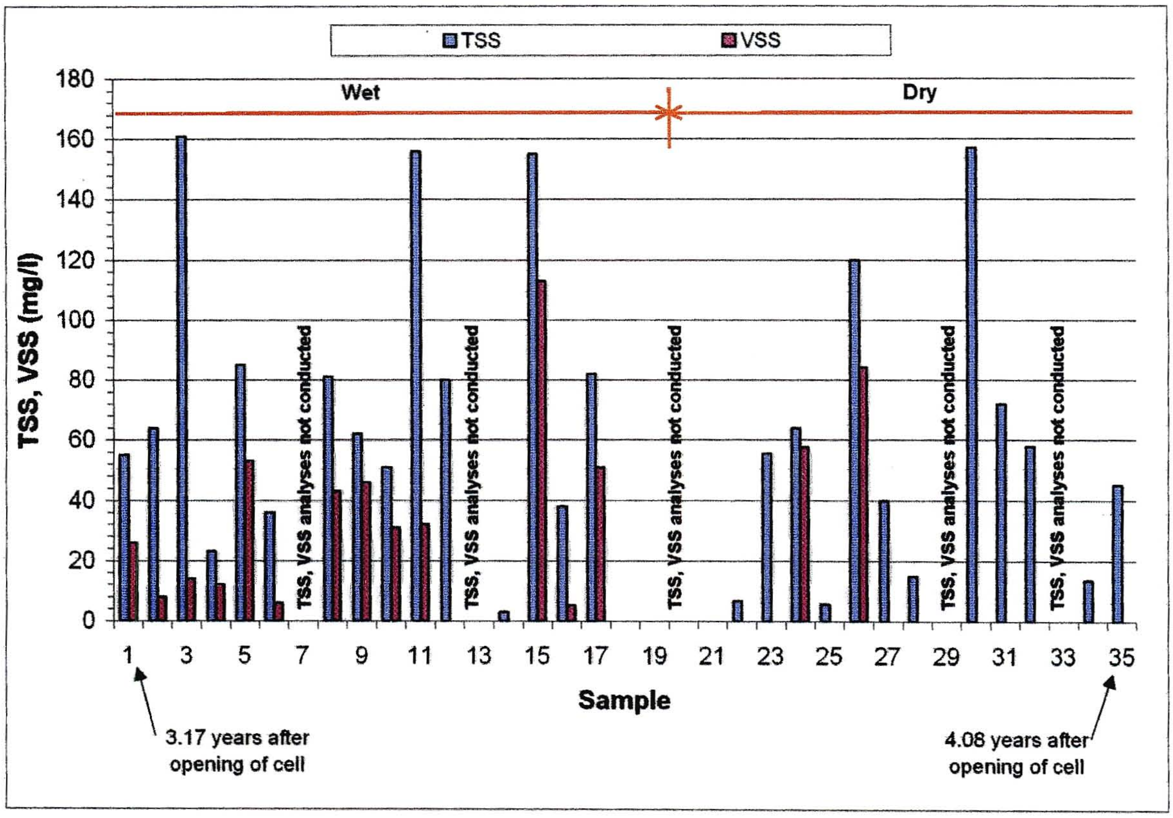


Figure 6.17 Variation of the Total Suspended Solids and Volatile Suspended Solids in the Cell 1 leachate

Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

The Total Dissolved Solids (TDS) concentrations (TSS subtracted from TS) over the sampling period are approximately equal to the TS concentrations, since the TSS are comparatively low. The TDS generally ranged between 6000 and 7000 mg/l. Qasim and Chiang (1994) report an average TDS concentration for a five year old landfill of 6800 mg/l.

Figure 6.18 shows the variation of the Volatile Solids to Fixed Solids ratio over the sampling period (VS/FS). The ratio is generally lower than the literature suggests (Qasim and Chiang, 1994) for a landfill younger than five years, indicating that the leachate has a relatively low biodegradability. The increasing trend of the ratio in the final eight samples analysed, however, suggests that the relative concentration of organic matter in the leachate is increasing.

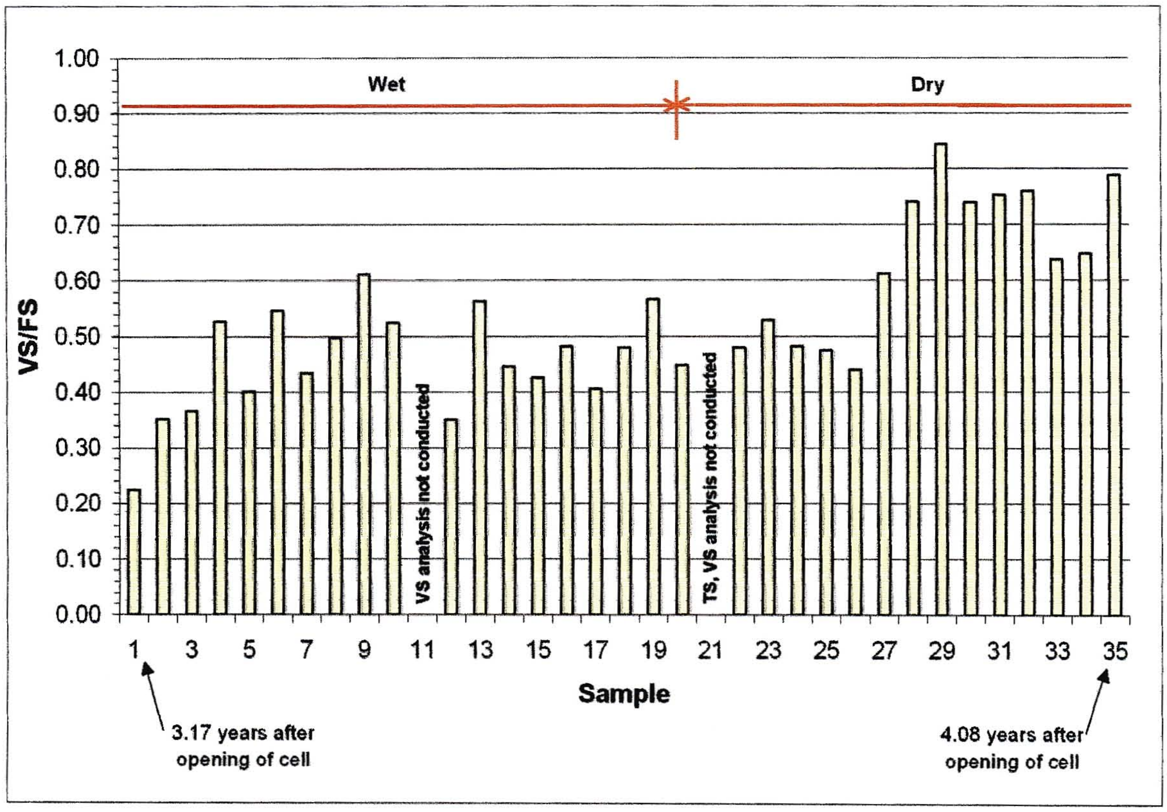


Figure 6.18 Variation of the Volatile Solids to Fixed Solids Ratio for the Cell 1 leachate
Note: Sample 1 collected in October 2000; Sample 35 collected in August 2001

6.3.6 Summary of Leachate Characteristics

The first leachate sampling campaign, beginning fifteen months after the opening of the cell provides an insight into the early behaviour of the waste body. The average COD concentration was relatively low and showed a relatively small variation over the sampling period. The slightly alkaline pH also showed little variability. These two parameters indicate that the leachate was fully methanogenic within the first fifteen months.

The results of the second leachate sampling campaign, which began 1.42 years after the cell was closed, showed that the landfill had reached a stable, methanogenic phase. The wet and dry 'seasons' did not seem to have an effect on the leachate characteristics as far as dilution was concerned. In general, the concentrations of the leachate parameters did not vary significantly over the sampling period (particularly when compared to the Randles Cell), most likely because of the cell closure prior to sampling. Although there was no low permeability capping layer placed over Cell 1, the final layer of cover material was relatively well compacted, which most likely limited the amount of infiltrating rainfall. Without the continued placing of fresh waste and limited rainfall infiltration, the leachate characteristics approach that of a stable methanogenic leachate as the younger, acetogenic waste in the cell decomposes and becomes methanogenic.

The ammoniacal nitrogen concentrations were generally lower than the literature suggests (Robinson, 1989; 1993) for a methanogenic leachate, and may have been due to the waste having a relatively low proportion of proteinous matter.

The relatively low COD and BOD concentrations, and the low BOD/COD and VS/FS ratios suggest that the leachate has a low biodegradability. The treatment of the leachate would therefore be aimed at the removal of ammoniacal-nitrogen rather than organics.

6.4 MARIANNHILL CELL 2 LEACHATE CHARACTERISATION (Mariannhill Landfill Site)

Leachate was collected from the Cell 2 discharge pipe (prior to mixing with the Cell 1 leachate) from October 2000 until August 2001. The first sample was collected approximately seventeen months (1.42 years) after the opening of the cell, during which period the cell was still active. The last sample was collected approximately twenty-seven months (2.25 years) after the cell was opened. The cell was closed during the leachate-sampling period, approximately twenty months (1.67 years) after the opening of the cell. Table 6.7 presents the leachate sample numbers and dates on which each sample was collected.

Table 6.7 Sample numbers and dates on which each sample was collected for the Cell 2 leachate.

Sample Number	Date of Sampling Event	Sample Number	Date of Sampling Event
1	4/10/2000	19	14/03/01
2	11/10/2000	20	28/03/01
3	18/10/00	21	4/4/2001
4	25/10/00	22	11/4/2001
5	1/11/2000	23	18/04/01
6	8/11/2000	24	3/5/2001
7	15/11/2000	25	9/5/2001
8	22/11/2000	26	16/05/01
9	28/11/2000	27	23/0501
10	13/12/2000	28	30/05/01
11	12/1/2001	29	6/6/2001
12	23/01/01	30	13/06/01
13	1/2/2001	31	20/06/01
14	7/2/2001	32	27/06/01
15	14/02/2001	33	4/7/2001
16	21/02/2001	34	18/07/2001
17	28/02/2001	35	1/8/2001
18	7/3/2001		

Note: Sample 1 was collected 1.42 years after the opening of the cell. The cell was closed 1.67 years after it was opened. Sample 35 was collected 2.25 years after the opening of the cell.

6.4.1 pH and COD analyses

Figure 6.19 shows the variation of the pH and COD in the leachate. The pH generally ranged between 7.5 and 9, with the majority of samples having a pH between 8 and 8.5. The COD generally ranged between 1000 and 2000 mg/l, with only four samples having a COD greater than 2900 mg/l. The leachate pH is relatively more alkaline than both the Randles Cell and Cell 1 leachates, and may have been a result of a slightly different waste composition in the cell. The relatively low COD concentrations are similar to that of the Cell 1 leachate. The pH and the COD both indicate that the leachate was produced from a methanogenic waste body (as for Cell 1).

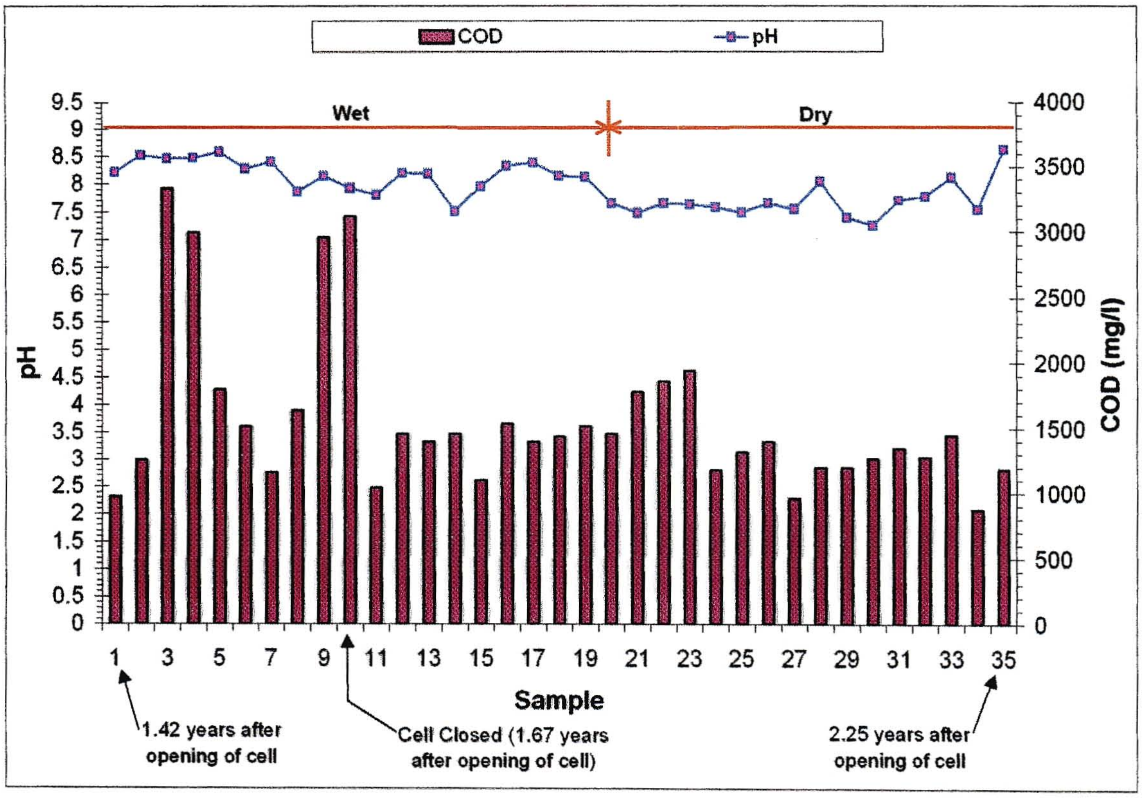


Figure 6.19 Variation of the pH and COD in the Cell 2 leachate

Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

The wet and dry season did not appear to have a marked affect on the leachate pH and COD. The Cell 2 waste body has similar characteristics to Cell 1, and the same reasoning applies as for Cell 1 (Section 6.3.1).

6.4.2 Ammoniacal-Nitrogen Analyses

Figure 6.20 shows the variation of ammoniacal-nitrogen in the leachate. The range of ammoniacal-nitrogen concentrations is similar to the Cell 1 leachate sampled over the same period (400 – 700 mg/l). The ammoniacal-nitrogen concentrations suggest that the waste body was in the early methanogenic phase. In this phase, areas in the cell are still acetogenic, resulting in the continuous release of ammonia.

The relatively low variability of the ammoniacal nitrogen concentrations indicates that there was no correlation between the rainfall 'seasons' and leachate dilution.

6.4.3 Alkalinity and Chlorides Analyses

Figure 6.21 shows the variation of the alkalinity and chloride concentrations in the leachate. The alkalinity concentrations generally varied between 4000 and 6000 mg/l. The chloride concentrations consistently ranged between 1500 and 2000 mg/l. Both these parameters were in the same range as and showed similar characteristics to the Cell 1 leachate.

The relatively low variation in the chloride concentrations indicates that there were no dilution effects due to the wet and dry 'seasons'.

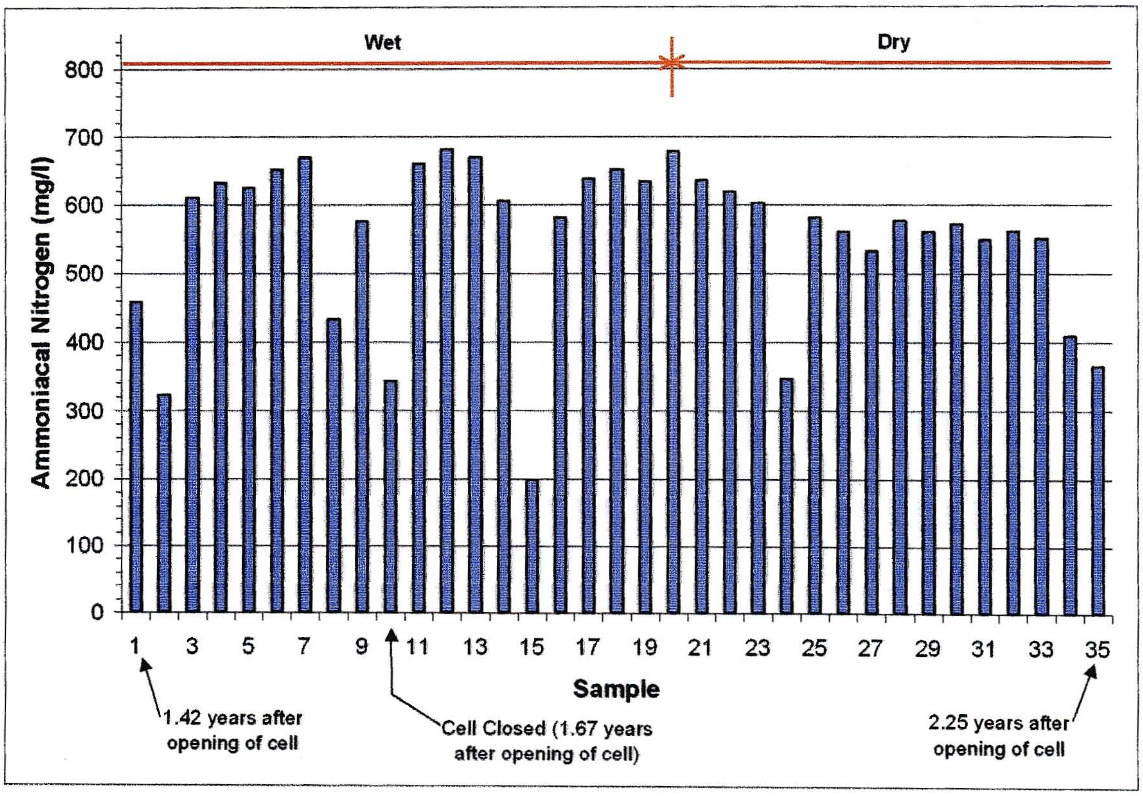


Figure 6.20 Variation of the ammoniacal-nitrogen in the Cell 2 leachate

Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

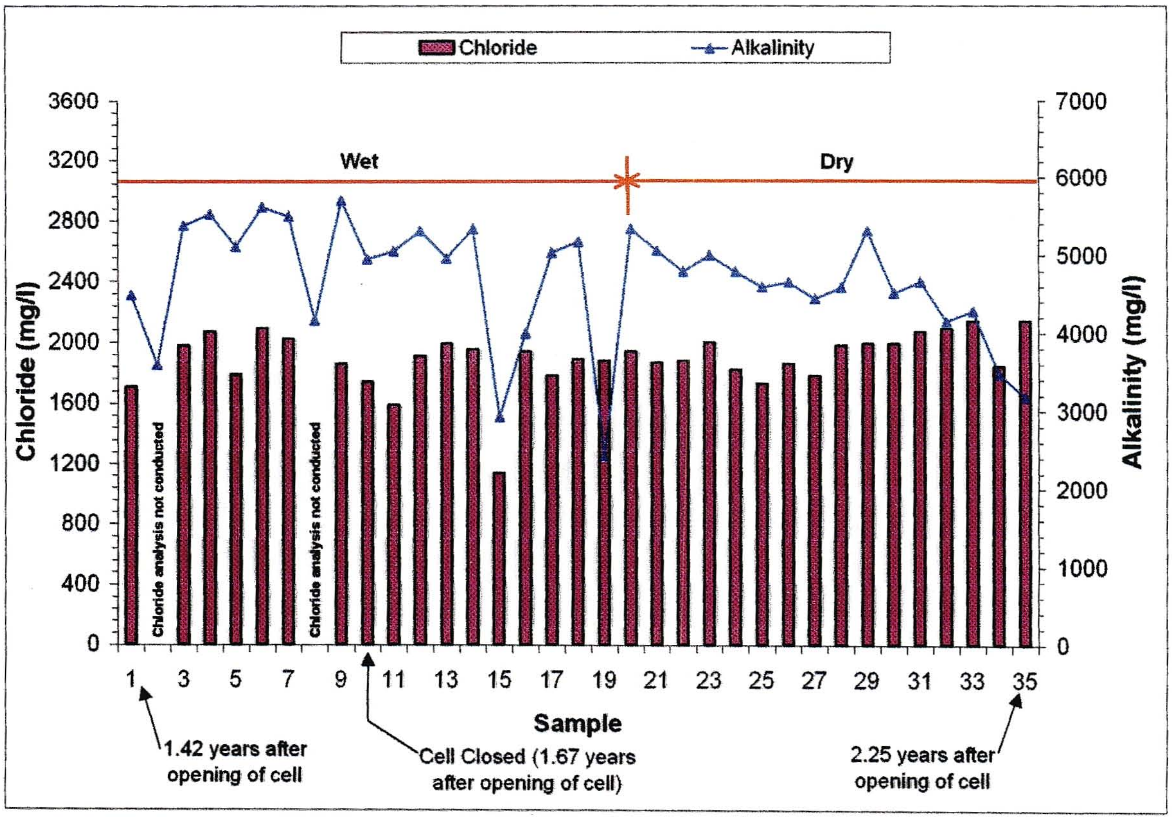


Figure 6.21 Variation of the alkalinity and chlorides in the Cell 2 leachate

Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

6.4.4 BOD Analyses

The BOD was determined sporadically over the sampling period, as for Cell 1. Table 6.6 presents the results of the BOD analyses and the respective BOD/COD ratios. The BOD concentrations were considerably lower than those reported in the literature (Robinson 1993, Andreottola and Cannas, 1992; Ehrig, 1989) for a relatively young leachate (younger than three years). The values are typically representative of a waste body that is approaching methanogenic conditions. The COD/BOD ratios are also considerably low and indicate that the leachate has a poor biodegradability.

Table 6.8 Results of the BOD analyses

Sample Number	Sampling Date	BOD (mg/l)	BOD/COD	Season
1	18/10/00	225.5	0.067515	Wet
21	4/4/2001	35.9	0.020169	Dry
25	9/5/2001	59.9	0.045379	Dry
26	16/05/01	62.9	0.044929	Dry
27	23/0501	83.9	0.069917	Dry
33	4/7/2001	25.1	0.017287	Dry
34	18/07/2001	45.7	0.052229	Dry
35	1/8/2001	72.3	0.061013	Dry

6.4.5 Solids Analyses

Figure 6.22 shows the variation of the Total Solids (TS) and Volatile Solids (TS) in the leachate. The TS concentrations generally ranged between 5000 and 7000 mg/l. The VS concentrations generally ranged between 1000 and 3000 mg/l. These values are similar to those of the Cell 1 leachate.

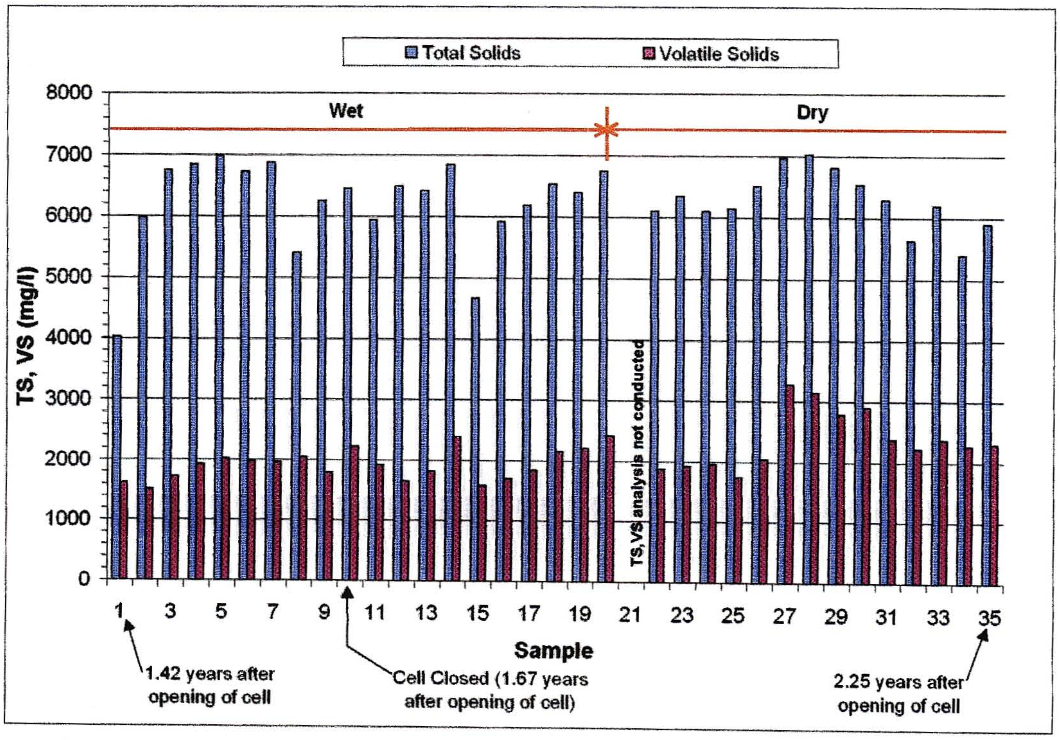


Figure 6.22 Variation of the Total Solids and Volatile Solids in the Cell 2 leachate

Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

Figure 6.23 shows the variation of the Total Suspended Solids (TSS) and the Volatile Suspended Solids (VSS) in the leachate. The TSS and VSS concentrations were relatively low. The maximum TSS and VSS were 104 and 60 mg/l respectively. There is a large variation in concentrations for both parameters over the sampling period as for the Cell 1 leachate (Section 6.3.5).

The Total Dissolved Solids concentrations were in the same range as the TS concentrations, since the TSS concentrations are considerably lower (a large proportion of the TS in the leachate are in the form of dissolved solids).

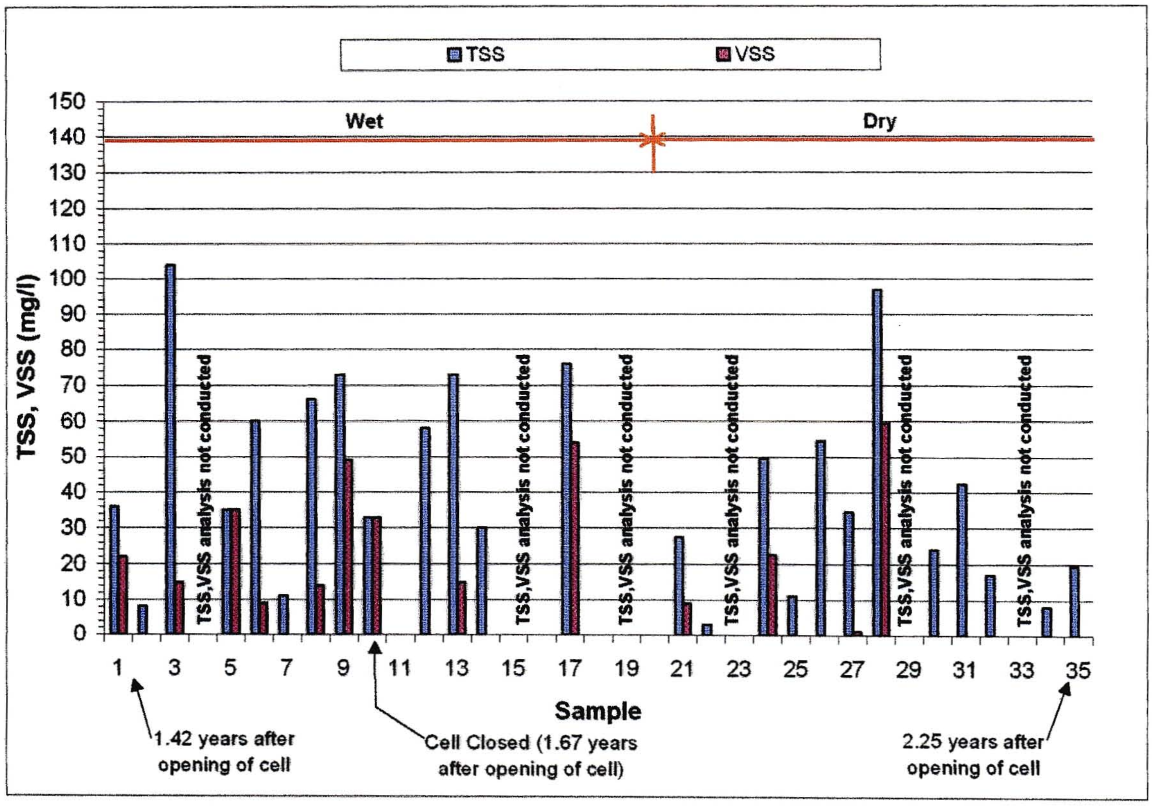


Figure 6.23 Variation of the Total Suspended Solids and Volatile Suspended Solids in the Cell 2 leachate

Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

Figure 6.24 shows the variation of the VS to Fixed Solids (FS) ratio. As for the Cell 1 leachate, the VS/TS ratios were relatively low, indicating that there is a small proportion of organic matter in the leachate. The increase in the ratio at the end of the sampling period suggests that the proportion of organic matter in the leachate is increasing

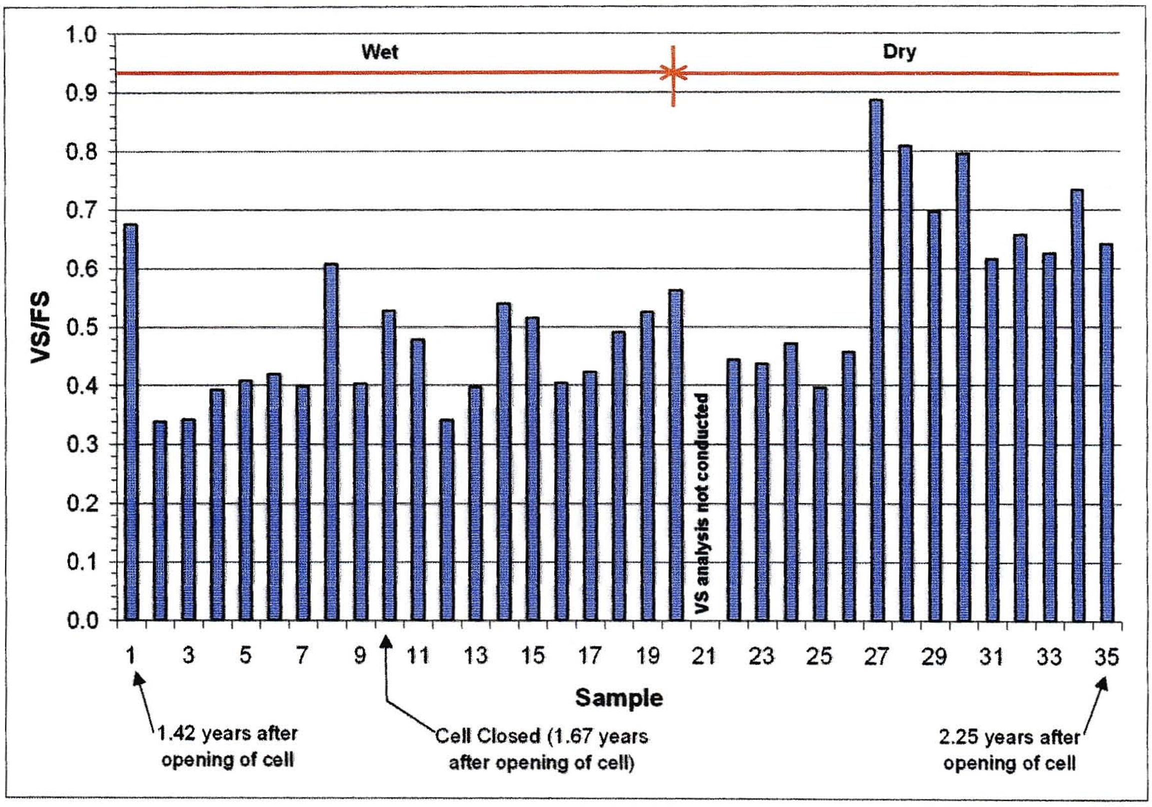


Figure 6.24 Variation of the Volatile Solids to Fixed Solids Ratio in the Cell 2 leachate
Note: Sample 1 collected in October 2000, Cell closed in December 2000, Sample 35 collected in August 2001

6.4.6 Summary of Leachate Characteristics

The concentrations of the leachate constituents over the sampling period are relatively low, particularly when compared to typical leachates of the same age. The leachate characteristics are typical of a stable methanogenic leachate, and suggest a large proportion of the waste body had reached a stable methanogenic stage within the first eighteen months of landfill operations.

The Cell 2 leachate has a particularly low biodegradability (similar to the Cell 1 leachate) and suggests that the wastes entering the site had a low proportion of biodegradable matter. The treatment objectives for the Cell 2 leachate would again be aimed at the removal of ammoniacal-nitrogen.

CHAPTER 7

RESULTS OF LANDFILL GAS CHARACTERISATION AND MODELLING

7.1 INTRODUCTION

The characterisation of the landfill gas emissions from the Bisasar Road and Mariannhill Landfill sites are presented in this chapter, as well as the results of the landfill gas modelling and the SAC calibration. Sections 7.2 to 7.5 present a qualitative characterisation of landfill gas sampled from the shallow probes placed at both landfills. Section 7.6 presents the characterisation from the gas extraction wells placed at Mariannhill Landfill Site. Only the concentrations of methane and carbon dioxide have been shown, as the oxygen concentrations generally only constituted a small fraction of the total gas composition.

7.2 BIOGAS CHARACTERISATION OF THE EXISTING WASTE PLATEAU (Bisasar Road Landfill Site)

Table 7.1 presents the averaged methane and carbon dioxide concentrations (as a percentage in air) for each sampling point in the EWP (for nine sampling campaigns). The standard deviation of the averaged data is also presented. Figure 7.1 presents the biogas concentrations graphically. The results of the individual sampling events are presented in Appendix B1.

It is evident from Figure 7.1 that the majority of the probes yielded biogas concentrations typical of methanogenic waste. Christensen et al (1996) and Farquhar and Rovers (1973) report concentrations of 55% methane and 40% carbon dioxide when methanogenic conditions have been established in the waste body. The top layer of the waste body was approximately one year old when sampling began.

The low biogas concentrations measured at points EWP 1 and EWP 13 could be a result of the following:

- Probes were placed into relatively inert waste (e.g. builders rubble)
- A relatively impermeable layer exists in the waste body below the sampling points, causing the gas to migrate horizontally rather than vertically.

Table 7.1 Average methane and carbon dioxide concentrations (percent volume in air) for the EWP.

Sampling Point	% Methane (CH_4)	Standard Deviation	% Carbon Dioxide (CO_2)	Standard Deviation
EWP 1	7.7	10.8	6.9	8.2
EWP 2	51.1	12.2	41.3	11.0
EWP 3	52.8	9.8	38.6	11.0
EWP 4	53.1	11.1	41.0	10.4
EWP 5	54.6	10.4	43.1	9.2
EWP 6	58.5	15.5	37.8	9.7
EWP 7	56.1	6.4	40.2	7.0
EWP 8	58.9	5.3	40.5	5.5
EWP 9	56.1	5.8	41.5	7.7
EWP 10	55.2	7.4	43.1	8.3
EWP 11	51.6	19.7	28.5	9.5
EWP 12	58.8	1.4	40.8	3.5
EWP 13	14.4	11.8	17.4	7.9
EWP 14	17.5	14.3	15.4	13.3
EWP 15	56.7	6.4	41.9	8.7
EWP 16	59.2	1.5	40.7	2.8
EWP 17	59.1	1.3	40.6	3.1
EWP 18	26.3	19.7	23.6	13.5
EWP 19	57.7	4.4	41.1	6.6
EWP 20	46.4	19.6	38.9	4.3

The relatively large standard deviations for some of the data points show that during occasional sampling events, the measured biogas concentrations deviated considerably from the mean. This was because of relatively intense rainfall events occurring during the sampling campaign, which resulted in parts of the waste body becoming saturated. The measured biogas concentrations after the rainfall events in these areas were therefore lower than samples taken during drier periods.

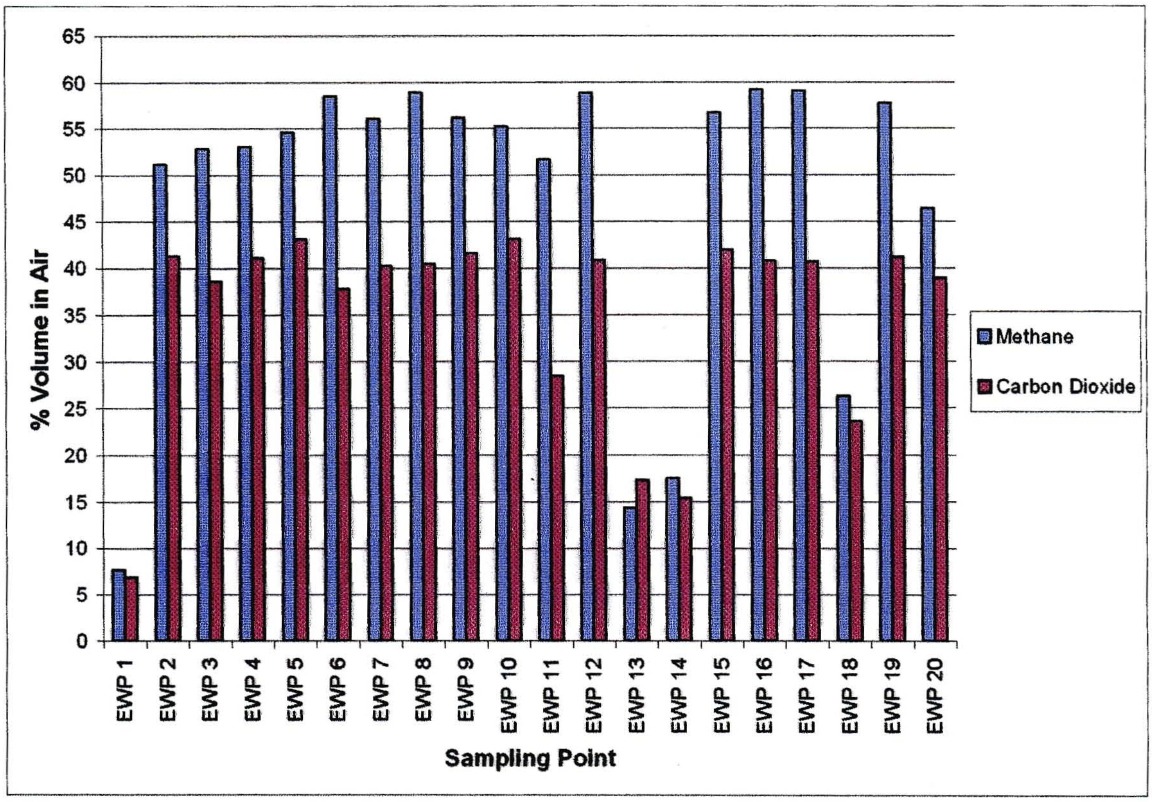


Figure 7.1 Average methane and carbon dioxide concentrations (% v/v) at each sampling point in the EWP.

7.3 BIOGAS CHARACTERISATION OF THE RANDLES CELL (Bisasar Road Landfill Site)

Table 7.2 presents the averaged methane and carbon dioxide concentrations (as a percentage in air) for each sampling point in the Randles Cell (for seven sampling campaigns). The standard deviation of the averaged data is also presented. Figure 7.2 presents the biogas concentrations graphically. The results of the individual sampling events are presented in Appendix B1.

As is shown in Figure 7.2, the sampling points RC1 through RC6 yielded concentrations of methane and carbon dioxide typical of those reported by Christensen et al (1996), Andreottola and Cannas (1992) and Farquhar and Rovers (1973) for waste in the acetogenic stage of decomposition (0 – 40% methane and 60% carbon dioxide). The waste in this area of the cell was approximately three months old.

Table 7.2 Average methane and carbon dioxide concentrations (percent volume in air) for the Randles Cell.

Sampling Point	% Methane (CH_4)	Standard Deviation	% Carbon Dioxide (CO_2)	Standard Deviation
RC 1	33.6	4.8	61.0	3.3
RC 2	20.7	6.5	63.4	6.7
RC 3	40.2	12.6	42.6	10.5
RC 4	25.3	9.5	58.4	8.6
RC 5	31.2	8.8	45.5	8.6
RC 6	48.3	11.0	48.6	7.9
RC 7	11.2	8.0	22.6	16.2
RC 8	2.0	1.8	6.8	3.3
RC 9	6.1	2.6	8.4	4.3
RC 10	47.7	24.3	26.9	16.0
RC 11	47.7	13.0	26.9	5.7
RC 12	16.4	12.2	9.0	8.0
RC 13	64.5	7.7	35.3	3.4

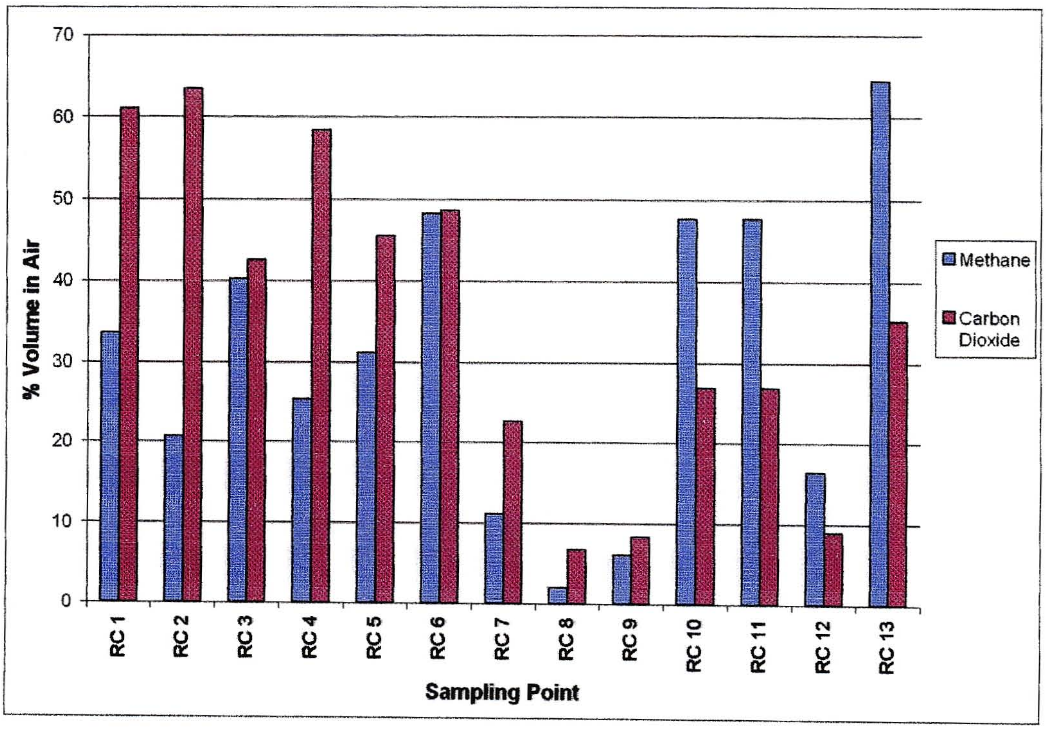


Figure 7.2 Average methane and carbon dioxide concentrations (% v/v) at each sampling point in the Randles Cell.

The sampling points RC 7 through RC 9 yielded considerably lower concentrations of biogas when compared with the other probes in the cell. The concentrations reported for these probes are typical of waste in the early acetogenic stage of waste (Christensen et al, 1996) (methane and carbon dioxide less than 20%). The area of the cell where these probes were located was the last to receive waste before landfilling operations moved out of the Randles Cell (waste was approximately one month old when sampling began). Consequently, the final layer of waste and cover layer was not compacted to the same extent as in other areas of the cell. This may have resulted in a longer aerobic phase, delaying the production of biogas.

The sampling points RC 10 through RC 13, which were located in the oldest waste in the cell (nine months), yielded biogas concentrations typical of waste in the methanogenic stage of degradation.

7.4 BIOGAS CHARACTERISATION OF MARIANNHILL CELL 1 (Mariannhill Landfill Site)

Table 7.3 presents the averaged concentrations of methane and carbon dioxide (percent volume in air) for each sampling point over the one-year sampling period for Mariannhill Cell 1. The standard deviation of the averaged data is also presented. Figure 7.3 presents the biogas concentrations graphically. The results of the individual sampling events are presented in Appendix B1.

As can be seen from Figure 7.3, the average concentrations of methane in the shallow probes lie between 40 and 50 percent for all 22 sampling points, with only two points having an average concentration below 45 %. The concentration of carbon dioxide in the cell ranges between 35 and 40 % for all 22 sampling points. These concentrations are typical associated with a methanogenic waste body. The waste into which the probes were placed was approximately one year old.

The relatively low standard deviations for the methane (maximum 10.99%; minimum 5.21%) and carbon dioxide (maximum 8.44%; minimum 3.80%) concentrations for the 43 samples analysed suggests that the waste body consistently produced methanogenic quality gas during this one year period. It can therefore be inferred that the waste body was already methanogenic at the start of the sampling campaign, and hence that methanogenisis was reached within one year after the last waste was placed in the cell.

The small variability of the gas concentrations spatially also suggests that there is a relatively uniform body of waste (in terms of composition) and hence a uniform production of gas in the cell.

Table 7.3 Average methane and carbon dioxide concentrations (percent volume in air) for Mariannhill Cell 1

Sampling Point	**% Methane (Ch_4)**	**Standard Deviation**	**% Carbon Dioxide (Co_2)**	**Standard Deviation**
1	49.4	6.7	40.0	3.8
2	44.5	5.2	38.1	4.4
3	46.5	10.2	37.4	5.5
4	47.0	7.1	37.6	6.1
5	50.0	7.7	36.5	6.4
6	46.6	9.0	39.0	7.3
7	46.5	8.0	36.4	6.8
8	46.5	7.6	37.2	6.6
9	47.7	7.1	36.3	6.9
10	44.9	11.0	34.7	8.4
11	47.5	8.3	36.7	6.5
12	47.0	8.0	38.1	6.3
13	47.9	7.1	37.2	7.7
14	46.5	8.6	37.7	6.3
15	47.1	7.2	38.3	5.1
16	46.7	9.2	36.5	7.0
17	46.6	9.1	38.8	5.5
18	47.8	9.4	38.9	5.6
19	47.4	9.1	40.0	5.5
20	46.7	8.0	38.4	5.2
21	46.6	9.6	38.1	7.3
22	45.9	9.9	38.8	6.0

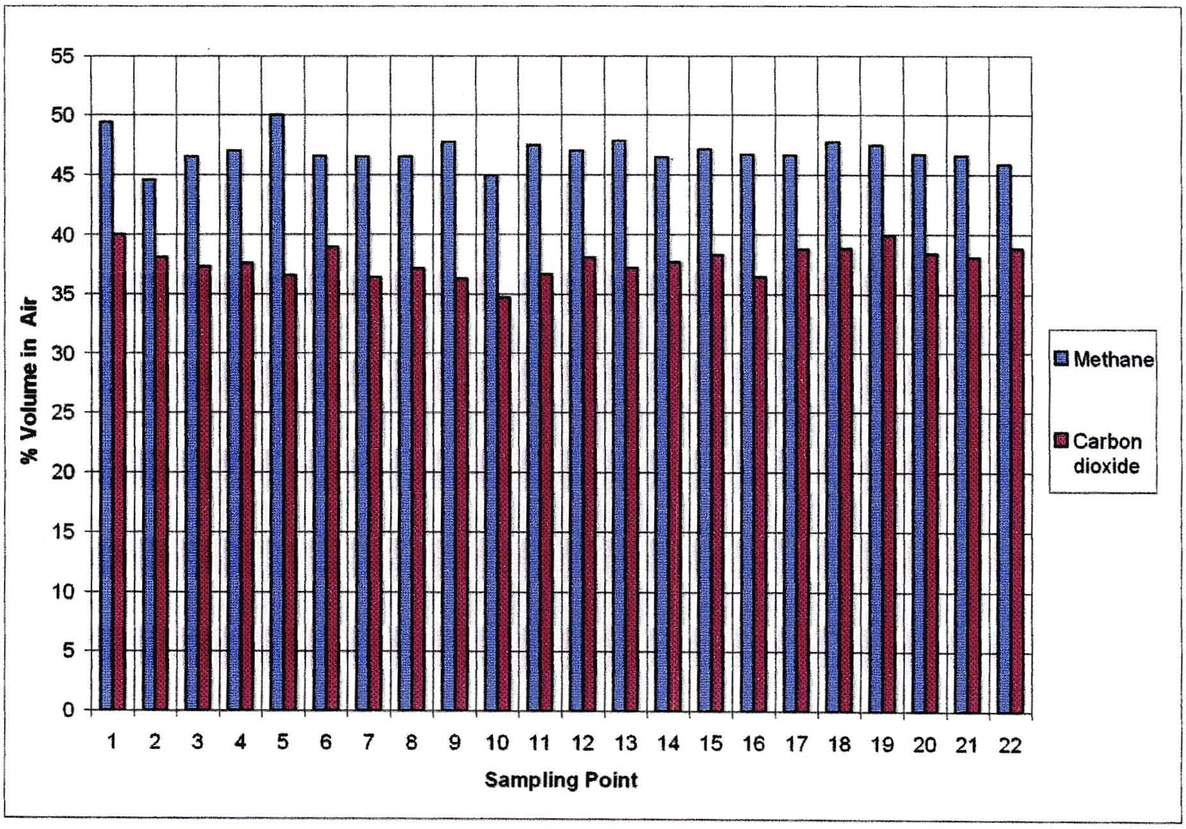


Figure 7.3 Average methane and carbon dioxide concentrations (% v/v) at each sampling point in Mariannhill Cell 1

7.5 BIOGAS CHARACTERISATION OF MARIANNHILL CELL 3 (Mariannhill Landfill Site)

Table 7.4 presents the averaged methane and carbon dioxide concentrations (as a percentage in air) for each sampling point in Mariannhill Cell 3. The standard deviation of the averaged data is also presented. Figure 7.4 presents the biogas concentrations graphically. The results of the individual sampling events are presented in Appendix B1.

As can be seen from Figure 7.4, the biogas concentrations measured indicate that in sampling points 1 – 8, the waste body had become methanogenic within the first six months since the first waste was placed in the cell (waste was between 4 and six months old at the beginning of sampling). The relatively low standard deviations of the data for these probes suggest stable methanogenic conditions. The relatively lower methane concentrations measured at sampling points 8 – 10 suggest that stable methanogenic conditions were not yet reached in all areas of the cell. The waste body in this area was most likely in the initial methanogenic phase (Christensen et al, 1996).

Table 7.4 Average Methane and Carbon Dioxide Concentrations (% v/v) for Mariannhill Cell 3

Sampling Point	**% Methane (Ch_4)**	**Standard Deviation**	**% Carbon Dioxide (Co_2)**	**Standard Deviation**
1	55.0	0.2	47.1	0.8
2	45.5	0.7	44.0	0.4
3	48.6	0.7	42.6	0.5
4	44.0	0.3	42.5	0.4
5	58.1	0.2	43.8	1.0
6	41.9	1.0	43.6	0.1
7	42.1	0.5	46.6	0.2
8	30.0	3.2	45.0	2.3
9	36.8	2.5	44.5	1.3
10	30.5	3.5	41.1	2.5

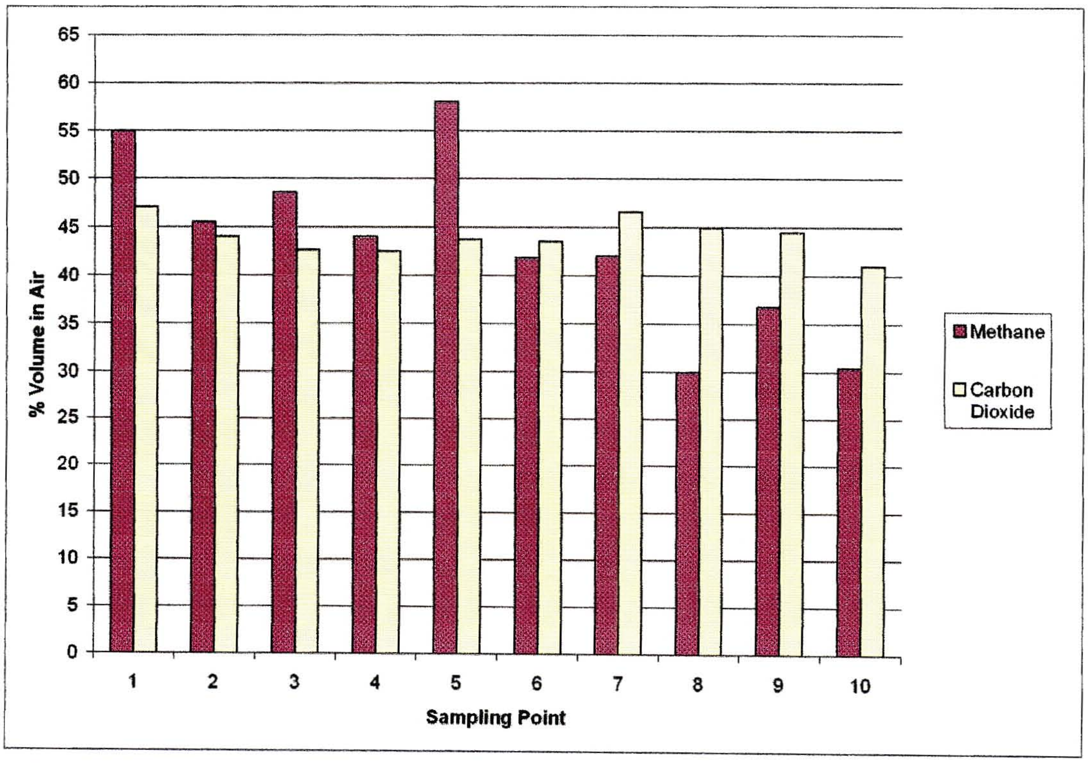


Figure 7.4 Average methane concentration (% v/v) at each sampling point in Mariannhill Cell 3

7.6 BIOGAS CHARACTERISATION OF MARIANNHILL CELL 1 AND 2 (GAS EXTRACTION WELLS)

Table 7.5 presents the average concentrations of methane for each gas extraction well over the three-month sampling period. The standard deviations of the measured concentrations are also presented. Figure 7.5 presents the results graphically. The results of the individual sampling events are presented in Appendix B1.

Table 7.5 Average Methane Concentrations (% v/v) for the gas extraction wells in Mariannhill Cell 1 and 2.

Sampling Point	% Methane (Ch_4)	Standard Deviation
GW1	39.6	4.3
GW2	41.6	4.2
GW3	44.8	4.8
GW4	47.3	3.4
GW5	43.2	3.1
GW6	50.2	2.8

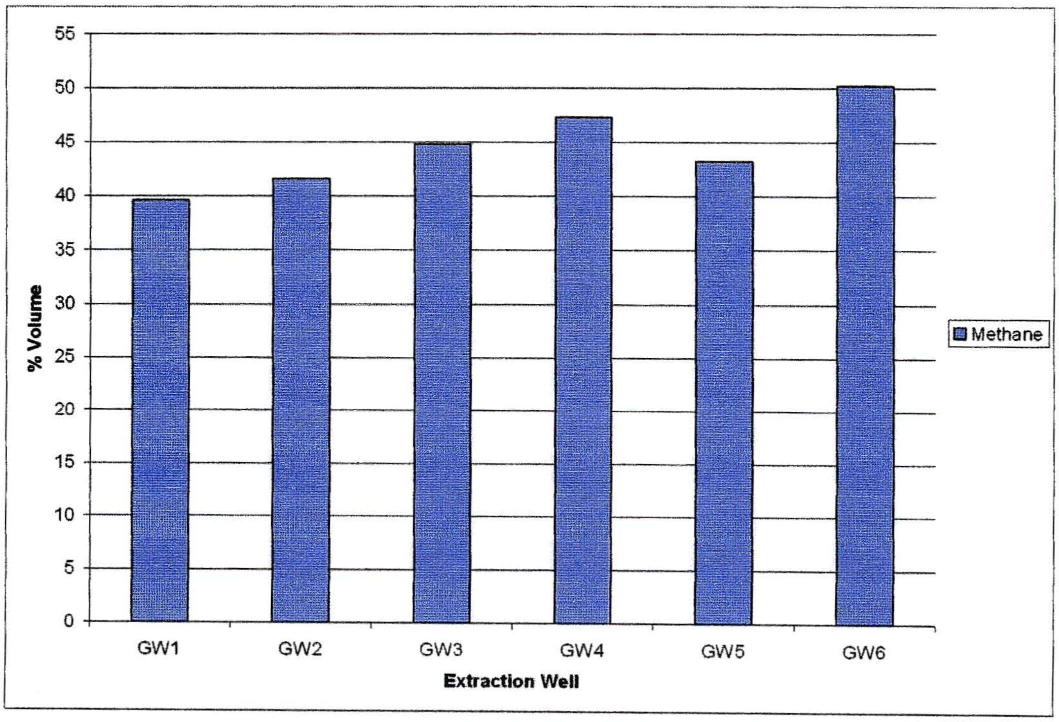


Figure 7.5 Average methane and carbon dioxide concentrations (%v/v) in each gas extraction well

The averaged biogas concentrations measured in the gas wells again indicate stable methanogenic conditions in the waste body. The biogas concentrations measured in the shallow probes placed in the same area (section 7.4) as the gas extraction wells show good correlation to that measured in the wells. The concentrations in the shallow probes tend to be slightly higher however, because in between sampling events excess gas may collect in the probes (residual gas). The active extraction of gas from the wells occurs approximately at the same rate as is being produced in the fill and hence the build-up of gas in the wells is prevented.

The shallow probes in Cell 1 were sampled twice following the installation of the extraction system. The results showed that there was no methane or carbon dioxide in the sampled gas. Since the probes were only placed to a depth of two metres, the non-detection of biogas indicates that the extraction system is effective in reducing biogas emissions to the atmosphere.

7.7 SUMMARY OF THE TIME REQUIRED FOR ESTABLISHMENT OF METHANOGENIC CONDITIONS FOR EACH SET OF SHALLOW PROBES

The monitoring of biogas concentrations in the shallow probes allows for a qualitative understanding of the time span required for stable methanogenic conditions to be reached in the waste body. Table 7.6 presents a summary of the approximate time in which methanogenic conditions were reached for each set of shallow probes. Although it has been shown that methane produced in the waste body within a month (Section 7.3), the results indicate that the approximate time for the establishment of stable methanogenic conditions ranges between six and nine months.

Table 7.6 Summary of the time required for establishment of methanogenic conditions for each set of shallow probes.

Set of Sampling Probes	Age of Methanogenic Waste
EWP	< 1 year
Randles Cell	< 9 months
Cell 1	< 1 year
Cell 3	4 – 6 months

7.8 BIOGAS PRODUCTION MODELLING – CHEMICAL-PHYSICAL/BIOCHEMICAL MODEL

7.8.1 Model Application

Cells 1 and 2 were analysed separately, with four gas producing waste components being considered. The characteristics of the waste components were estimated (carbon content, moisture content etc.), providing the amount of carbon available for conversion to biogas. The components were then separated according to their relatively biodegradability, as discussed in section 5.8.1 (easily biodegradable, biodegradable and slowly biodegradable). The model outputs include the specific and cumulative gas production curves, which provide production rates on a per ton basis. With the mass of waste in each cell known, the total gas emissions can be calculated.

The physical and chemical characteristics of the various waste components were in most cases estimated from the available literature, qualitatively adapted for the sub-tropical climatic conditions experienced in Kwa-Zulu Natal. Determining parameter values from in-situ tests was beyond the scope of this research. Figure 7.6 shows the process followed in obtaining the model outputs

7.8.2 Waste Components

The relative masses of the waste components were based on a combination of weighbridge data and the Waste Stream Analysis (WSA) (Appendix C1). The weighbridge data was used to determine the mass of the waste components entering the site, however it only provides the total mass of 'solid waste' entering the site via the collection vehicles (i.e. household waste). The actual masses of the individual components that make up 'solid waste' are therefore unknown.

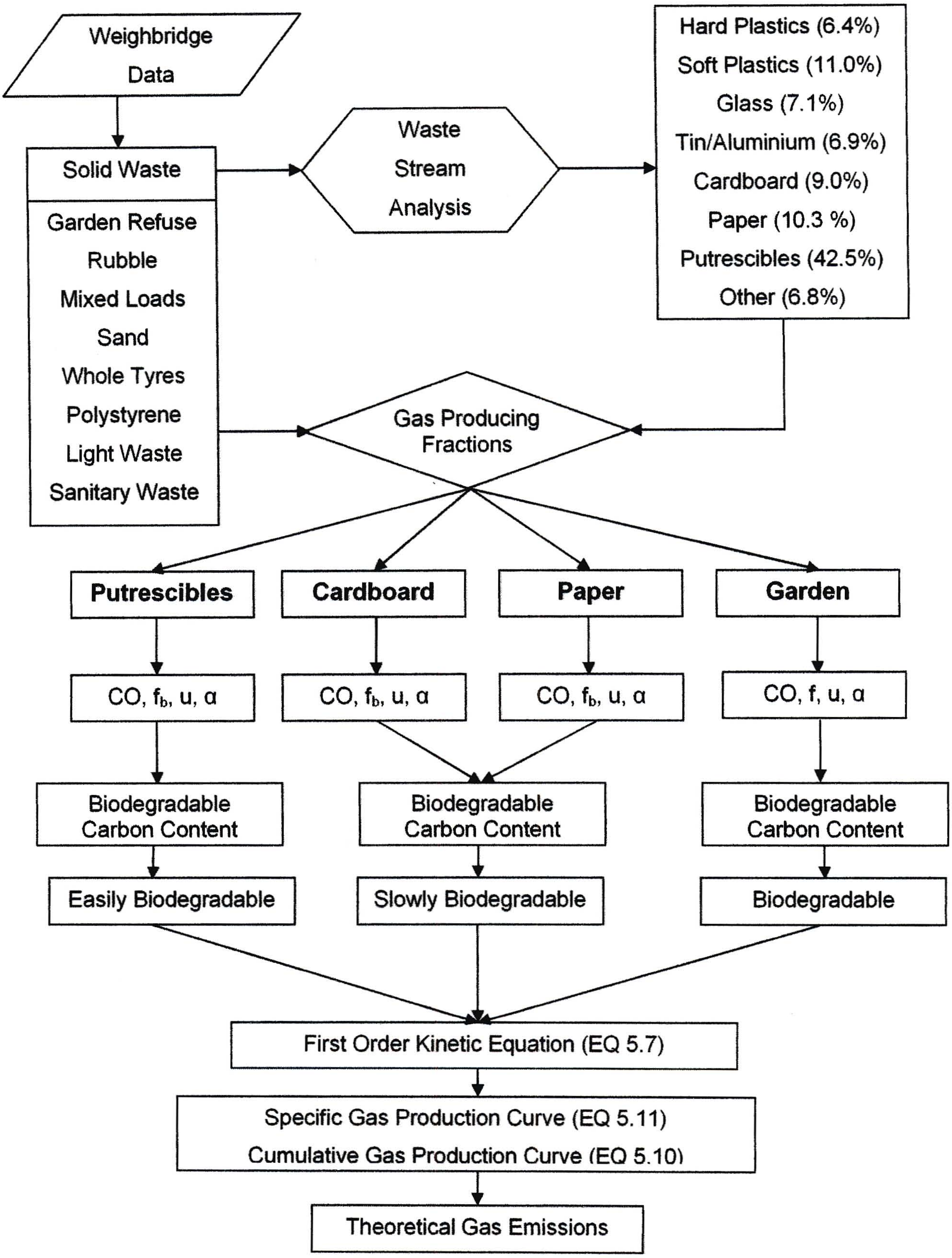


Figure 7.6 Determining gas production rates using the Chemical-Physical/Biochemical Model

It is assumed that the waste stream analysis provides a good estimate of the 'solid waste' composition. The waste stream data for all the housing developments was summed to provide a total mass of each component of waste generated. The relative masses of each component (soft plastics, hard plastics etc.) were then calculated based on the total mass of all the components. This provided the percentage contribution of each component to the total waste stream, as shown in Figure 7.6. The mass of 'solid waste' obtained from the weighbridge data was then separated into the components given by the WSA. The weighbridge and WSA data is presented in Appendix C1.

The four biodegradable waste components that were considered included putrescibles, garden refuse, cardboard and paper. Putrescibles were considered as easily biodegradable; garden refuse as biodegradable; and paper and cardboard as slowly biodegradable.

7.8.3 Organic Carbon Available in Each Waste Component for Conversion to Biogas

The parameter values for organic carbon (CO_i) and the fraction of this carbon that may be converted to biogas ($(f_b)_i$) in each waste component were obtained from Cossu et al (1996) and Gendebien et al (1992). The literature values were considered as representative, since they are a function of the waste component and not of the in-situ conditions. The moisture content in each component (u_i) was adapted from Cossu et al (1996) and Peavy et al (1985). The moisture content for garden refuse quoted from these two literature sources were in the range of 50 – 60 %. The upper bound value was chosen as representative of the relatively wet climate experienced in Kwa-Zulu Natal, which most likely results in wetter garden refuse. The moisture contents for putrescibles, paper and cardboard were not adjusted, since the climatic conditions do not affect the moisture contents of these components.

7.8.4 Biodegradation Rates

There is widespread literature available on the theoretical rates of waste decomposition (k). Muntoni et al (1996) suggest that the rates vary between 0.7 year^{-1} for easily biodegradable fractions (half life of 1 year) and 0.05 year^{-1} (half life of 15 years) for slowly biodegradable fractions. Augenstein and Pacey (1991), Lifshits and Galueva (1997) and Coops et al (1995) indicate rates varying between these two ranges. Half times of one, five and ten years (k = 0.693, 0.193 and 0.069 year^{-1} respectively) have been chosen for the three biodegradable fractions. These relatively high biodegradation rates were considered representative of the warm, humid conditions, which facilitate a higher rate of decomposition. The characterisation of biogas and leachate in this research (Section 6.7 and Section 7.7 respectively) showed that methanogenic conditions are reached in a relatively short time (six to nine months), indicating that the rate of degradation is relatively high. Results of the model with varying k values are presented in Section 7.10.1.

7.8.5 Landfill Temperature

It was not possible to measure landfill temperatures during the course of the research. Various literature sources were consulted, with Yoshida et al (1997) showing temperatures in the Tokyo Port Landfill ranging between 30 and 70^0C in the fill. Houi et al (1997) found that temperatures in a landfill in Southern France (Montech) were extremely varied, with temperatures in the uppermost layers ranging between 29 and 37^0C (0 – 5m below landfill surface), in the middle layers between 50 and 60^0C (5 – 15m below landfill surface) and in the lower layers between 38 and 50^0C (bottom 15 – 20m of landfill). Typical temperatures in a British landfill were shown to be between 30 and 40^0C (Christensen and Kjeldsen, 1989). An average landfill temperature of 45^0 C was therefore considered as representative of the Mariannhill Landfill Site.

Table 7.7 presents all the inputs for the model.

Table 7.7 Inputs for the Chemical-Physical/Biochemical Model

Biodegradability	**Easily Biodegradable**		**Biodegradable**		**Slowly Biodegradable**			
Waste Fraction	Putrescibles		Garden Refuse		Cardboard		Paper	
	Mass (tons)	% of Total in Cell	Mass (tons)	% of Total in Cell	Mass (tons)	% of Total in Cell	Mass (tons)	% of Total in Cell
Cell 1	13103	16.96	11027	14.27	2792	3.61	3192	4.13
Cell 2	14424	13.84	24694	23.70	3513	2.95	3073	3.37
Temp * (°C)**	45		45		45		45	
C*	0.48		0.48		0.44		0.44	
f_b*	0.8		0.7		0.47		0.82	
u*	0.7		0.6		0.08		0.08	
α	0.8		0.8		0.8		0.8	
β	0.9		0.9		0.9		0.9	
$t_{1/2}$**	1		5		10		10	
k**	0.693		0.139		0.069		0.069	
k_e	0.063		0.063		0.062		0.062	

*Adapted from Cossu et al (1996)

** Adapted from Muntoni et al (1996), Augenstein and Pacey (1991), Lifshits and Galueva (1997) and Coops et al (1995).

*** Adapted from Loiu et al (1997), Christensen and Kjeldsen, (1989), Yoshida (1997)

7.8.6 Predicted Specific and Cumulative Gas Production Rates for Cell 1 and Cell 2

Figures 7.7 and 7.8 present the specific and cumulative gas production curves respectively for Cell 1. Figures 7.9 and 7.10 present the specific and cumulative gas production curves respectively for cell 2. Table 7.8 summarises the results of the model application for Cells 1 and 2, and provides production rates quoted in the literature for comparison. The model calculations and the yearly specific and cumulative gas production rates are presented in tabulated form in Appendix C. The fraction of decomposable refuse refers to the fraction of the total refuse mass in the cell that is expected to produce gas. The biodegradable carbon content is the fraction (of the total mass in the cell) of carbon that may be converted to biogas. These are the outputs of the Chemical-Physical Submodel.

The maximum theoretical biogas productions were calculated from the cumulative production curve at time infinity (when all the biodegradable organic carbon has been converted to biogas). The maximum rates of production are obtained from the start of the specific production curve (when there is maximum biodegradable organic carbon available for conversion to biogas). These are the outputs of the Biochemical Submodel.

Table 7.8 Summary of biogas production rates and comparison with existing literature

	Cell 1	Cell 2	Literature
Fraction of Decomposable Refuse (p_i total) (kg/kg_{MSW})	0.3897	0.4386	N/A
Biodegradable organic carbon content ($CO_{e\ TOT}$) (kg_c/kg_{MSW})	0.049	0.055	N/A
Maximum theoretical biogas production (m^3/ton_{MSW})	92.445	102.99	60 – 180 (Tabasaran, 1976) 55 – 225 (Pacey, 1981) 100 – 400 (Campbell, 1985)
Max rate of production (m^3/ton.year)	21.157	20.022	3.9 – 130 (Wise et al, 1987) 12.8 – 18.6 (Stegmann, 1986) 12 – 22 (Rovers et al, 1978)

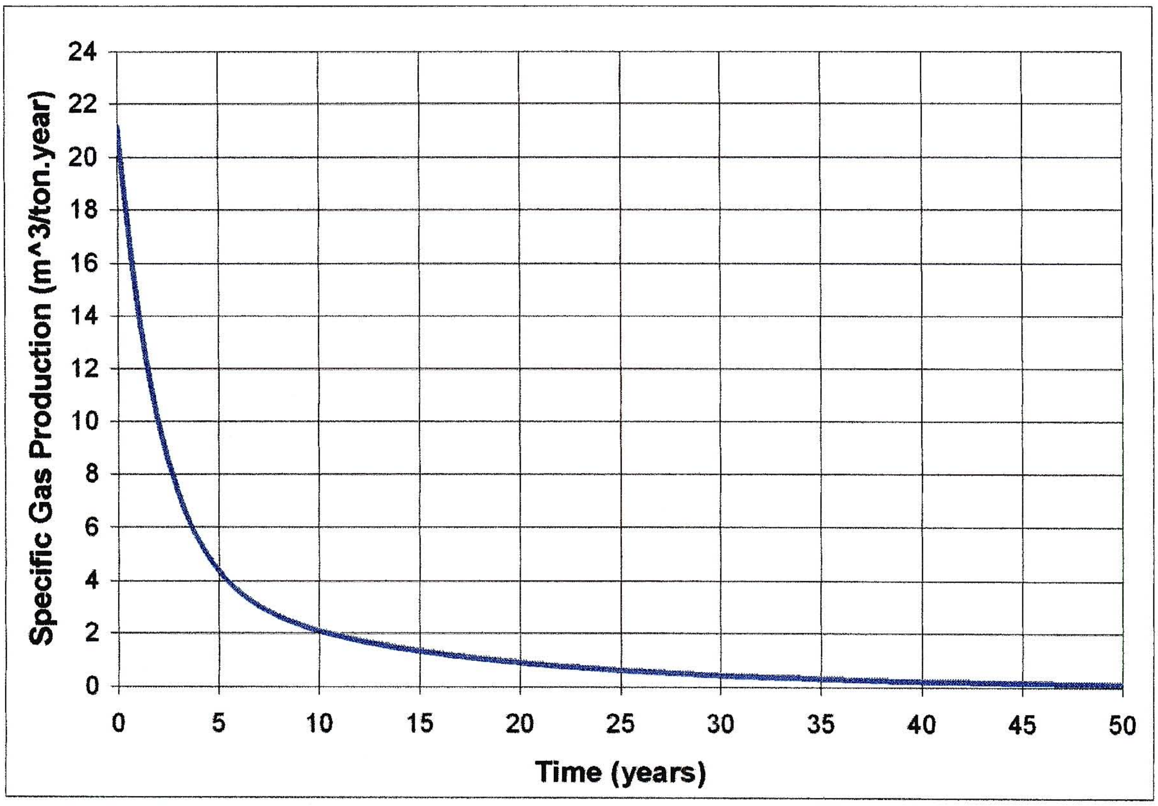


Figure 7.7 Specific gas production curve for Cell 1

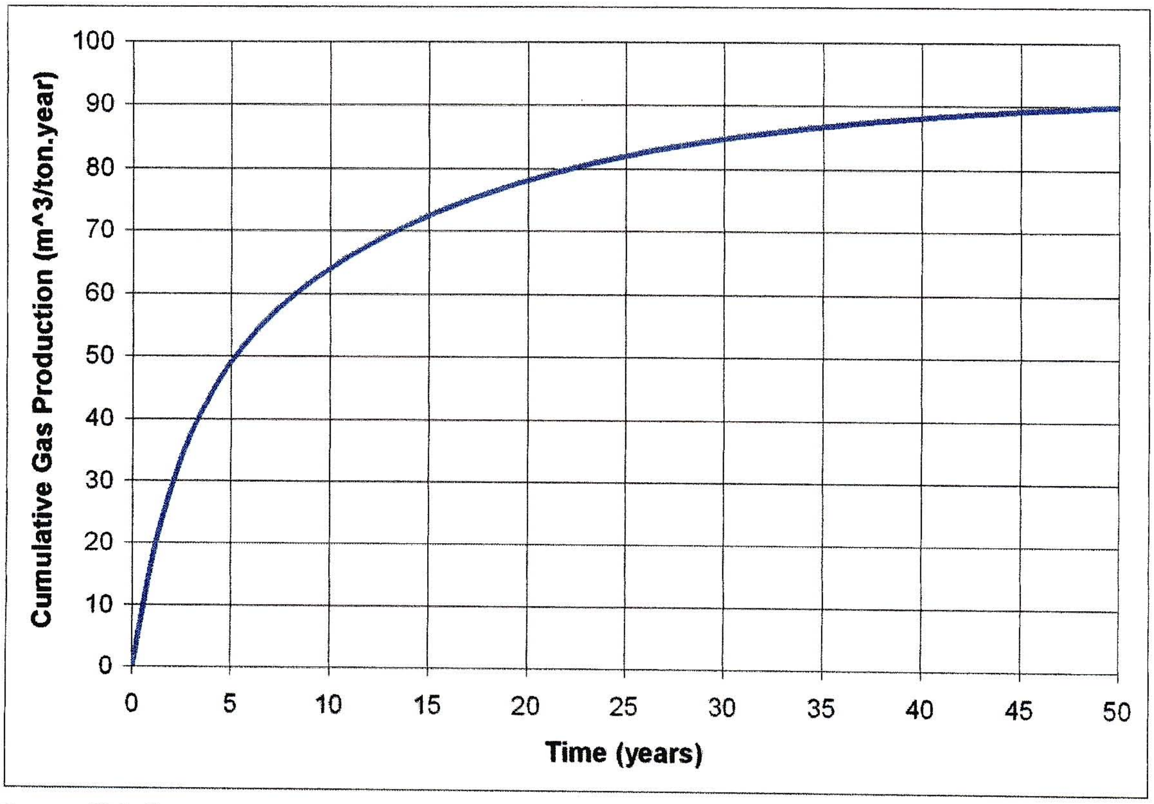


Figure 7.8 Cumulative gas production curve for Cell 1

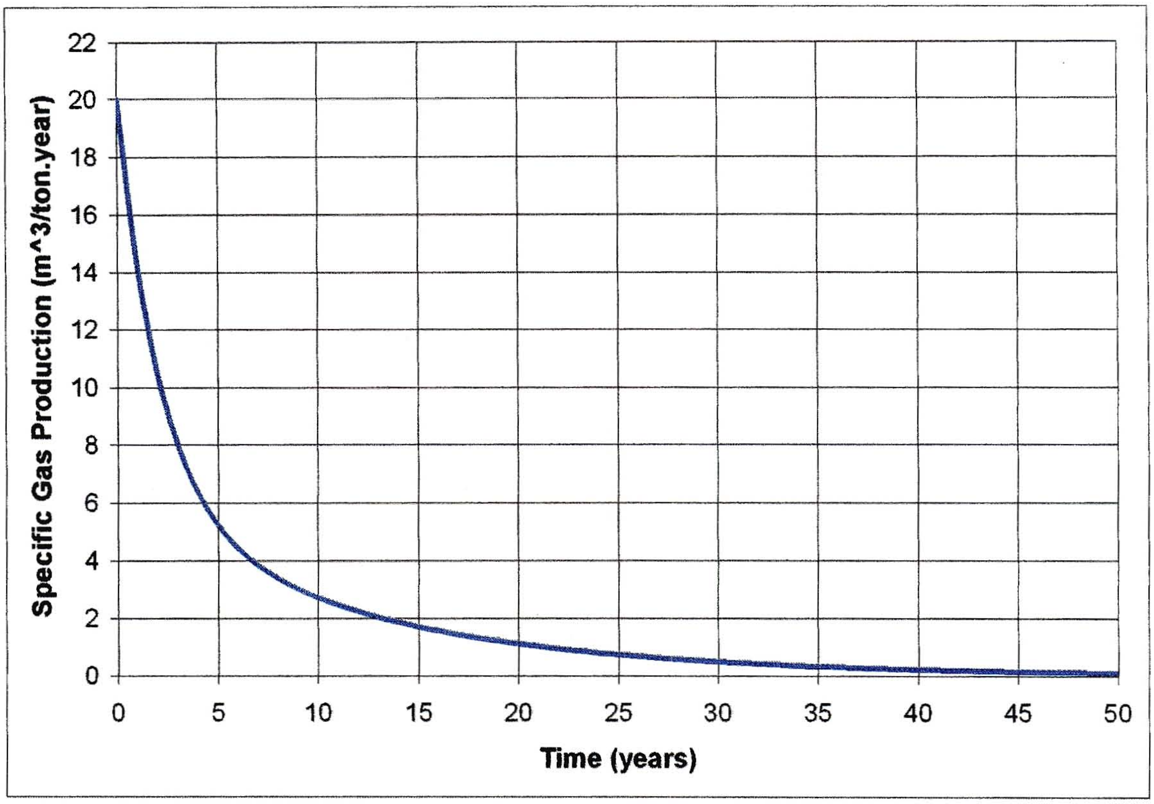


Figure 7.9 Specific gas production curve for Cell 2

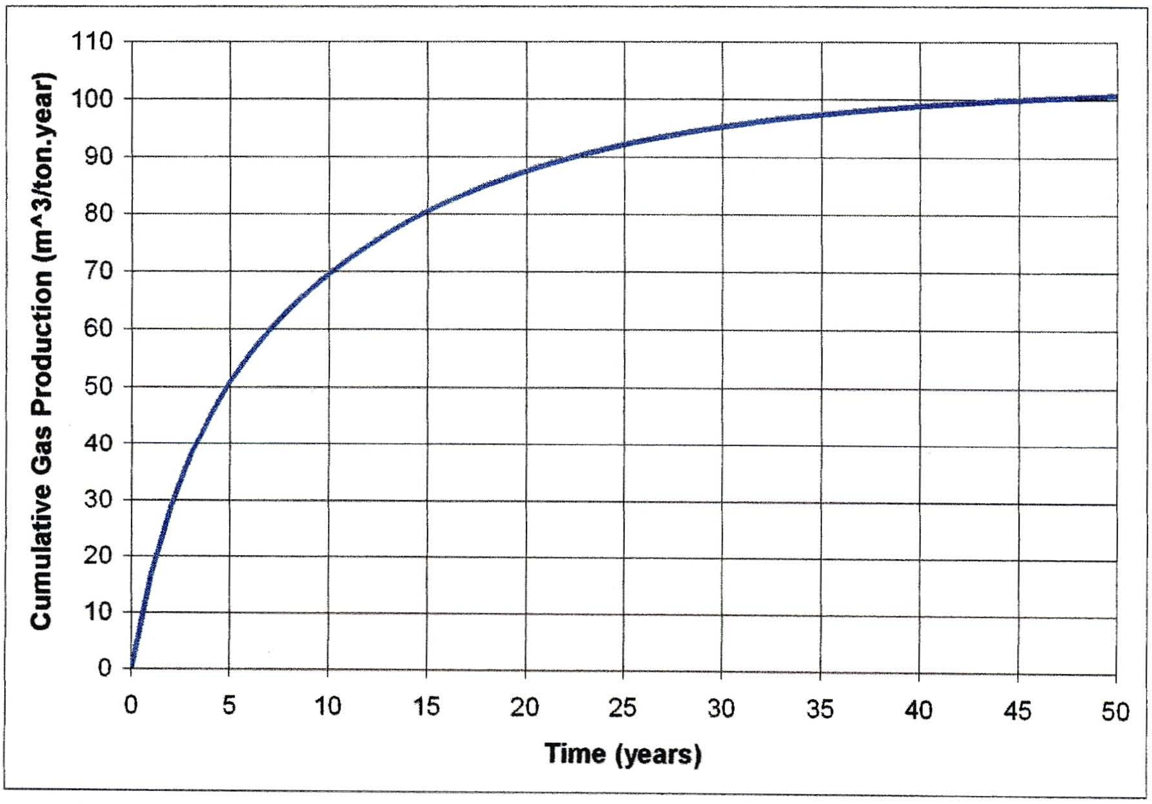


Figure 7.10 Cumulative gas production curve for Cell 2

7.8.7 Predicted Landfill Gas Emissions from Cell 1 and Cell 2

The specific gas production curve presents the model user with a gas generation rate per ton of MSW for each cell. The user can then apply these rates to the mass of waste in each cell to obtain a theoretical volume of landfill gas that the cell will produce.

The specific production curve starts at the maximum rate of biogas production, coinciding with a maximum amount of carbon available. The maximum rate of conversion of organic carbon to landfill gas in the waste body is assumed to occur when methanogenic conditions have been reached, since the methanogenic bacteria at this stage are well established and are actively converting the soluble organic matter to landfill gas (carbon dioxide and methane). From the results of the biogas characterisation in Section 7.7, a lag time of six months has been chosen for the establishment of stable methanogenic conditions. A linear increase in the specific gas generation rate from the start of landfilling to the establishment of methanogenic conditions is assumed. Results from the Brogborough test cells in the UK indicate linear increases of specific gas generation (Knox et al, 1999).

Another consideration is that the waste in the cell is not placed instantaneously and hence different age wastes in the cell will be producing gas at different rates at any given time. The total volume of waste in each cell was therefore divided into four layers.

The first three waste layers in Cell 1 were considered in six monthly intervals (i.e. the mass of waste placed in six months) from July 1997 (opening of the Cell) to Dec 1998. A final layer of four months was considered, from January 1999 to April 1999 (closure of cell).

A first waste layer placed in two months was considered for Cell 2 from May 1999 (opening of the cell) to June 1999. The remaining three layers were considered in six monthly intervals, from July 1999 to December 2000 (Closure of cell).

The gas emissions, which are based on the mass of each layer of waste, were calculated with the first emissions appearing six months after the start of landfilling of the layer. Considering the first layer for example, the opening of the cell corresponds to the start of the layer (time (t) = 0 years). The first emissions appear six months after the opening of the cell (t = 0.5 years), increasing linearly to a peak (corresponding to the maximum rate on the specific production curve) six months after the placement of the layer. In this example, the peak emissions for the layer therefore occur one year after the opening of the cell. The emissions for each layer are calculated separately, and the results superimposed to produce a 'total gas emission' curve for the cell.

Figures 7.11 and 7.12 present the theoretical gas emissions for Cell 1 and Cell 2 respectively. The gas emissions for each individual layer and the 'total gas emission curve' have been presented. Table 7.9 presents the peak theoretical gas emissions from Cell 1 and Cell 2 and the time after the opening of each cell when the respective peaks occur. The yearly biogas emissions are presented in tabulated form in Appendix E.

Table 7.9 Peak gas emissions from Cell 1 and Cell 2

	Peak Emission (m^3)	**Time From Opening Of Cell to Peak Emission (Years)**
Cell 1	1378543	2
Cell 2	1783274	2.17

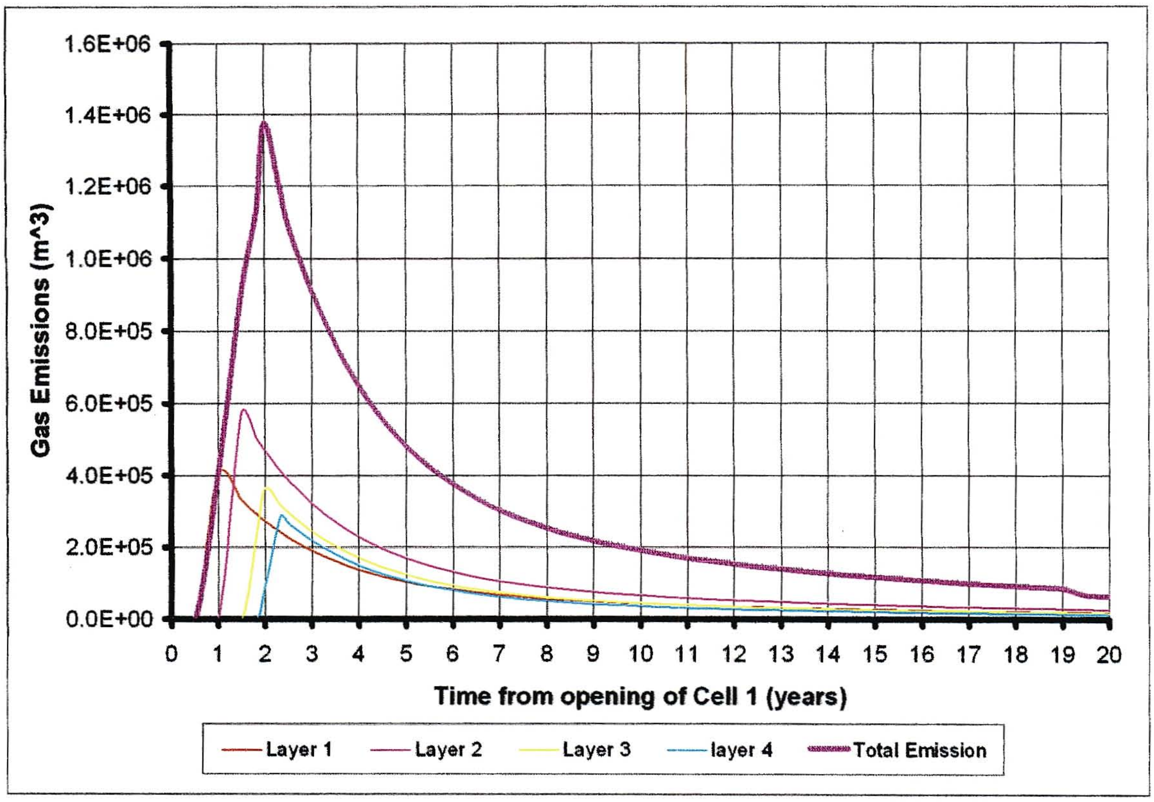


Figure 7.11 Gas emissions for Cell 1

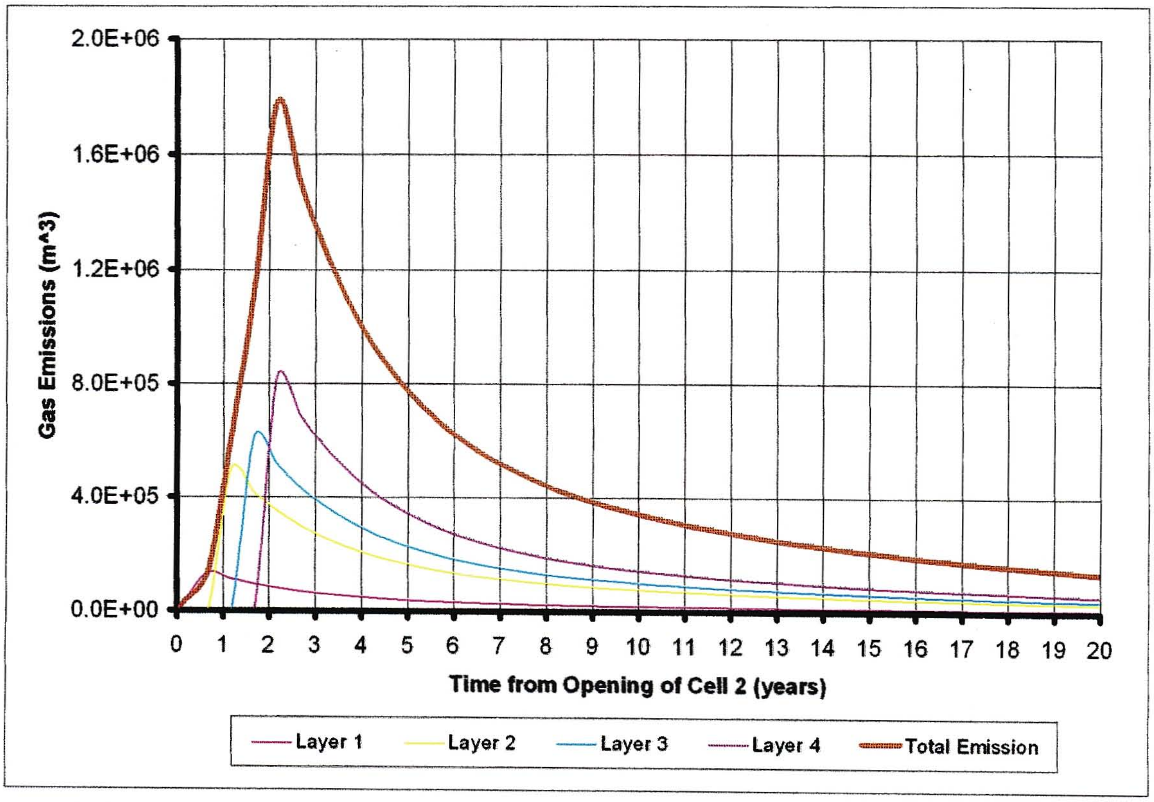


Figure 7.12 Gas emissions for Cell 2

7.9 BIOGAS PRODUCTION MODELLING - LANDGEM MODEL

The gas emissions for Cells 1 and 2 were modeled separately. The model requires that the mass of waste in each cell be given in yearly intervals. The waste in both Cells 1 and 2 was placed over a period below two years (Cell 1 – 1.67 years and Cell 2 – 1.83 years). For the purpose of the model, the waste mass in each cell was halved to obtain yearly masses, with the total waste mass considered as having being placed over two years.

7.9.1 Methane Generation Rate and Generation Potential

The results of the biogas characterisation from the shallow probes in Cell 1 and the gas wells in Cells 1 and 2 indicate that methane constitutes approximately 50% of the gas produced at the Mariannhill Landfill Site. The methane generation potential (L_0) for each cell was therefore assumed to be half of their maximum theoretical biogas production (determined from the Chemical-Physical/Biochemical model, Section 7.8.6).

The methane generation rate (k) was calculated from the US EPA method 2E (US EPA, 1991) (Section 5.9.3). Table 7.11 lists the required input values. The method is based on the gas extraction system in place in Cells 1 and 2. Since both cells do not have separate extraction systems, an average k value for both cells was calculated. Where parameter values for the method differ for Cell 1 and Cell 2, an average value was considered (weighted according to the percentage mass in each cell). The average methane generation potential for the two cells was calculated as follows:

$$\%\,\text{Mass in Cell 1} = \frac{77273\,(\text{tons})}{181467\,(\text{tons})}.100 = 42.6\,\%$$

$$\%\,\text{Mass in Cell 2} = \frac{104194\,(\text{tons})}{181467\,(\text{tons})}.100 = 57.4\%$$

Methane generation potential for Cell 1 = 92.445/2 = 46.223 (m^3/ton_{MSW})

Methane generation potential for Cell 2 = 102.99/2 = 51.497 (m^3/ton_{MSW})

Table 7.10 Input values for the calculation of the methane generation rate k

Parameter	Cell 1
Average well Depth (m)	15
Average stabilised radius of influence (m)	30
Refuse density (ton/m^3)	1.2
Averaged fraction of decomposable refuse	0.418
Averaged Methane Generation Potential (m^3/ton$_{MSW}$)	49.250
Average stabilised flow rate per well (m^3/min)	0.694
Average age of waste (years)	2.25

Table 7.11 Inputs for the LandGEM Model

Parameter	Cell 1	Cell 2
Methane Generation Potential (L_0) (m^3/ton$_{MSW}$)	46.223	51.497
Methane Generation Rate (k) (year^{-1})	0.209	0.209
Mass of Waste in Cell (tons)	77273	104194

7.9.2 Results of the LandGEM model

The model user may choose the outputs of the program to be in either graphical or text form. The model predicts gas emissions for two hundred years after the opening of each cell. The user may also choose the type of gas emission (methane, carbon dioxide or NMOC). The graphical output provides yearly emissions in tons. The text output provides the emissions in both tons and cubic metres of gas. For the purposes of comparing the output of this model with the Physical-chemical/Biochemical model, the text output for both the methane and carbon dioxide volumes have been combined (to obtain the total gas emissions) and plotted for twenty years after the opening of each cell. The complete graphical and text output for both methane and carbon dioxide emissions for Cell 1 and Cell 2 are presented in Appendix D. Figures 7.13 and 7.14 present the total emissions for Cell 1 and Cell 2 respectively. Table 7.12 reports the maximum emissions for Cell 1 and Cell 2.

Table 7.12 Maximum Emissions for Cell 1 and Cell 2

	Maximum Emissions (m^3)	**Time From Opening of Cell to Peak Emissions (Years)**
Cell 1	1473400	2
Cell 2	2032000	2

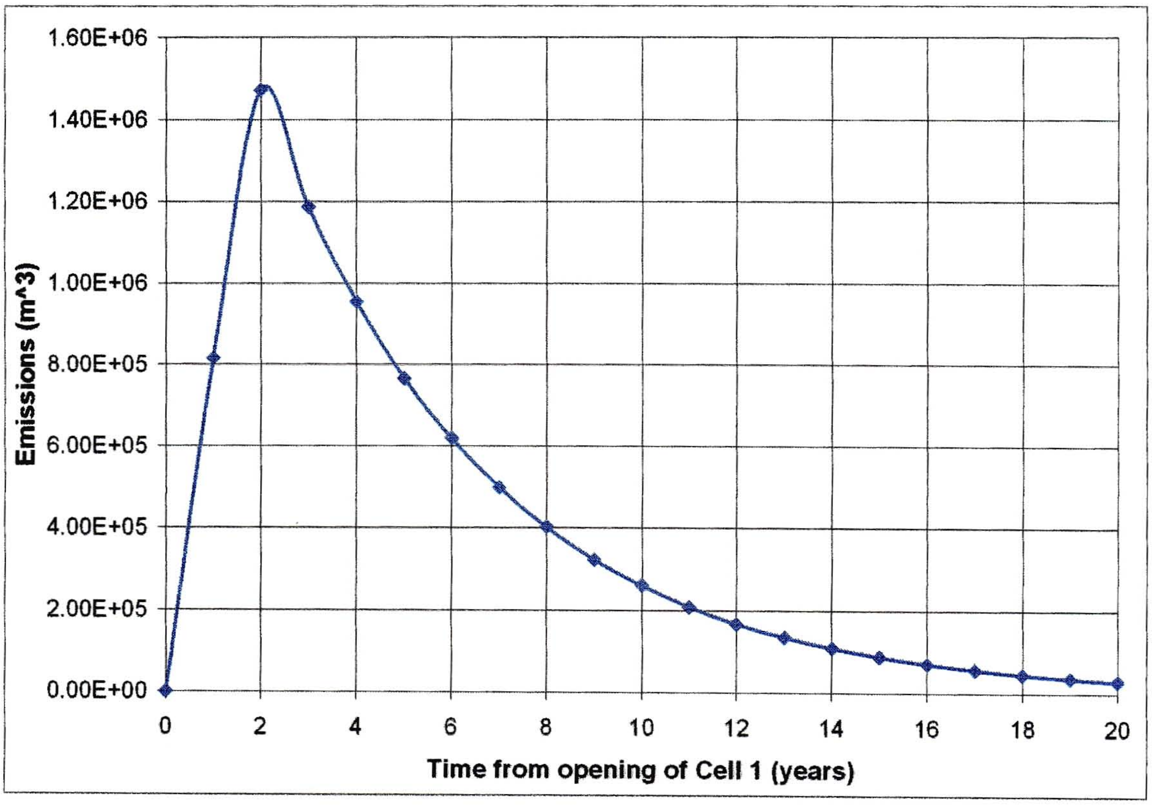


Figure 7.13 Gas emissions for Cell 1 (LandGEM Model)

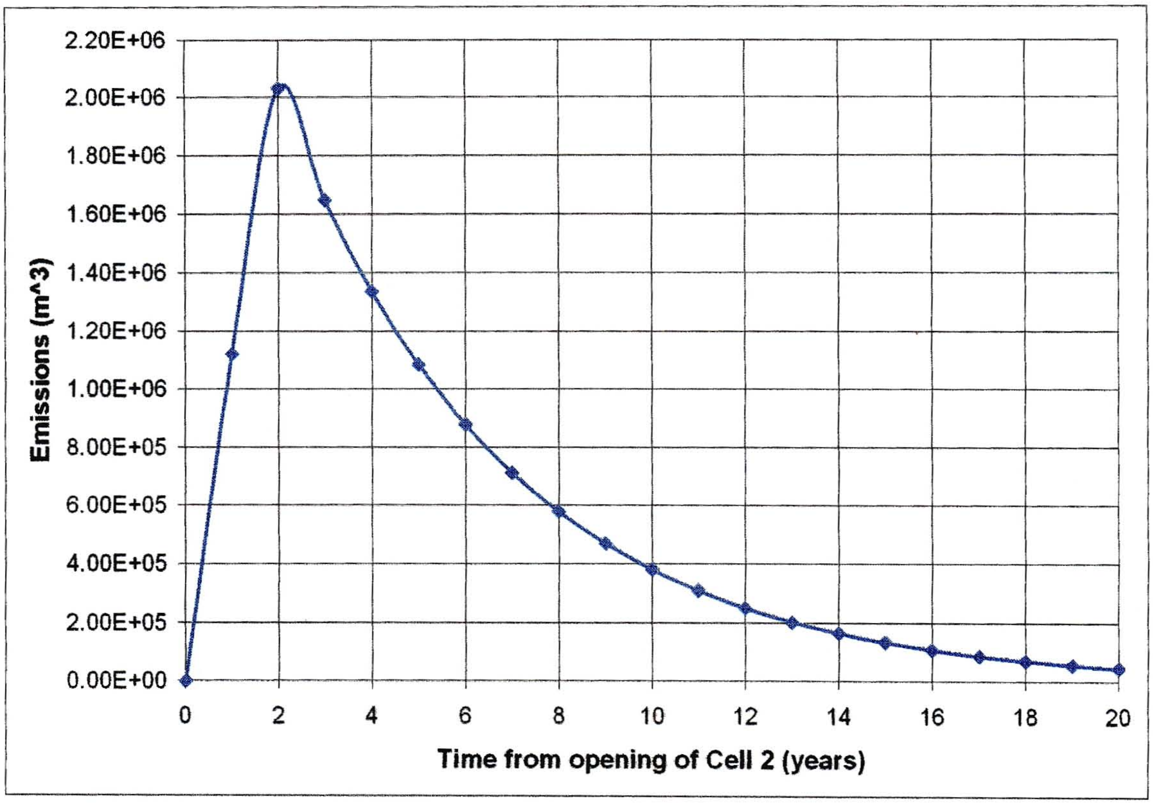


Figure 7.14 Gas emissions for Cell 2 (LandGEM model)

7.10 COMMENTS AND COMPARISON OF MODELS

7.10.1 Chemical-Physical/Biochemical Model

The theoretical rate of production (specific production rate) and maximum theoretical biogas production are comparable to literature. The maximum theoretical biogas production for both cells are slightly lower than the values quoted, which is a result of the relatively low quantities of biodegradable organic carbon (4.9 % and 5.5 % of the total mass of refuse for Cells 1 and 2 respectively). Although the gas producing waste components account for approximately 40% of the total mass in both cells (Table 7.8); the relatively low mass of biodegradable carbon in each cell is a result of the chemical-physical properties of the waste components (particularly garden refuse, paper and cardboard).

Comparing the results of Cell 1 and Cell 2, it can be seen that Cell 2 has a higher maximum theoretical biogas production (Table 7.8). This is because the waste in the cell has a higher total carbon content per ton of MSW than in Cell 1 (Table 7.7). The initial rate of production (Figure 7.7) in Cell 1 is higher than Cell 2 (Figure 7.9) however. This is due to Cell 1 having a larger mass of *easily biodegradable* carbon per ton of MSW (more putrescible waste) as opposed to Cell 2 (16.96 % compared to 13.84 %). Cell 2 has a larger mass of *biodegradable* carbon per ton of MSW (more garden refuse) as opposed to Cell 2 (14.27 compared to 23.70 %), which results in greater production rates later in the life of the cell. The total emissions for Cell 2 are larger than Cell 1 because there is a greater mass of waste in Cell 2.

The most significant parameter affecting the predicted biogas production is the biodegradation constant (k). Ideally, the rate constants should be obtained from laboratory testing of waste samples from the site. This would however require long term monitoring of waste degradation (especially for the slowly biodegradable fractions), which was not possible during the course of this research. Altering the k value changes the theoretical rate of gas production, however the total volume of gas that will be produced by the site remains unchanged. Figure 7.15 presents cumulative gas production curves for varying k values (based on varying half-lives) for Cell 1. As is shown in Figure 7.15, relatively high k values will result in the model showing higher initial production rates (and greater peak emissions) earlier in the landfill cell's lifetime (Figure 7.15 - Cum. Prod. Curves 1 and 2). Relatively low k values will result in the model showing lower production rates initially (and lower peak emissions), but with a less rapid decline in rates as the landfill cell ages, i.e. the emissions will be more evenly spread over the lifetime of the cell (Cum. Prod. Curves 3 and 4). The relatively high set of k values (Figure 7.15 - Cum Prod. Curve 1) chosen in this research are reasonable considering the relatively rapid change from initial acetogenic conditions to methanogenic conditions that were found during the research.

It is also important to note that the model assumes all the organic carbon in the waste body is converted to biogas. In practice, some of the carbon will be leached from the waste by percolating water and some will remain amalgamated in the solid matrix of the waste (Muntoni et al, 1995).

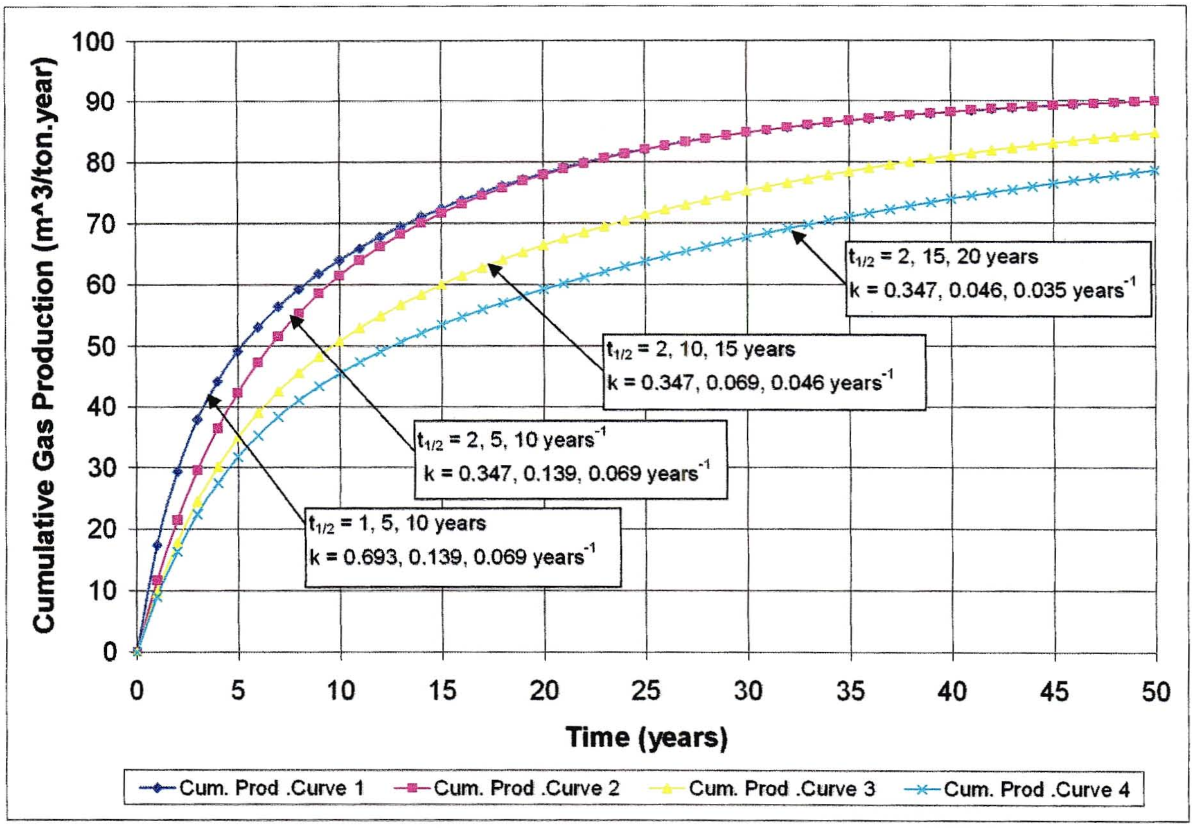


Figure 7.15 Cumulative production rates for Cell 1 with varying k values

7.10.2 LandGEM Model

The gas emissions predicted by the LandGEM model are comparable to that predicted by the Chemical-Physical/Biochemical model. The value for the methane generation constant (k) again has the most significant effect on the predicted landfill gas output. A comparison of the results of both models is shown in Figures 7.15 and 7.16 for Cells 1 and 2 respectively.

Figures 7.15 and 7.16 show that the peak emissions of the two gas generation curves occur at approximately the same time. The slightly higher peak in the emissions predicted by the LandGEM model are as a result of the relatively high k value calculated by Method 2E (US EPA, 1991). The k value of 0.209 year^{-1} represents an average half time for the biodegradation of the whole waste body of 3.32 years. This is compared to the Chemical-Physical/Biochemical model, which has half times for the three biodegradable fractions of 1, 5 and 10 years.

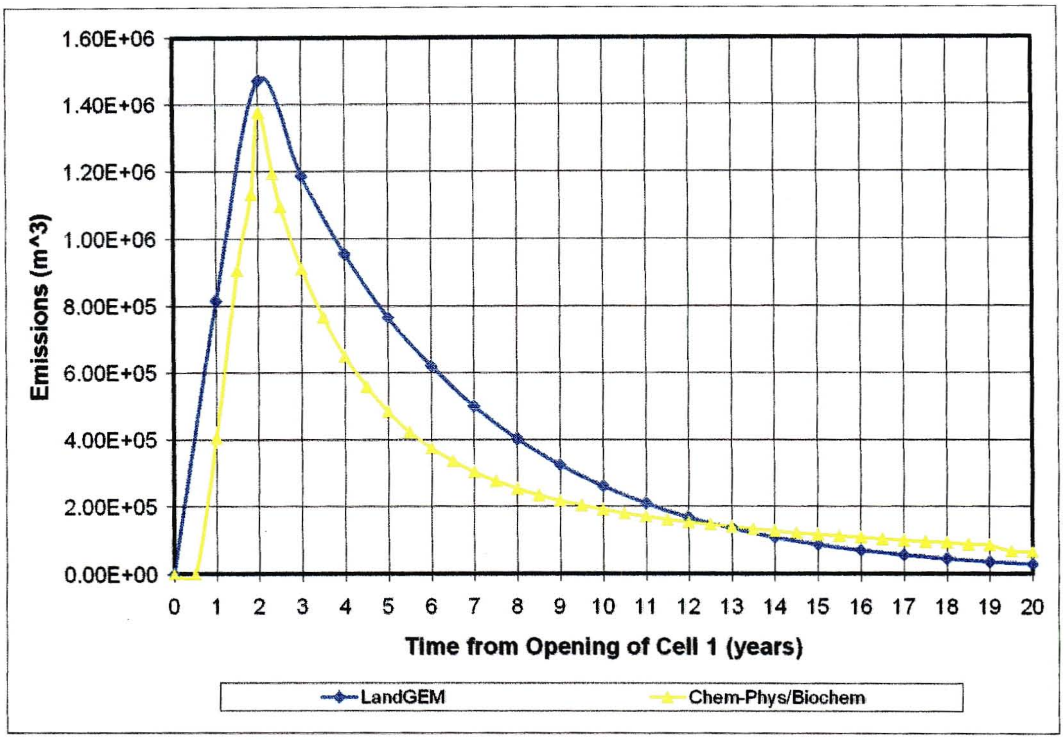


Figure 7.15 Comparison of the LandGEM model and the Chemical-Physical/Biochemical for Cell 1

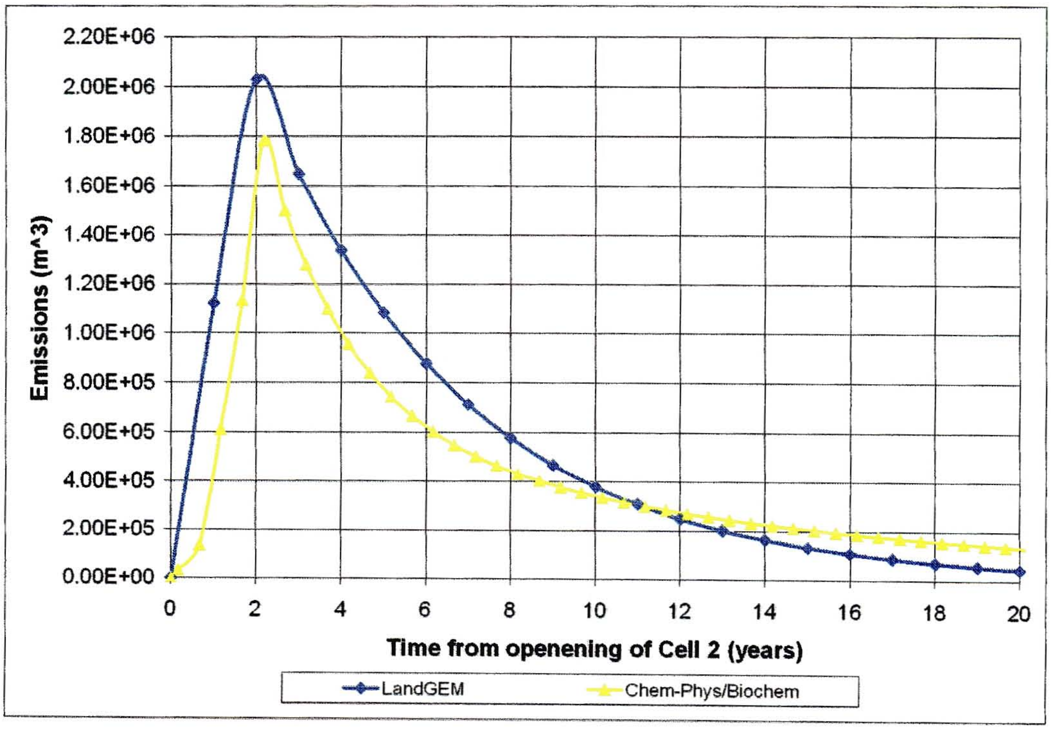


Figure 7.16 Comparison of the LandGEM model and the Chemical-Physical/Biochemical for Cell 2

The results of the LandGEM model indicate that there is little difference between single phase and multi-phase models, as was suggested by Coops et al (1995). The relatively simple, and easy to use LandGEM model produces comparable results to the more complex Chemical-Physical/Biochemical Model. It should be noted however, that the inputs for the LandGEM model were derived from the Chemical-Physical/Biochemical Model, and from the gas extraction system on site. The specified model parameters are vastly different to the default parameters ($k = 0.209$ year^{-1} as opposed to 0.04 year^{-1} and $L_o = 46.223$ m^3/ton$_{MSW}$ (Cell 1) and 51.497 m^3/ton$_{MSW}$ (Cell 2) as opposed to 100 m^3/ton$_{MSW}$), which would have been used had there been no site-specific inputs. Applying the default values in this instance would therefore lead to erroneous results i.e. the lower default k value would result in a lower peak emission rate, whilst the higher default value for the methane generation constant would result in a larger predicted total gas volume.

The scope of the Chemical-Physical/Biochemical model ensures that it is readily adaptable to site-specific parameter values. The fewer input values required for the LandGEM model (particularly if no gas extraction system is in place on the site in question) results in it being more rigid and less adaptable to individual sites.

The use of the two gas emissions models in tandem would present the best case. The LandGEM model could initially be applied to a landfill site or cell to determine the approximate emissions relatively quickly and simply; i.e. without detailed analysis of the waste stream and waste characteristics. This would then inform the landfill manager as to the possible risks associated with the biogas emissions. If the model reveals potentially harmful emission volumes, the manager could then apply the Chemical-Physical/Biochemical model with a more detailed analysis of the waste stream and waste characteristics, providing an accurate estimation of the biogas emissions. The manager can then decide which gas control measure is required (e.g. gas extraction, passive venting). In the cases where gas extraction is necessary, the predicted gas emissions may be used to size the extraction system.

7.11 VALIDATION OF THE SAC TECHNIQUE USING A TEST BED

7.11.1 Calibration of SAC

The emission rate from the test bed was calculated as follows:

Molecular weight of CO_2 = 12+2(16) = 44 g/mol

Using the ideal gas equation, the density of carbon dioxide can be determined. Equation 7.1 is the ideal gas equation (at 25^{0}C and 1 atmosphere):

$$D_{CO_2} = \frac{MW.P}{R.T} = \frac{(1)(44)}{(0.0821).(298)} = 1.798 \text{ g/l} \qquad \textbf{EQ 7.1}$$

Where:

D_{CO2} = Density of carbon dioxide (g/l)

P = Pressure (atm)

R = Universal gas constant (0.0821L.atm.mol^{-1}.K^{-1})

T = Temperature (^{0}K)

The carbon dioxide flux through the test bed surface for the two different flow rates (2 l/min and 5 l/min) were calculated as in Equation 7.2:

$$\varphi = 1000.\frac{Q_i}{A_b}.D_{CO_2} \qquad \textbf{EQ 7.2}$$

Where:

Φ = Flux through the test bed (mg/min.m^2)

Q_i = Flow rate into the test bed (l/min)

A_b = Area of the test bed (1.44 m^2)

D_{CO2} = Density of carbon dioxide (g/l)

For a flow rate of 2 l/min, N = 2498 mg/min.m^2

For a flow rate of 5 l/min, N = 6243 mg/min.m^2

For each sampling run, the increase of concentration of carbon dioxide in the SAC was plotted against time. The best-fit line through the data represents the methane flux through the bed. Of the twenty-one runs performed, seven with the flux of 2498 mg/min.m^2 and three with the flux of 6243 mg/min.m^2 were excluded because little or no carbon dioxide was detected in the SAC during each run. An example of the flux calculation using the SAC is given below.

Table 7.13 presents the carbon dioxide concentrations in the SAC at each time step for the first sampling run (as measured by the GC). The flow rate into the bed was set at 2498 mg/min.m^2. Figure 7.17 presents the concentration profile of carbon dioxide in the SAC with time. Table 7.14 summarises the results of all the sampling runs.

Table 7.13 GC results for the first sampling run.

Date	14 September 2001	
Actual flux	2498 mg/min.m^2	
Time step	**Conc of CO_2 in SAC (%)**	**Conc of CO_2 in SAC (ml/l)**
0	0.225	2.25
1	0	0
2	0.252	2.52
4	0.859	8.59
8	0.176	1.76
16	0.066	0.66
32	3.532	35.32

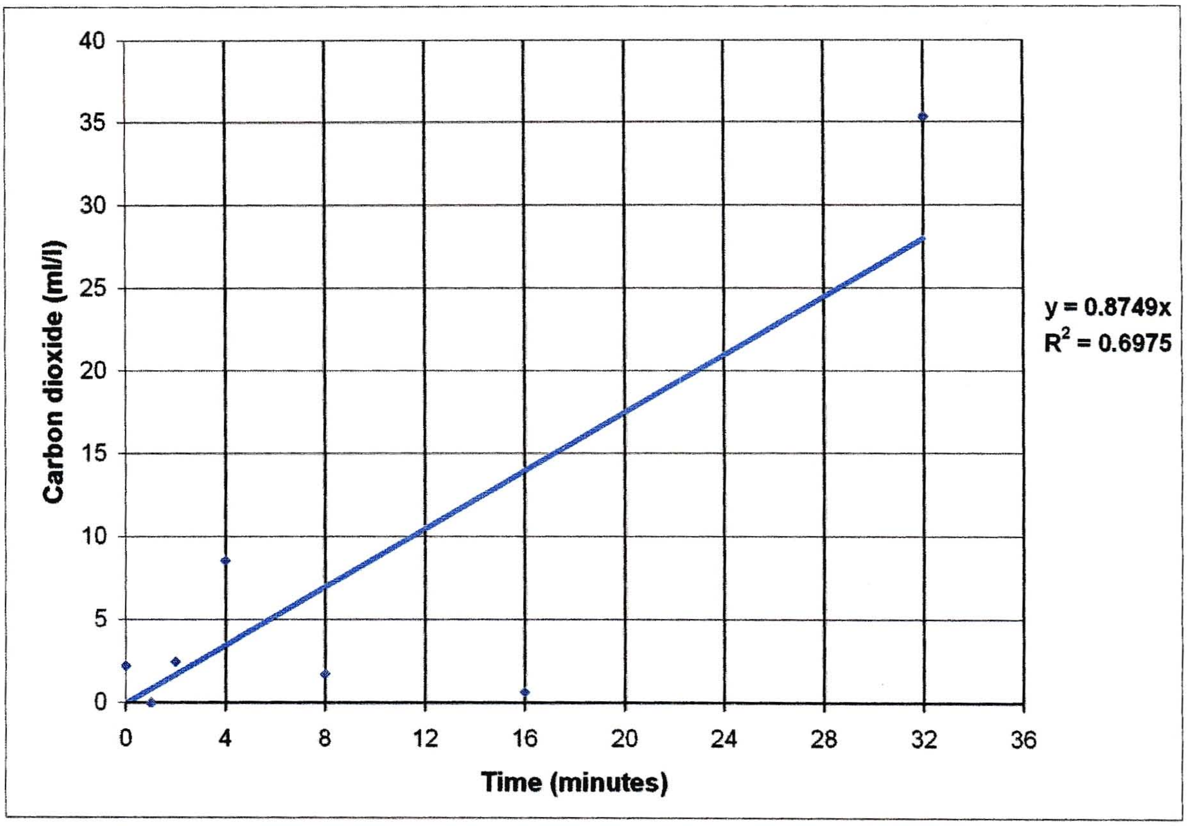


Figure 7.17 The concentration profile of carbon dioxide in the SAC.

The best-fit line through the concentration profile data represents the carbon dioxide flux. In some sampling runs, the best-fit line intercepted the y-axis at a negative value. In such cases, the intercept was set at zero. Using Equation 4.3 (Section 4.5.2), with dc/dt = 0.8749 ml/l.min (R^2 = 0.6975), volume of box = 76.969 litres and area covered by box = 0.385 m^2:

$$\Phi = \frac{76.969\ (\mathrm{l})}{0.385\ (\mathrm{m}^2)} 0.8749\ \left(\frac{\mathrm{mg}}{\mathrm{m}^2.\mathrm{min}}\right) \frac{1\,(\mathrm{atm})28\ (\mathrm{g/mol})}{0.082\ (\mathrm{l.atm}\ /\ \mathrm{mol.K})298\ (\mathrm{K})}$$

$$= 313.4\ \frac{\mathrm{mg}}{\mathrm{m}^2\ \mathrm{min}}$$

The ratio of the actual to measured flux is:

$$\text{Actual/Measured} = \frac{2498}{313.4} = 7.97$$

Table 7.14 Summary of measured fluxes from the test bed using the SAC

Sampling Date	Correlation coefficient (R^2)	Measured Flux ($mg/min.m^2$)	Actual Flux ($mg/min.m^2$)	$\frac{\text{Actual}}{\text{Measured}}$
14/9/01	0.70	313.45	2498	8.0
14/9/01	0.82	50.52	2498	49.5
26/9/01	0.98	245.12	2498	10.2
26/9/01	0.76	283.89	2498	8.8
4/10/01	0.70	250.07	2498	10.0
4/10/01	0.64	72.37	2498	34.5
26/10/01	0.76	95.66	2498	26.1
6/9/01	0.25	20.46	6243	305.2
6/9/01	0.96	121.85	6243	51.2
7/9/01	0.96	319.93	6243	19.5
4/10/01	0.64	72.30	6243	86.30

As is illustrated in Table 7.14, the fluxes measured with the SAC compare poorly with the actual flux through the soil surface of the test bed. It is acknowledged that SAC tend to underestimate actual fluxes (Morris, 1999). Fasolt et al (1995) found emission fluxes to be a factor of 3 – 5 too small when compared to actual fluxes, while Morris (1999) found that the measured emissions to be a factor of 1-2 too small. The factors in this research are considerably higher than the literature suggests. In addition, only four of the sampling runs fulfilled the $R^2 > 0.8$ criteria (as discussed in Chapter 5, Section 4.5.2).

The results also indicate that the measured fluxes, whilst considerably inaccurate, are not consistent from one sampling run to another. Table 7.15 reports the means and standard deviations of the measured fluxes for the two influxes. The poor precision of the measured fluxes indicates that there were most likely random sampling errors in the experimentation technique. The inconsistencies in the results did not therefore allow for the meaningful validation of the SAC.

Table 7.15 Means and standard deviations of the measured fluxes from the test bed.

	Actual Flux = 2498 mg/min.m^2	**Actual Flux = 6243 mg/min.m^2**
Mean of Measured Fluxes (mg/min.m^2)	187.30	133.63
Standard Deviation of Measured Fluxes (mg/min.m^2)	110.18	130.92

7.11.2 Possible Sources of Error in the SAC Technique

The are several possible factors that may have influenced the results from the SAC, as discussed below:

- The seal between the SAC and the soil surface was not sufficiently airtight, allowing dilution of the atmosphere inside the chamber. This source of error may have been particularly relevant for the sampling runs where there was little carbon dioxide detected in the chamber.

- The glass sample vials and septums did not provide an effective gas tight seal, and the samples were diluted before GC analysis. In addition, the gas chromatograph at the School Of Chemical Engineering was often not immediately available, which resulted in there being relatively long periods before samples could be tested.

- The chamber did not behave like a mixed reactor. The concentration of carbon dioxide may not have been uniform in the chamber atmosphere, leading to some samples having a relatively high concentration of carbon dioxide, whilst others have low concentrations. This may explain the samples where the correlation coefficient was low.

- The accuracy of the gas chromatograph is was not determined.

- The sampling runs were started before the test system had stabilised. Although the gas was allowed to flow into the box for a specified time before any sampling runs were performed, it may not have been sufficiently long to allow a steady flux to pass through the bidum and sand layers. This may explain the relatively low fluxes measured in all the sampling runs.

7.11.3 Improvements for Future Use of the Test Bed and SAC Technique

The limited time-scale of this research did not allow for the adjustment and improvement of the SAC technique. Possible improvements are discussed below:

- The most significant improvement to the technique would require a more rapid analysis of the extracted samples, thereby reducing the effect of sample dilution. Ideally, the samples should be tested in as short a time as possible after the completion of a run. The GC used in this research could only analyse samples individually, with each analysis taking approximately ten minutes. Due to demand for the GC, a large number of sampling runs could not be performed. Because of this slow data turnaround, it was difficult to calibrate the SAC and eliminate the possible sources of error. An auto-sampler GC, which can analyse a large number of samples in a relatively short time, would be more appropriate for this type of research. The problems of leakage from the sampling vials remain in this type of sample analysis however, and hence the further investigation into alternative sample storage methods is required. This is particularly relevant for measuring surface emissions on site; because sampling campaigns generally take whole days to perform. The person measuring the emissions therefore has no choice but to store the samples until they can be taken to the laboratory for analysis.

- A viable alternative to the GC are portable Flame Ionisation Detectors (FID) and Photo Ionisation Detectors (PID), which are able to measure low concentrations of most gases. Incorporating one of these instruments into the sampling set-up would allow for the measurement of gas concentrations in the chamber in real-time, eliminating the need to collect and store samples. The rapid data turnaround would allow for a simpler calibration of the method. A considerably large number of analyses could be performed and the sources of error quickly identified and eliminated.

- A better seal between the base of the SAC and the soil/landfill surface could be achieved by placing the chamber into a collar inserted in to the ground. The collar has a water-filled trough fixed on top into which the SAC is placed.

- Stabilisation of the gas flux through the soil surface of the test bed could best be achieved by allowing the gas to pass through the system for a long period (overnight for example).

- Attaching a small, motorised fan to the chamber wall could mix the internal chamber atmosphere. This would ensure an more even distribution of the gas in the chamber.

It is important to note that the use of the modern techniques for sample analysis implies significant financial cost. Auto-sampler gas chromatographs are highly expensive, and their use often requires specialist training. For this reason, they are usually limited to commercial laboratories. Flame and Photo Ionisation detectors are considerably less costly (though still relatively expensive), however their use extends beyond the laboratory. They can be used for on-site testing of surface emissions, ambient air quality monitoring and monitoring of gas quality in probes and gas wells. In most circumstances, an instrument of this type will be appropriate for site operators who wish to carry out routine monitoring of gas emissions.

CHAPTER 8

CONCLUSIONS

8.1 WASTE DEGRADATION RATES AND LANDFILL MANAGEMENT

The results of the leachate characterisation reveal that the leachate pollutant load is reduced to relatively low levels relatively soon after the closure of a landfill cell. The Randles Cell, which was monitored from the start of landfilling operations, produced leachate with a relatively low COD and a stable, neutral pH (typical of methanogenic conditions) within three months of the waste being placed in the cell. The leachates from Cell 1 and Cell 2 had relatively low pollutant levels, both during waste disposal operations in the cells and after the cells were completed.

The results of the landfill gas characterisation showed that the production of methane (and therefore the onset of methanogenisis) begins within one month of the waste being placed. Levels of methane and carbon dioxide associated with fully methanogenic conditions in the waste body were detected in all four sets of shallow probes, with each set of probes being placed in waste no more than one year old. The Randles Cell and Cell 3 showed these high levels of methane and carbon dioxide within nine and four months respectively, indicating that fully methanogenic conditions are reached within one year. This is compared with time-scales in the literature, which suggest that a minimum of two to three years is required for methanogenic conditions to be established (Robinson, 1993).

The changes in leachate and biogas composition with time presented in this dissertation show differences when compared with the theoretical results of leachate and biogas quality developments presented in the literature (Farquhar and Rovers, 1973 (Figure 3.3)). The initial high COD peak and low pH associated with an acetogenic waste body as presented by Farquhar and Rovers (1973) did not occur to the same extent in the leachates studied (indicating a relatively short acetogenic phase). The methane and carbon dioxide generation in the landfill cells revealed a shorter lag time in reaching the stable methanogenic biogas concentrations (there was a relatively steep rise to the peak methane emissions in particular).

It is evident that compacting the freshly deposited waste daily and using a permeable cover material, together with the influence of a hot, humid climate increases the rate of biological degradation. The management of the landfill in the form of small containment cells has proven to be successful. The results indicate that the landfill cells react well to the prevailing climatic conditions, with the high rainfall and relatively small waste body allowing for the natural flushing of leachate pollutants to low levels.

8.1.2 Biogas Recovery Potential

With the degradation of the waste occurring at relatively high rates, the production of methane can be expected relatively soon after the waste has been placed. The *cellular* landfill management technique potentially improves the collection and utilisation of landfill gas. The application of the gas models presented in this research revealed that the peak in gas emissions could occur within six months of a cell being closed. This allows for the installation of a gas extraction system almost immediately after the cell is closed, thereby minimising the environmental risk. The landfill gas models also showed that the majority of the emissions are produced within the first ten years of the cell closing. It is acknowledged that the performance of gas extraction systems that have been in operation for long periods of time decreases (after 5 – 10 years) (Couth, 2000b). This is generally due to settlement in the waste body, which can cause blockages in the extraction wells due to bending and buckling of the pipes. Should this occur, a large proportion of the gas would have already been extracted, and the smaller volumes of gas being produced would not require an extraction system with the initial collection efficiency.

8.2 CALIBRATION OF THE SAC

The results of the SAC calibration were highly variable, indicating that there are numerous possible sources of error when measuring surface emissions. Considerable caution is required when using the SAC technique, particularly with respect to the surface seal, storage of extracted samples and injection into the GC, since any air dilution will lead to inaccurate results.

8.3 FUTURE RESEARCH

The monitoring of landfill emissions and waste degradation rates from full-scale landfill cells has limitations. There are a number of factors that influence the biodegradation processes in a landfill, which, due to the size and heterogeneity of the waste body, are essentially unknown. Small-scale test cells on site, or laboratory scale lysimeters would allow for better control and more accurate monitoring of the factors affecting waste decomposition (e.g. climate, moisture distribution, waste compaction, waste age etc.). The relationship between the changes in leachate and biogas composition and waste decomposition phases would be more easily defined, since all the waste placed in the test cells or lysimeter would be of the same age.

The application of the gas production models represents preliminary work, since the input parameters for the gas production models were generally based on theoretical waste characteristics. Detailed research into various waste components and their characteristics (carbon content, moisture content etc.), and the rate at which different biodegradable fractions decompose, would be particularly beneficial to landfill managers who wish to gain an accurate view of potential gaseous emissions. Landfill gas pumping trials could be performed in order to determine the rate of gas production empirically, since the optimum rate of extraction is approximately equal to the rate of gas generation.

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APPENDIX A

Appendix A1 – Estimation of Accuracy and Errors in Leachate Sample Analysis

Appendix A2 – Climate Data and Analytical Leachate Results for the Randles Cell, Cell 1 and Cell 2

The analytical leachate tests were performed in accordance with the *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al, 1989), which included the daily standardisation of standard solutions and calibration of testing instruments. The precision and accuracy of the analyses of the main leachate parameters (COD, chloride, alkalinity and ammoniacal-nitrogen) were determined for the samples tested at the University of Natal. Multiple analyses of single samples were conducted for this purpose.

Precision is a measure of the closeness with which multiple analyses of a given sample agree with one another (Clesceri et al, 1989). The variation in the analysed sample results is given by the standard deviation, as is shown in Equation A1.1.

$$S_D = \sqrt{\frac{\sum_{x=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad \textbf{EQ.}\ \text{A.1.1}$$

where:

S_D = Standard deviation

x_i = Concentration of the ith sample

$\bar{x}$ = Mean concentration of the multiple samples

n = Number of samples

The coefficient of variation assesses the extent of variability relative to the mean, and allows comparison between data sets. The coefficient of variation is given by Equation A1.2.

$$\text{coefficient of variation} = \frac{S_D}{\bar{x}} \qquad \textbf{EQ.}\ \text{A1.2}$$

COD

Two synthetic samples with known COD of 501 and 502 mgO_2/l respectively were prepared. Sixteen COD analyses were performed on each synthetic sample using the Open Reflux Method (ASTM method number 5220). Table A1.1 presents the results of the analyses.

Table A1.1 Multiple COD analyses on two Synthetic Samples of known COD concentration

SAMPLE	DATA SET 1 (Actual COD = 501 mgO_2/l)	DATA SET 2 (Actual COD = 502 mgO_2/l)
1	509	515
2	491	495
3	519	502
4	487	498
5	515	505
6	505	495
7	498	515
8	502	498
9	512	495
10	505	509
11	505	519
12	488	522
13	512	522
14	495	515
15	512	509
16	512	515
Mean	504	508
Std Deviation	9.88	9.88
Coefficient of Variation (%)	1.96	1.94
% Bias	0.64	1.41

The coefficient of variation is relatively small, and indicates a good precision in the analytical COD testing. The typical coefficient of variation given by Clesceri et al (1989) for this test is 5.6%. The results show only a slight bias (larger mean COD than actual COD for both data sets), indicating that the sample analyses were both precise and accurate.

CHLORIDE

A synthetic sample with a chloride concentration of 499 mg/l was prepared. Sixteen chloride analyses were performed on this sample, as well as sixteen analyses of a leachate sample, using the Argentometric Method (ASTM method number 4500-Cl^-). Table A1.2 presents the results of the analyses.

Table A1.2 Multiple chloride analyses on a synthetic sample of known concentration and a leachate sample of unknown concentration

SAMPLE	**DATA SET 1 – Synthetic Sample (Actual Cl^- = 499 mg/l)**	**DATA SET 2 – Leachate Sample (mg/l)**
1	490	1740
2	481	1702
3	481	1721
4	485	1740
5	490	1731
6	485	1750
7	481	1731
8	481	1731
9	481	1721
10	481	1721
11	481	1759
12	481	1731
13	481	1740
14	495	1711
15	481	1759
16	485	1731
Mean	484	1732
Std Deviation	4.36	15.66
Coefficient of Variation (%)	0.90	0.90
% Bias	3.06	-

The coefficients of variation for both data sets are relatively low and indicate a good precision in the analytical testing. Clesceri et al (1989) report a coefficient of 4.2% for this test. The mean concentration of the analysed synthetic sample shows a slight bias, with the mean value being 15 m/l lower than the actual value. The percentage bias is relatively low however and indicates that the analytical results were accurate.

ALKALINITY

Eight alkalinity analyses were performed on a single leachate sample using the Titration Method (ASTM method number 2320). Table A1.3 presents the results of the analyses.

Table A1.3 Multiple alkalinity analyses of a single leachate sample

SAMPLE	DATA SET 1 (Leachate Sample) (mg/l)
1	1495
2	1490
3	1495
4	1490
5	1485
6	1485
7	1495
8	1490
Mean	**1491**
Std Deviation	**4.17**
Coefficient of Variation (%)	**0.28**

The coefficient of variation is small and indicates good precision in the testing procedure.

AMMONIACAL-NITROGEN

Eight ammoniacal-nitrogen analyses were performed on each of two leachate samples using the Titrimetric Method (ASTM method number 4500-NH_3). Table A1.3 presents the analytical results.

Table A1.3 Multiple ammoniacal-nitrogen analyses of two leachate samples

SAMPLE	**DATA SET 1 (Leachate Sample) (mg/l)**	**DATA SET 2 (Leachate Sample) (mg/l)**
1	560	377
2	558	370
3	558	372
4	548	372
5	552	367
6	547	367
7	548	382
8	560	372
Mean	**554**	**372**
Std Deviation	**5.72**	**5.04**
Coefficient of Variation (%)	**1.03**	**1.35**

The coefficients of variation for both data sets are relatively low, indicating a good precision in the testing procedure.

Table A2.1 Weather Data from January 1997 to July 2001

MONTH	TEMP	HUMIDITY (%)	RAIN (mm)
Jan-97	24	82	187.2
Feb-97	24	82	94.6
Mar-97	23.3	81	54
Apr-97	20.6	78	147
May-97	18.3	77	37.6
Jun-97	16.7	72	90
Jul-97	16.4	77	150
Aug-97	18.4	80	5.2
Sep-97	19.2	83	65.4
Oct-97	20.3	83	145.2
Nov-97	20.3	86	265.6
Dec-97	22.3	82	72
Jan-98	23.9	82	85.8
Feb-98	24.6	86	147
Mar-98	23.6	84	77.4
Apr-98	22.3	82	211
May-98	19	77	48.8
Jun-98	16.7	72	0
Jul-98	17.4	72	21.6
Aug-98	18	70	64
Sep-98	19.2	76	24.2
Oct-98	20.2	76	58.6
Nov-98	22	77	97.2
Dec-98	23	79	120.8
Jan-99	25.3	78	89.4
Feb-99	24.9	80	225.6
Mar-99	25.1	78	39.8
Apr-99	22.9	73	33
May-99	20	74	30.6
Jun-99	17.7	69	64.6
Jul-99	17.9	72	3.2
Aug-99	18.7	71	9.6
Sep-99	19	72	71.2
Oct-99	20	77	201
Nov-99	22.6	78	49
Dec-99	24.1	84	259.4
Jan-00	23.4	80	147.7
Feb-00	25.1	81	154.5
Mar-00	24.6	83	148.1
Apr-00	21	79	64.7
May-00	18	78	142.2
Jun-00	18	73	8.2
Jul-00	17	70	15.4
Aug-00	19	74	24.7
Sep-00	19	72	39.8
Oct-00	20	82	33.1
Nov-00	22	79	107
Dec-00	22	81	66.1

Jan-01	24	70	65.5
Feb-01	24	72	69.6
Mar-01	24	72	39.2
Apr-01	22	74	72.8
May-01	20	69	15.4
Jun-01	19	66	0
Jul-01	18	60	41
AVERAGE	20.9	76.7	83.7

Table A2.2 Average Rainfall for the Durban Region (20 year average)

MONTH	AVERAGE RAINFALL (mm)
January	134
February	113
March	120
April	73
May	59
June	28
July	39
August	62
September	73
October	98
November	108
December	102
TOTAL	1009

Table A2.3 Results of the analytical testing for the Randles Cell leachate

SAMPLING DATE	TIME FROM OPENING OF CELL (Days)	COD (mg/l)	pH	BOD (mg/l)	BOD-COD RATIO	ALKALINITY (mg/l)	CHLORIDES (mg/l)	AMMONIACAL-NITROGEN (mg/l))
9/2/99	18	8080	6.3	*	*	2840	*	*
28/4/99	95	1730	7.78	220	0.13	880	1456	84
29/6/99	157	2260	7.97	85	0.04	5180	1811	100
2/7/99	160	3030	7.6	1300	0.43	5250	1818	521
6/7/99	164	3210	7.7	700	0.22	5400	1793	661
9/7/99	167	2890	7.73	100	0.03	5300	1899	756
13/7/99	171	2080	7.68	442	0.21	5400	1917	764
15/7/99	173	2080	7.66	272	0.13	5300	1935	750
20/7/99	178	1920	7.66	306	0.16	5200	1953	771

22/7/99	180	2000	7.96	357	0.18	5110	1970	774
26/7/99	184	2480	7.5	480	0.19	5170	1985	719
5/8/99	193	2480	7.55	720	0.29	5270	1985	682
10/8/99	198	3440	7.6	690	0.20	5665	1985	730
13/8/99	201	1024	7.6	127	0.12	5600	1985	749
16/8/99	204	3190	7.84	600	0.19	5590	2024	672
23/08/99	211	2280	7.64	774	0.34	5670	2272	803
30/08/99	218	4190	7.74	776	0.19	5920	2340	817
6/9/99	225	2800	7.64	800	0.29	4280	1631	518
13/9/99	232	1892	7.64	320	0.17	5010	1985	663
20/9/99	239	1306	7.58	375	0.29	5110	2056	719
27/9/99	246	1333	7.6	760	0.57	5460	2198	812
30/09/99	249	1323	7.74	650	0.49	5400	1323	765
7/10/99	256	1349	7.49	420	0.31	5210	2127	747
14/10/99	263	1230	7.55	520	0.42	5000	2127	752
23/11/99	303	550	7.4	*	*	3180	1152	454
15/12/99	325	1200	8.6	*	*	2420	*	245
29/12/99	339	342	8	*	*	1740	*	151
19/01/00	360	*	7	*	*	4840	*	62.2
26/1/00	367	599	7.4	*	*	10400	*	43
3/2/00	375	530	7.2	*	*	1140	*	0.3
9/2/00	381	483	7.3	*	*	1900	*	20.2
16/2/00	388	354	7.1	*	*	1760	*	78
1/3/00	402	555	7.6	*	*	2380	*	152
10/3/00	411	710	7.4	*	*	1960	*	116
15/03/00	416	661	7.1	*	*	2520	*	0.5
22/03/00	423	785	7.3	*	*	2800	*	218
29/03/00	430	634	7.3	*	*	2160	*	110
5/4/00	437	477	7.5	*	*	1500	*	260
12/4/00	444	1110	7.4	*	*	2060	*	310
19/4/00	451	1380	7.6	*	*	3320	*	*
3/5/00	465	873	7.8	*	*	870	*	*
27/9/00	612	1601	7.25	*	*		*	348
4/10/00	619	1698	7.26	*	*	4715	*	640
11/10/00	626	2150	7.32	*	*	4700	*	606
18/10/00	633	3160	7.34	394	0.12	4585	2224	648
25/10/00	640	2960	7.6	*	*	4895	2239	628

1/11/00	647	1820	7.57	*	*	5315	2199	685
8/11/00	654	2360	7.66	*	*	5670	2189	755
15/11/00	661	1980	7.69	*	*	5825	2469	760
22/11/00	668	5780	6.97	*	*	4470	2479	511
29/11/00	675	3720	7.59	*	*	5470	2179	457
13/12/00	689	3760	7.2	*	*	4730	1969	428
10/1/00	717	2260	7.56	*	*	5855	2599	876
17/01/01	724	2340	7.77	*	*	5880	2629	837
23/01/01	730	2220	7.84	*	*	5895	2759	856
1/2/01	739	1880	7.43	*	*	5905	2549	838
7/2/01	745	2060	7.53	*	*	5780	2539	866
14/02/01	752	1740	7.09	*	*	4555	2479	727
21/02/01	759	2320	7.49	*	*	4875	2759	851
28/02/01	766	2340	7.52	*	*	6070	2549	864
7/3/01	773	2200	7.41	*	*	6215	2699	894
14/03/01	780	2380	7.49	*	*	6245	2749	900
28/03/01	787	2320	7.34	*	*	6230	2839	877
4/4/01	794	2440	7.44	363	0.15	6315	2904	887
11/4/01	801	2360	7.52	340	0.14	5560	2689	747
18/4/01	808	2600	7.69	404	0.16	6450	2809	423
03/05/01	823	2500	7.3	*	*	6415	2879	868
9/5/01	829	2700	7.47	322	0.12	6215	2869	936
16/05/01	836	2500	7.57	304	0.13	6320	2909	857
23/05/01	843	2240	7.44	*	*	6220	2969	869
30/05/01	850	2400	7.56	416	0.17	6590	2829	960
6/6/2001	857	2580	7.35	*	*	6780	2929	932
13/06/01	864	2802	7.25	*	*	6960	2979	1046
20/0601	871	2903	7.59	*	*	6805	3009	1103
27/0601	878	2730	7.74	*	*	6815	3009	1028
4/7/01	885	2788	7.46	427	0.18	7065	3019	1029
18/07/01	899	2771	7.47	363	0.13	7015	3309	1028
1/8/2001	912	2589	7.62	457	0.18	6510	3049	1017

* Parameter analysis not conducted

Table A2.3 (contd.) Results of the analytical testing for the Randles Cell leachate

SAMPLING DATE	TIME FROM OPENING OF CELL (Days)	TS (mg/l)	VS (mg/l)	FS (mg/l)	VS/FS	TSS (mg/l)	VSS (mg/l)
9/2/99	18	435	*	*	*	*	*
28/4/99	95	7160	1692	5468	0.31	0	0
29/6/99	157	7590	1894	5696	0.33	24	22
2/7/99	160	7380	1998	5382	0.37	76	18
6/7/99	164	7924	1854	6070	0.31	34	22
9/7/99	167	7920	1758	6162	0.29	68	24
13/7/99	171	7816	1780	6036	0.29	76	36
15/7/99	173	7880	1794	6086	0.29	68	42
20/7/99	178	7680	1618	6062	0.27	70	32
22/7/99	180	7630	1550	6080	0.25	72	38
26/7/99	184	7508	1680	5828	0.29	4	4
5/8/99	193	7624	1828	5796	0.32	1	1
10/8/99	198	8180	2136	6044	0.35	20	8
13/8/99	201	8228	2082	6146	0.34	32	20
16/8/99	204	8096	1910	6186	0.31	40	33
23/08/99	211	8814	2334	6480	0.36	53	47
30/08/99	218	9028	2288	6740	0.34	56	48
6/9/99	225	6680	1624	5056	0.32	48	32
13/9/99	232	7532	1712	5820	0.29	56	44
20/9/99	239	7992	2032	5960	0.34	56	40
27/9/99	246	8240	1888	6352	0.30	40	40
30/09/99	249	8092	1624	6468	0.25	32	32
7/10/99	256	7828	1760	6068	0.29	15	15
14/10/99	263	7652	1748	5904	0.30	8	8
23/11/99	303	*	*	*	*	*	*
15/12/99	325	*	*	*	*	*	*
29/12/99	339	*	*	*	*	*	*
19/01/00	360	*	*	*	*	*	*
26/1/00	367	*	*	*	*	*	*
3/2/00	375	*	*	*	*	*	*
9/2/00	381	*	*	*	*	*	*
16/2/00	388	*	*	*	*	*	*
1/3/00	402	*	*	*	*	*	*

10/3/00	411	7720	*	*	*	*	*
15/03/00	416	3648	*	*	*	*	*
22/03/00	423	4632	*	*	*	*	*
29/03/00	430	3315	*	*	*	*	*
5/4/00	437	2874	*	*	*	*	*
12/4/00	444	4589	*	*	*	*	*
19/4/00	451	5488	*	*	*	*	*
3/5/00	465	4683	*	*	*	*	*
27/9/00	612	6628	1614	5014	0.32	31	0
4/10/00	619	6696	1256	5440	0.23	71	32
11/10/00	626	6788	1884	4904	0.38	120	8
18/10/00	633	6640	1546	5094	0.30	132	22
25/10/00	640	6492	1602	4890	0.33	19	1
1/11/00	647	7152	1956	5196	0.38	47	36
8/11/00	654	7646	2504	5142	0.49	26	0
15/11/00	661	7828	2006	5822	0.34	*	*
22/11/00	668	8074	3990	4084	0.98	47	13
29/11/00	675	7418	2384	5034	0.47	45	28
13/12/00	689	6888	2242	4646	0.48	36	0
10/1/00	717	7872	2434	5438	0.45	*	*
17/01/01	724	7952	1984	5968	0.33	3	0
23/01/01	730	8034	2086	5948	0.35	*	*
1/2/01	739	8164	2514	5650	0.44	*	*
7/2/01	745	7788	2070	5718	0.36	9	0
14/02/01	752	7716	2090	5626	0.37	115	86
21/02/01	759	7878	1978	5900	0.34	152	135
28/02/01	766	8118	2148	5970	0.36	100	50
7/3/01	773	8584	2480	6104	0.41	*	*
14/03/01	780	8710	2772	5938	0.47	*	*
28/03/01	787	8770	2716	6054	0.45	*	*
4/4/01	794	*	*	*	*	*	*
11/4/01	801	7628	2236	5392	0.41	52	32.5
18/4/01	808	8780	3010	5770	0.52	18.5	1.5
03/05/01	823	8710	2588	6122	0.42	*	*
9/5/01	829	8756	2464	6292	0.39	*	*
16/05/01	836	8526	2242	6284	0.36	59	47.5
23/05/01	843	9522	3134	6388	0.49	47.5	0

30/05/01	850	10066	4232	5834	0.73	38	0
6/6/2001	857	9692	3414	6278	0.54	*	*
13/06/01	864	9264	3348	5916	0.57	24	0
20/0601	871	9366	3402	5964	0.57	*	*
27/0601	878	9806	2938	6868	0.43	31.5	0
4/7/01	885	9548	3280	6268	0.52	*	*
18/07/01	899	9764	3498	6266	0.56	93	0
1/8/2001	912	10568	3446	7122	0.48	52	0

* Parameter analysis not conducted

Table A2.4 Results of the initial analytical testing for the Cell 1 leachate (adapted from Strachan, 2000)

SAMPLING DATE	pH	COD (mg/l)	AMMONIACAL -NITROGEN (mg/l)	ALKALINITY (mg/l)	SODIUM (mg/l)
9/10/1998	7.6	1878	288	5343	914
22/10/98	7.5	1289	8.2	5200	1730
29/10/98	8	1637	200	5250	1044
5/11//98	7.6	1307	436	4535	1080
19/11/98	7.6	1195	7.8	6200	1035
26/1198	8	1191	171	4460	1230
3/12/1998	8	1239	259	4680	935
10/12/1998	7.8	1022	67	3600	880
17/12/98	7.5	1091	304	5260	1000
24/12/98	8.7	1030	182	3660	1040
31/12/98	8.8	1195	282	3400	1075
7/1/1999	7.9	1514	375	4740	1015
14/1/99	7.8	1297	310	4970	1120
21/1/99	7.8	3430	700	4864	1475
28/1/99	7.9	1190	953	4520	1060
4/2/1999	7.9	1364	423	4800	1125
11/2/1999	7.7	1440	524	4940	995
17/2/99	8	2570	1028	4860	*
24/2/99	7.9	940	452	940	800
3/3/1999	7.7	1460	430	4460	924
10/3/1999	7.8	1242	582	4000	*
17/3/99	8.3	945	426	2846	1698

31/3/99	8.2	1940	458	3220	1168
MAX	8.80	3430	1028	6200	1730
MIN	7.50	940	8	940	800
MEAN	7.91	1452	385	4380	1112
STDEV	0.33	567	258	1083	244

* Parameter analysis not conducted

Table A2.5 Results of the analytical testing for the Cell 1 leachate (conducted at the University of Natal)

SAMPLE NUMBER	SAMPLING DATE	pH	COD (mg/l)	ALKALINITY (mg/l)	AMMONIACAL-NITROGEN (mg/l)	CHLORIDE (mg/l)
1	4/10/00	7.68	1269	5495	710	1699
2	11/10/00	8.25	1530	5720	637	*
3	18/10/00	7.84	2900	5860	685	1839
4	25/10/00	7.82	2720	6180	743	1909
5	1/11/00	7.97	1440	6105	474	1969
6	8/11/00	7.66	1440	6050	472	1869
7	15/11/00	7.84	1280	6195	444	1589
8	22/11/00	7.52	1100	5675	517	*
9	28/11/00	7.65	3300	6115	693	1879
10	13/12/00	7.49	3240	5790	624	1869
11	12/1/01	7.83	1260	5520	393	1819
12	23/01/01	7.89	1240	5470	480	1979
13	1/2/01	7.5	1200	5455	356	1909
14	7/2/01	7.6	1340	5465	623	1829
15	14/02/01	7.44	1260	4855	646	1819
16	21/02/01	7.51	1320	4290	302	1959
17	28/02/01	7.57	2000	5240	333	1729
18	7/3/01	7.59	1920	5420	377	1769
19	14/03/01	7.65	2100	5460	373	1729
20	28/03/01	7.46	1360	5380	665	1779
21	4/4/01	7.51	1280	5435	388	1794
22	11/4/01	7.62	2540	6185	282	2059
23	18/04/01	7.67	2000	6005	688	2059

24	3/5/2001	7.48	1480	5285	280	1779
25	9/5/01	7.46	1400	5260	659	1689
26	16/05/01	7.51	1840	5480	644	1869
27	23/0501	7.63	1240	5575	699	1959
28	30/05/01	7.71	1340	5645	283	1979
29	6/6/01	7.4	1300	5295	657	1979
30	13/06/01	7.3	1270	5350	663	1859
31	20/06/01	7.77	1290	5365	702	1889
32	27/06/01	7.66	1375	5150	673	1859
33	4/7/2001	7.62	1491	5280	670	1889
34	18/07/01	7.56	966	5060	637	1819
35	1/8/01	7.7	1258	4980	657	1859

* Parameter analysis not conducted

Table A2.5 (contd.) Results of the analytical testing for the Cell 1 leachate (conducted at the University of Natal)

SAMPLE NUMBER	SAMPLING DATE	TS (mg/l)	VS (mg/l)	FS (mg/l)	VS/FS (mg/l)	TSS (mg/l)	VSS (mg/l)
1	4/10/00	6148	1128	5020	0.22	55	26
2	11/10/00	6538	1702	4836	0.35	64	8
3	18/10/00	6582	1764	4818	0.37	161	14
4	25/10/00	4644	1602	3042	0.53	23	12
5	1/11/00	6824	1956	4868	0.40	85	53
6	8/11/00	6876	2428	4448	0.55	36	6
7	15/11/00	6808	2062	4746	0.43	*	*
8	22/11/00	6346	2108	4238	0.50	81	43
9	28/11/00	6482	2458	4024	0.61	62	46
10	13/12/00	6506	2238	4268	0.52	51	31
11	12/1/01	*	*			156	32
12	23/01/01	8034	2086	5948	0.35	80	*
13	1/2/01	6454	2326	4128	0.56	*	*
14	7/2/01	6310	1946	4364	0.45	3	*
15	14/02/01	6400	1912	4488	0.43	155	113
16	21/02/01	6170	2006	4164	0.48	38	5
17	28/02/01	6188	1788	4400	0.41	82	51
18	7/3/01	6546	2124	4422	0.48	*	*

19	14/03/01	6496	2348	4148	0.57	*	*
20	28/03/01	6146	1902	4244	0.45	*	*
21	4/4/01	*	*	*	*	0	0
22	11/4/01	7002	2272	4730	0.48	6.5	0
23	18/04/01	6664	2306	4358	0.53	55.5	0
24	3/5/2001	5744	1870	3874	0.48	64	57.5
25	9/5/01	6392	2058	4334	0.47	5.5	0
26	16/05/01	6494	1986	4508	0.44	120	84
27	23/0501	7266	2760	4506	0.61	40	0
28	30/05/01	7400	3150	4250	0.74	15	0
29	6/6/01	7408	3390	4018	0.84	*	*
30	13/06/01	6536	2780	3756	0.74	157	0
31	20/06/01	6470	2778	3692	0.75	72	0
32	27/06/01	6460	2790	3670	0.76	58	0
33	4/7/2001	6628	2582	4046	0.64	*	*
34	18/07/01	5924	2330	3594	0.65	13.5	0
35	1/8/01	6594	2906	3688	0.79	45	0

*Parameter analysis not conducted

Table A2.6 Results of the analytical testing for the Cell 2 leachate (conducted at the University of Natal)

SAMPLE NUMBER	SAMPLING DATE	pH	COD (mg/l)	ALKALINITY (mg/l)	AMMONIACAL-NITROGEN (mg/l)	CHLORIDE (mg/l)
1	4/10/00	8.23	976	4495	458	1709
2	11/10/00	8.54	1260	3605	323	*
3	18/10/00	8.48	3340	5390	610	1979
4	25/10/00	8.49	3000	5535	633	2069
5	1/11/00	8.6	1800	5120	625	1789
6	8/11/00	8.29	1520	5625	652	2089
7	15/11/00	8.42	1160	5505	669	2019
8	22/11/00	7.88	1640	4170	433	*
9	28/11/00	8.15	2960	5715	576	1859
10	13/12/00	7.94	3120	4960	343	1739
11	12/1/01	7.82	1040	5065	660	1589

12	23/01/01	8.21	1460	5320	681	1909
13	1/2/01	8.19	1400	4970	669	1989
14	7/2/01	7.52	1460	5345	606	1949
15	14/02/01	7.97	1100	2945	199	1140
16	21/02/01	8.34	1540	4005	582	1939
17	28/02/01	8.4	1400	5040	638	1779
18	7/3/01	8.15	1440	5185	652	1889
19	14/03/01	8.13	1520	2440	634	1879
20	28/03/01	7.66	1460	5345	678	1939
21	4/4/01	7.48	1780	5070	636	1864
22	11/4/01	7.66	1860	4805	619	1879
23	18/04/01	7.64	1940	5010	603	1999
24	3/5/2001	7.59	1180	4800	347	1819
25	9/5/01	7.49	1320	4605	581	1729
26	16/05/01	7.66	1400	4665	561	1859
27	23/0501	7.55	960	4450	533	1779
28	30/05/01	8.05	1200	4600	577	1979
29	6/6/01	7.4	1200	5315	561	1989
30	13/06/01	7.26	1270	4525	572	1989
31	20/06/01	7.71	1351	4670	549	2069
32	27/06/01	7.78	1278	4160	562	2089
33	4/7/2001	8.12	1452	4290	551	2139
34	18/07/01	7.54	875	3485	409	1839
35	1/8/01	8.64	1185	3190	365	2139

*Parameter analysis not conducted

Table A2.6 (contd.) Results of the analytical testing for the Cell 2 leachate (conducted at the University of Natal)

SAMPLE NUMBER	SAMPLING DATE	TS (mg/l)	VS (mg/l)	FS (mg/l)	VS/FS (mg/l)	TSS (mg/l)	VSS (mg/l)
1	4/10/00	4022	1620	2402	0.67	36	22
2	11/10/00	5972	1512	4460	0.34	8	0
3	18/10/00	6746	1722	5024	0.34	104	15
4	25/10/00	6840	1928	4912	0.39	*	*
5	1/11/00	6978	2022	4956	0.41	35	35
6	8/11/00	6724	1986	4738	0.42	60	9

7	15/11/00	6882	1960	4922	0.40	11	*
8	22/11/00	5402	2040	3362	0.61	66	14
9	28/11/00	6244	1794	4450	0.40	73	49
10	13/12/00	6446	2226	4220	0.53	33	33
11	12/1/01	5932	1920	4012	0.48	*	*
12	23/01/01	6492	1652	4840	0.34	58	0
13	1/2/01	6418	1822	4596	0.40	73	15
14	7/2/01	6840	2398	4442	0.54	30	0
15	14/02/01	4670	1588	3082	0.52	*	*
16	21/02/01	5918	1702	4216	0.40	*	*
17	28/02/01	6188	1840	4348	0.42	76	54
18	7/3/01	6534	2150	4384	0.49	*	*
19	14/03/01	6392	2200	4192	0.52	*	*
20	28/03/01	6752	2430	4322	0.56	*	*
21	4/4/01	*	*	*	*	27.5	9
22	11/4/01	6102	1876	4226	0.44	3	0
23	18/04/01	6344	1928	4416	0.44	0	0
24	3/5/2001	6092	1954	4138	0.47	49.5	22.5
25	9/5/01	6146	1744	4402	0.40	11	0
26	16/05/01	6510	2044	4466	0.46	54.5	0
27	23/0501	6970	3276	3694	0.89	34.5	1
28	30/05/01	7026	3142	3884	0.81	97	59.5
29	6/6/01	6812	2796	4016	0.70	*	*
30	13/06/01	6540	2898	3642	0.80	24	0
31	20/06/01	6286	2392	3894	0.61	42.5	0
32	27/06/01	5628	2230	3398	0.66	17	0
33	4/7/2001	6196	2384	3812	0.63	*	*
34	18/07/01	5398	2284	3114	0.73	8	0
35	1/8/01	5904	2306	3598	0.64	19.5	0

APPENDIX B

Appendix B1 – Biogas Characterisation of Samples Collected from Shallow probes and Gas Wells at the Bisasar Road Landfill Site and the Mariannhill Landfill Site

Table B1.1 Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in the Existing Waste Plateau (EWP)

SAMPLING POINT	**SAMPLING DATE**										
	13/9/99	23/9/99	27/9/99	12/10/99	14/10/99	13/10/99	14/10/99	17/10/99	2/11/99	MEAN	STD DEVIATION
EWP 1	3.7	0	34.6	13.1	3.4	13.7	0.2	0.2	0.2	7.7	10.8
EWP 2	48	23.5	59.6	55.4	58.7	36.8	59.1	59.6	59.6	51.1	12.2
EWP 3	41.7	35.7	63.4	58.7	58.1	40.5	60.1	58.7	58.7	52.8	9.8
EWP 4	46	30.6	63.7	58.4	59.8	38.3	59.7	60.5	60.5	53.1	11.1
EWP 5	46.2	28.1	62	57.4	57.4	62.5	59.1	59.3	59.3	54.6	10.4
EWP 6	38.6	29.1	65.1	56	60.7	65	86.4	62.9	62.9	58.5	15.5
EWP 7	58.4	*	61	57.5	57.1	39.5	59	58	58	56.1	6.4
EWP 8	54.2	*	63.8	59.6	61	46.9	61.2	62.4	62.4	58.9	5.3
EWP 9	57.7	43.5	60.8	58.4	58.1	47.6	59.2	60	60	56.1	5.8
EWP 10	56.2	38.1	61.2	57.9	59	45.9	58.8	60	60	55.2	7.4
EWP 11	4.5	29	65.9	61.4	63.1	66.4	57.8	58.3	58.3	51.6	19.7
EWP 12	*	58	60.6	56.8	57.5	60.1	60.8	58.4	58.4	58.8	1.4
EWP 13	*	18.5	19.3	7.4	16	40.8	1	6.1	6.1	14.4	11.8
EWP 14	*	0	10.4	13.1	11.6	0.1	37.4	33.8	33.8	17.5	14.3
EWP 15	42.9	47.5	62.2	58.3	58.3	62	59.6	59.8	59.8	56.7	6.4
EWP 16	*	57.3	61.9	57.2	58.3	60.5	59.6	59.4	59.4	59.2	1.5
EWP 17	*	58.6	61.3	56.7	57.7	60.2	59.4	59.5	59.5	59.1	1.3
EWP 18	*	4.8	21.3	9.2	37.8	58.5	*	*	*	26.3	19.7
EWP 19	*	46.5	61.3	57.6	57.6	60.9	58.5	59.7	59.7	57.7	4.4
EWP 20	*	4.4	62.3	28.9	38.2	60.3	59.6	58.8	58.8	46.4	19.6

*Biogas not sampled

Table B1.3 Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in the Randles Cell (RC)

SAMPLING POINT	SAMPLING DATE												
	23/9/99	27/9/99	12/10/99	13/10/99	14/10/99	15/10/99	18/10/99	19/10/99	20/10/99	21/10/99	8/11/99	MEAN	STD DEV.
RC 1	*	*	44.1	29.3	30.3	32.1	37.4	35.8	35	30.8	27.4	33.6	4.8
RC 2	*	*	31.8	17	19.5	19.6	21.1	20.2	22.7	7	27.4	20.7	6.5
RC 3	*	*	58.4	41.5	43.2	41.6	44.0	44.0	50.8	13.2	25.3	40.2	12.6
RC 4	*	*	44.1	20.6	22	22	24.8	25.1	27.6	6.9	34.2	25.3	9.5
RC 5	*	*	27.5	16.5	32.1	31.4	38.6	33.6	40.9	17.7	42.3	31.2	8.8
RC 6	*	*	66.3	48.5	50.2	49	50.8	50.6	52.9	21.5	44.6	48.3	11.0
RC 7	*	*	10.4	5.8	8.2	10.1	9.7	7.3	31.9	6.1	*	11.2	8.0
RC 8	*	*	6.3	1.3	1.4	1.3	1.1	1.0	0.4	*	3.5	2.0	1.8
RC 9	*	*	11.7	5.6	5.3	6.5	5.5	6.1	*	*	2.3	6.1	2.6
RC 10	58	60.4	83.2	61.8	61.1	59.6	53.1	18.3	20.7	*	0.6	47.7	24.3
RC 11	57.4	59.5	83.2	61.8	61.1	59.6	61.3	61.3	61.9	23.7	59.5	47.7	13.0
RC 12	41.2	0.3	27.4	15	10.5	11.1	20.3	5.5	*	*	*	16.4	12.2
RC 13	59.1	61.7	84.8	62.7	62.2	60.8	62.2	62.7	*	*	*	64.5	7.7

*Biogas not sampled

Table B1.2 Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in the Existing Waste Plateau (EWP)

SAMPLING POINT	SAMPLING DATE										
	13/9/99	23/9/99	27/9/99	12/10/99	14/10/99	13/10/99	14/10/99	17/10/99	2/11/99	MEAN	STD DEVIATION
EWP 1	5.3	0.8	25	15.3	2.4	11.8	0.1	0.3	1.2	6.9	8.2
EWP 2	53.2	19.5	48.1	49.3	51.2	25.2	41.5	42.1	41.8	41.3	11.0
EWP 3	57.8	19.2	42.9	43.8	45.8	22.8	37.9	38.5	38.5	38.6	11.0
EWP 4	57.5	21.2	46.4	47.1	48.7	27.7	40.3	40.3	40.2	41.0	10.4
EWP 5	57.8	21.8	46.4	47.4	48.8	45.9	40	39.9	40.1	43.1	9.2
EWP 6	60.1	20.3	39	36.1	41.5	38.9	34.7	34.2	35	37.8	9.7
EWP 7	44.1	point	44.5	45.8	46.7	23.6	38.6	38.9	39.3	40.2	7.0
EWP 8	42.1	point	44.3	45.5	47	28.1	39	38.8	38.9	40.5	5.5
EWP 9	47.1	22.2	46.2	48.1	48.9	40	40.6	40.2	40.4	41.5	7.7
EWP 10	48.2	21.7	47.2	49.8	49.9	47.8	41.1	41.2	41.1	43.1	8.3
EWP 11	9	14	34.9	35	37.3	36.2	29.2	29.7	30.9	28.5	9.5
EWP 12	*	43.9	42	45.1	41	43.2	38.8	33.2	39.5	40.8	3.5
EWP 13	*	21	20.4	4	9.6	28.9	10.2	22.3	22.4	17.4	7.9
EWP 14	*	0	6.8	12.3	8.7	0	30.6	30.2	34.5	15.4	13.3
EWP 15	57.3	23	43.9	45.6	46.6	45.6	38.5	38.1	38.5	41.9	8.7
EWP 16	*	41.1	41.8	43.5	43.4	43.8	36.5	37.2	38.5	40.7	2.8
EWP 17	*	43	40.9	43.3	44.5	43.1	36.8	36.9	36.6	40.6	3.1
EWP 18	*	12.2	24.6	5.3	34.8	41.3	*	*	*	23.6	13.5
EWP 19	*	26.3	44.6	47.2	47.2	46.3	39.3	39.1	39	41.1	6.6
EWP 20	*	32.3	42.5	33.4	43.9	44.4	37.5	38.1	38.8	38.9	4.3

*Biogas not sampled

Table B1.4 Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in the Randles Cell (RC)

SAMPLING POINT	**SAMPLING DATE**												
	23/9/99	27/9/99	12/10/99	13/10/99	14/10/99	15/10/99	18/10/99	19/10/99	20/10/99	21/10/99	8/11/99	MEAN	STD DEV.
RC 1	*	*	65.6	63.5	62.3	63.1	60.5	59.9	58	53.8	62.6	61.0	3.3
RC 2	*	*	67.7	65.7	67.2	68.3	67.6	67.2	58	46.7	62.6	63.4	6.7
RC 3	*	*	48.8	48.1	48.4	48.3	48.1	48	46.8	26.9	19.6	42.6	10.5
RC 4	*	*	65.6	61.4	61.5	61.5	60.0	60.1	60.2	34.5	60.8	58.4	8.6
RC 5	*	*	36.3	37.9	57	47.9	49.3	48	50	29.1	54	45.5	8.6
RC 6	*	*	51.9	52	57.7	52.0	50.1	49.6	47.9	27.5	49	48.6	7.9
RC 7	*	*	6.9	14.5	9.1	23.6	21.3	16.2	61.8	27.7	*	22.6	16.2
RC 8	*	*	5.2	9.9	10.6	9.6	6.9	3.9	0.3	*	7.6	6.8	3.3
RC 9	*	*	8.4	11.8	1.2	13.9	9.7	10.8	*	*	3.0	8.4	4.3
RC 10	45.9	44.8	37.5	37	16.7	37.5	32.9	5.3	10.8	*	0.9	26.9	16.0
RC 11	47.4	45.5	38.1	37.6	37.4	38.1	37.4	37.2	36.7	23.5	38.1	26.9	5.7
RC 12	27.9	0.1	8.4	8.9	6.4	7.5	11.1	1.5	*	*	*	9.0	8.0
RC 13	42.7	38.6	32.3	35.6	34.1	33.8	33.1	31.9	*	*	*	35.3	3.4

*Biogas not sampled

Table B1.5 Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	SAMPLING DATE												
	31/3/00	10/4/00	12/4/00	17/4/00	19/4/00	26/4/00	4/5/00	8/5/00	10/5/00	15/5/00	19/5/00	22/5/00	5/6/00
1	60.8	61.1	67.2	42.3	42.9	43.4	43.4	43.1	43.1	43	46.7	44.6	45.2
2	59	51.6	47.6	43.3	43.3	43.5	43.7	42.6	42.6	44.1	47.6	45.5	46.1
3	58.8	29.6	46.8	43	42.7	43	34.7	29.7	42.4	43.6	5.9	45.2	45.9
4	58.6	39.6	49.9	42.6	42.3	42.7	16.6	42.6	42.6	43.5	45.4	45.2	45.2
5	62.9	52.8	55	29.1	47.6	46.3	27.2	44.5	45.4	47.1	43.9	48.4	48.5
6	59.1	21.9	30.5	68.5	43.1	42.1	26.3	41.3	41.6	42.7	57.5	44.4	45.4
7	60.2	31.7	31	49.7	44.7	44.1	28.1	40.2	41.4	36.1	41.3	46.1	47
8	60.2	39.6	34.4	46.5	43.7	44	28.6	43.7	42.1	42.8	43.6	44.4	45
9	60.2	34.1	37.1	37.63	43.8	43.7	29.3	43.2	43.3	44.1	45	45.6	46.3
10	60.1	1	49.7	18.4	44.1	43.8	21.5	43.1	43.4	43.3	39	45.2	46.1
11	61.5	20.5	33.1	42.7	45	45	29.9	44.5	44.7	45.7	46.2	47.25	47.6
12	60.6	32.6	25.4	41.1	43.4	43.8	29.2	43.7	43.2	44.1	44.5	45.5	46.1
13	61.7	36.3	27.4	42.6	43	45	29.2	43.8	44	44.4	45.1	46.2	46.3
14	60.6	30	20	41	42.1	43.6	30.3	43.1	43.2	43.9	44.5	45.8	46.5
15	60.7	25.3	35.7	40.7	41.6	43.8	29.8	43.3	43.1	43.9	44	45.3	46
16	60.8	25.2	9.2	40.9	42.3	44.8	50.9	44.7	44.8	45.9	46.3	47.4	47.8
17	60.2	14.1	14	42.2	43.4	44.2	37.9	43.4	43.5	44.4	44.2	45.5	45.7
18	62.2	11.5	20.3	41.3	44	45.7	27.3	44.3	45.3	45.3	45.8	47.3	47.2
19	62.6	12.4	27.8	42.4	43.1	44.2	25.9	43.7	44	43.1	43.8	44.9	45.7
20	61.2	22	26.5	42	42.8	44.3	29.3	42.9	43.1	44	44.2	45.4	45.9
21	61	16.4	5.2	41.5	41.7	44	44.6	43.1	43.2	44.3	44.4	45.4	46.1

22	60.6	19.5	3.1	40.2	41.1	43.5	43.7	42.4	42.8	43.3	43.8	45.2	45.6

Table B1.5 (contd.) Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**												
	7/6/00	9/6/00	14/6/00	19/6/00	21/6/00	26/6/00	28/6/00	30/6/00	3/7/00	5/7/00	12/7/00	14/7/00	17/7/00
1	47.5	46.5	47.2	47.2	47.1	47.5	47.1	44.7	53.3	52.3	51.8	53.2	49.9
2	46.9	47.5	47.9	47.8	47.7	48	47.8	44.9	53.6	52.4	51.6	53.5	50
3	35	46.8	46.8	47	46.9	47.2	46.9	44.2	52.9	51.7	50.7	52.2	48.9
4	43.6	46.4	46.7	47.1	46.6	46.9	46.6	43.9	52.2	51.1	50.4	51.8	48.3
5	52.1	50	49.8	49.8	49.1	50	50.3	47.2	56.4	55.4	54.4	56	52.2
6	43.9	46.8	46.7	46.8	47	47	44.5	44.1	40.4	51.8	51.2	50.2	49
7	45.6	48.2	47.9	47.9	47.6	47.8	45	44.9	50.8	52.3	54.7	51	49.4
8	35.2	46.6	46.6	46.6	46.5	46.7	44	43.9	50	51.5	51.1	50.1	48.7
9	40.1	47.4	47.6	47.3	47.5	47.6	44.7	44.7	50.9	52	51.4	50.6	49.3
10	44.2	46.7	47.5	47.3	47.3	47.6	44.7	44.5	50.6	52.1	51.3	50.4	49.4
11	39.8	49.2	48.9	48.9	49	49	46.5	46.4	52.5	53.9	53.4	42.4	51
12	42	49.2	47.5	47.5	47.5	47.5	44.6	44.7	50.5	53	52.9	51.5	49.1
13	52.9	47.8	47.7	47.9	48	47.8	45.3	45.1	51.1	52.5	52.1	51.3	49.8
14	45.3	47.4	47.3	47.4	47.3	47.3	44.6	44.5	50.4	51.5	51.3	50.5	49
15	45.1	47.4	47.3	47.5	47.5	47.4	44.8	44.3	40.5	51.7	51.5	50.6	48.8
16	46.6	48.5	48.3	48.2	47.7	48.7	46.3	46.2	51.6	52.7	51.8	51.2	49.4
17	53.3	47.2	46.9	47.2	47.2	47.5	44.5	44.3	50	51.5	51	50.3	48.6
18	40.9	49.1	49	48.8	48.9	48.5	46.4	46	51.9	52.9	53	51.9	50.2
19	40.8	48.4	47.6	48.7	48.9	48.5	45.6	45.5	51.9	53.4	52.7	51.7	50.7

20	41.2	47.2	47.2	47.2	47.3	47.3	44.7	44.5	50.3	51.9	51.4	50.5	48.9
21	45	46.9	47.2	47.1	47.5	47.6	45.1	44.8	50.2	51.7	50.9	50.2	48.8
22	44.5	46.9	46.6	46.5	46.8	46.9	44.3	44.3	49.8	51.2	50.8	49.8	46.6

Table B1.5 (contd.) Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**												
	26/7/00	2/8/00	14/8/00	22/8/00	28/8/00	21/9/00	26/9/00	3/10/00	17/11/00	27/11/00	15/1/01	30/1/01	13/2/01
1	36.5	45.4	34.1	45.9	49.4	49.7	45.3	58	56	53.6	55.8	58.1	56.5
2	50.5	45.7	35.4	44.6	37.9	48.3	48.4	57.7	46.6	56.6	56.4	45.3	*
3	49.3	45.5	31	38.4	44.8	46.2	46.8	54.1	69.4	55.7	57.2	56.2	55.6
4	45.3	45.1	32.5	42.4	44.6	45	45.9	53.3	52.9	54	56.9	48.7	55.5
5	45.3	48.5	34.4	44.9	36.4	50.4	49.9	54.1	54.9	58.8	60.8	48.6	58.1
6	31.8	46.8	32	35.4	45.7	46.3	45.4	52.4	52.7	55.6	56.3	54.2	54.3
7	49.5	46.6	29.6	36	45.7	32.1	44.5	54.5	43	54.9	57.1	54.5	55.1
8	49	46.6	34	42.8	26.6	34.4	47.9	53.6	56.1	54.4	56.9	55.1	54.2
9	49.1	45.4	33.4	43.2	48.8	43.7	48.7	54.7	60	56.2	57.7	55.6	56.2
10	27.3	40	30.9	39.9	38.9	46.6	45.3	46.1	56	54.6	56.4	54.5	54.8
11	51.2	48.5	31.9	35.4	43.8	38	45.8	54.8	55.2	56.3	57.7	55.5	56.4
12	36.6	37.8	31.5	40.6	47.9	48.4	48.6	54.9	54.2	56.4	58.3	54.7	56.4
13	50.2	46.2	32.7	42.5	48.4	46.4	43.7	54.5	54.3	55.5	57.5	54.5	55.4
14	23.4	46.9	31.5	42.7	46.6	47.8	47.4	54	53.8	55.1	56.9	54.8	55.7
15	48.5	46.3	35.1	43.3	45.6	46.3	48.2	54.2	53.4	55.5	56.5	55	55.8
16	40	39	27.2	38.2	42.3	42.9	39.7	53.5	54.5	54.7	57.2	54.3	56
17	48.4	47.6	32.7	43.1	49.1	48.6	48.3	53.8	54.4	54.5	56.5	54.4	*

18	50.3	49.3	35	48	48.9	49.6	45.9	55.3	54.2	56.3	57.7	55.4	56.7
19	50.6	47.4	37	45.6	47.1	48.7	47.2	55.2	54.8	55.9	58.8	46.7	57
20	40.2	46.1	35.4	41.9	43.6	46.8	44.9	54.5	53.6	55.8	57.2	55.4	56
21	48.6	45.8	33.6	45.2	47.3	48	40.3	53.5	54.1	54.5	56.2	54.2	56
22	47.8	46.9	25.7	46	47.6	48.6	35.8	53.4	53.9	54.3	55.9	54.4	55.4

Table B1.5 (contd.) Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	SAMPLING DATE					
	20/2/01	27/2/01	6/3/01	13/3/01	MEAN	STD DEVIATION
1	53.8	54.4	59	50	49.4	6.65
2	55.9	46.8	57.7	54.5	44.5	5.21
3	55.4	55.8	56.7	54.3	46.5	10.16
4	55.5	55.3	56.4	53.9	47.0	7.10
5	58.7	59.5	60.2	57.1	50.0	7.66
6	54.3	55.9	55.6	54.1	46.6	8.99
7	55.6	55.8	57.1	54	46.5	7.96
8	55.6	56.1	57.3	53.9	46.5	7.63
9	55.9	56.4	57.9	54.5	47.7	7.11
10	53.8	54.9	56.3	53	44.9	10.99
11	56.9	56.6	57.3	55.2	47.5	8.33
12	55.5	56.3	58.1	54.9	47.0	7.97
13	55.5	55.2	57.5	54	47.9	7.12
14	55.8	55.6	57.8	53.9	46.5	8.62
15	55.4	55.7	57.8	54.5	47.1	7.17

16	56	54.7	56.3	54.4	46.7	9.21
17	55.5	55	57	*	46.6	9.09
18	57	56.7	57.7	54.5	47.8	9.44
19	57.1	58.4	59.2	55.3	47.4	9.08
20	55.8	55.6	57.3	54.2	46.7	7.98
21	55.4	54.6	56.3	54.3	46.6	9.56
22	55	54.6	56.7	50	45.9	9.89

*Biogas not sampled

Table B1.6 Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**												
	31/3/00	10/4/00	12/4/00	17/4/00	19/4/00	26/4/00	4/5/00	8/5/00	10/5/00	15/5/00	19/5/00	22/5/00	5/6/00
1	43.4	41	40.2	41	40.9	41.7	40.8	40.8	41.4	40.7	38.6	38.9	37.9
2	42.4	36.8	30.5	40.3	40.4	40.8	40.6	40.3	41.1	40.3	37.6	38.3	37.5
3	42	28.6	27.8	40.6	40.6	41.1	34.3	33.9	40.6	40.2	24	38.5	37.8
4	42.4	28.2	26.5	41.5	40.9	41.3	25.9	40.5	41.2	40.3	22.3	38.1	38.4
5	41.6	26.7	22.8	31	39.8	39.7	25	39.7	40.3	39.8	21.2	37.8	37.4
6	44.4	20	14.4	42.9	42.5	43.2	24	42.8	42.6	42.1	39.2	39.9	38.3
7	41.3	21	16.8	31.2	39	39.9	23.1	36.7	37.9	32.2	33.7	37.1	36.2
8	42.8	25.6	17.9	31.2	40.8	41	24.6	38.8	41.7	41.2	29.9	38.8	38.4
9	40.8	17.9	17.4	25.8	39.3	39.7	24.1	39.6	39.7	39.1	25.2	37.2	36.4
10	41.4	1.7	20.1	25.1	39.4	39.5	21.4	39.6	40	39.5	22.3	37.2	37.1
11	40.8	18.5	18.6	38.8	38.7	39.1	22.6	38.7	38.6	38.3	35.9	36.4	35.8
12	41.7	24	18.7	40.5	40.4	40.4	24.2	40.1	41	40.2	38	38.8	37.9

13	41.3	24.1	17.9	40.4	40.7	40.4	25.1	40.1	40.4	40.2	37.7	38.5	37.5
14	41.1	22.5	17.7	40.1	40.2	40.7	26.5	40.3	40.3	39.7	37.5	37.9	36.4
15	41.4	21.4	21.9	40.7	40.3	40.5	29.7	40.3	40.5	40.1	37.5	35.5	36.5
16	39.8	21.9	15.6	40.7	40.4	38.8	29.7	37.9	38.2	37.5	35.4	38.5	35
17	42.6	18.1	18	38.1	41.6	40.8	37.3	39.9	40.3	40.1	37.9	38.4	38
18	39.9	17.9	18.8	41	41.4	39.5	38.4	41.5	39.4	40.8	37.5	39.9	37.9
19	42.2	18.5	21.3	42.1	41	42.2	36.7	42.1	42.2	42.3	39.5	39.9	38.9
20	41.4	20.7	21.3	41.7	38.8	40.2	33.6	40.6	40.5	40.2	37.8	38.2	37.2
21	41.1	20.1	14.5	40.5	40.4	40.6	39.1	40.1	40.1	39.6	37.4	38.2	36.9
22	39.7	21.6	13.4	40.6	40.9	40.9	39.7	40.1	40.5	40.1	37.7	38.2	37.4

Table B1.6 (contd.) Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**												
	31/3/00	10/4/00	12/4/00	17/4/00	19/4/00	26/4/00	4/5/00	8/5/00	10/5/00	15/5/00	19/5/00	22/5/00	5/6/00
1	38.1	38.9	38.5	38.7	39.1	38.4	38.4	38.6	42	41.7	42.9	42.1	32.9
2	36.8	38.3	38.5	37.9	38.1	37.8	38	37.6	40.9	40.7	41.8	41.1	28
3	27	38.4	38.4	38.1	38.3	38.2	37.8	37.9	41.3	41.1	41.9	41.2	33.7
4	23.5	39.3	38.7	38.3	38.8	38.5	38.4	38.3	41.8	41.7	42.5	42	39.6
5	21.7	38.5	38	38.1	37.8	37.9	37.6	37.5	41.3	41.1	41.5	41.3	39
6	21.8	40	39	39.5	39	39.1	39.1	38.4	41.9	42.3	43.3	42.2	39.7
7	17.3	37.3	36.8	37.5	37.6	37.2	37.3	37.3	40.7	40.6	41.6	40.6	38
8	21.9	39.3	38.6	38.1	38	38.5	38.7	38.5	41.7	41.6	42.6	41.9	39.1
9	19.7	37.9	37.4	37.3	37.4	37.4	37.6	36.9	40.7	40.7	41.6	40.7	38.1
10	21.5	37.3	37.3	37.6	37.5	37.6	37.6	37.2	40.5	40.9	41.5	40.8	38.2

11	18.5	37.1	36.4	36.8	36.5	36.5	36.4	36.4	39.5	39.7	40.5	39.7	36.9
12	20.2	39.1	38.3	38.9	38.6	38.2	38.2	38	41.7	41.5	43.2	41.5	39
13	24.8	38.4	37.7	38.2	37.8	37.7	37.8	37.7	41	41	42	40.8	38.5
14	26.1	38.6	37.7	37.9	37.9	37.6	37.9	38	40.9	41	42	41	38
15	29.7	38.5	37.5	38.1	38	37.5	37.9	37.6	40.6	40.9	42.3	40.9	38.3
16	35.5	36.8	35.9	36.5	35.8	36.2	36	36	38.8	39.9	41.3	40.1	37.1
17	37.6	39.1	38	39.1	38.1	38.2	38.6	38.5	41.8	42.2	43.2	41.8	38.6
18	30.1	38	37.1	38	37.8	38	38.1	38.1	41.3	42.1	43.4	41.6	39
19	31.3	40.3	39.1	39.7	38.8	38.6	38.7	39.4	41.3	42.4	43.7	42.3	39.2
20	30.8	38.9	38	38.5	37.8	37.7	38.1	37.7	41.1	41.2	42.4	41.3	38.6
21	7.1	38.5	38	38.5	37.6	37.8	37.8	37.7	40.8	41.4	42.6	41.1	38.9
22	37.6	39	38.1	38.8	38	38.1	38.2	38.1	41.4	42.4	43.1	41.7	38.1

Table B1.6 (contd.) Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**												
	31/3/00	10/4/00	12/4/00	17/4/00	19/4/00	26/4/00	4/5/00	8/5/00	10/5/00	15/5/00	19/5/00	22/5/00	5/6/00
1	30.5	36.4	29.1	36.9	39	39.6	36.6	54.1	43.5	43.5	43.2	43.5	43
2	38.9	36	29.7	35.6	31.5	38.8	39.1	44.7	29.8	43.8	43.4	30.1	*
3	39	36.7	27.4	32.4	36.8	38.1	39	44.9	25.8	43	42.3	24.7	42.4
4	37.1	37.2	29	36.1	36.5	37.1	38.8	45.3	22.5	43.2	44.2	30.2	41.9
5	34.6	36.6	28	34.5	31.3	38.8	38.7	41.6	20	43.8	42.3	35.3	42.2
6	28.2	39.5	29.1	31.7	40	39.8	39.9	47.5	45	44.5	46.8	44.8	44.7
7	38.3	36.9	25.9	30.4	39	29.2	37.4	45.4	35.5	42.7	43.7	42.9	42.4
8	39.2	37.9	29.4	35.1	24.1	30.6	39.2	45.4	29.3	43.1	42.8	43.1	37.3

9	38.3	35.6	28	34.8	35.3	34.6	38.2	46.1	26.4	42.7	42.5	42.4	41.3
10	23.3	32.8	26.4	32.3	31.4	36.8	36.4	33.7	20.8	40.7	43.4	41.8	40.2
11	37.8	36.9	27	29	37.1	33	37	44.5	42.7	43.9	44.1	43.3	41.6
12	31.1	32	27.6	33.8	39.3	39.2	39	45.4	44.7	43.9	43.4	43.4	42.8
13	38.9	36.4	27.7	34.2	3.8	36.6	35.8	44.8	45.4	43.5	43.4	42.5	41.9
14	20.9	37.5	27.1	35.2	37.5	37.6	38.6	44.3	44.4	45.7	42.2	42.4	43
15	38.1	37.1	29.6	35	38	37.6	39.1	44.6	45.1	43.3	43.5	42.3	41.8
16	32.6	33.8	24.5	33.6	36.8	36.4	33.9	44.6	43.9	44.4	43.7	43.6	41.7
17	39.6	39.2	28.6	36.1	36.5	38.5	39.9	45.3	44.1	43.6	44.1	43.7	*
18	39.1	38.5	29.2	37.2	39.7	39.4	37.6	46.5	46.2	43.9	42.6	42.4	41.6
19	39.3	37.6	31.8	37.2	40.8	40.3	40.3	45.8	45.8	45.6	45.9	44.7	43.8
20	33	37.4	29.7	34.5	35.9	37.2	36.7	45.4	45.5	44	43.7	42.5	41.7
21	39.6	39.6	29.7	38.4	38.2	38.6	34.8	43.3	45.3	44.2	45.5	42.3	41.8
22	39.4	40.4	23.3	38.6	40.3	39.7	31.5	47.3	44.4	44.6	43.4	43.9	41.4

Table B1.6 (contd.) Concentration of carbon dioxide *(% vol/vol)* in the biogas sampled from shallow probes in Cell 1

SAMPLING POINT	**SAMPLING DATE**					
	20/2/01	27/2/01	6/3/01	13/3/01	MEAN	STD DEVIATION
1	40	40.7	41.9	41.7	40.0	3.80
2	41.9	27	42.5	44.2	38.1	4.42
3	42.1	42.4	42.6	43.7	37.4	5.53
4	41.6	43	42	44.2	37.6	6.07
5	41.7	43	41	44.1	36.5	6.44
6	43.6	42.3	44.4	43.6	39.0	7.26

7	42	42.4	42	44.6	36.4	6.78
8	42.1	43.1	41.1	44.8	37.2	6.56
9	41.1	41.9	40.8	43.8	36.3	6.94
10	39.3	40.7	40.1	42.8	34.7	8.44
11	41.1	42.3	41.3	43.6	36.7	6.53
12	42.5	42.4	41.6	44.5	38.1	6.32
13	41.4	41.3	41.5	44.3	37.2	7.73
14	42.2	41.9	40.9	44.1	37.7	6.30
15	41.4	42.5	40.6	44.3	38.3	5.08
16	10.8	42	42.6	43.8	36.5	6.97
17	42.3	42.5	41.6	*	38.8	5.52
18	41.9	42.5	41.7	44.6	38.9	5.57
19	43.2	42.8	43.2	46.5	40.0	5.47
20	42.5	42.6	41.2	44.8	38.4	5.21
21	41.4	43.3	42.5	44	38.1	7.33
22	42	43.1	41.9	41.7	38.8	6.01

*Biogas not sampled

Table B1.7 Concentration of *methane (% vol/vol)* in the biogas sampled from shallow probes in Cell 3

SAMPLING POINT	SAMPLING DATE							
	7/9/01	10/9/01	17/9/01	21/9/01	28/9/01	29/10/01	MEAN	STD DEVIATION
1	54.6	54.9	55.2	55.2	55.2	54.8	55.0	0.2
2	44.7	44.9	46.2	46.2	46.2	44.8	45.5	0.7
3	49.8	48.9	47.9	47.9	47.9	48.9	48.6	0.7
4	44.6	43.6	44	44	44.1	43.8	44.0	0.3
5	58	58.4	58	58	58	57.9	58.1	0.2
6	42.5	39.9	42.3	42.8	42.5	41.2	41.9	1.0
7	41.5	41.8	42.3	42.9	42.3	41.5	42.1	0.5
8	32.4	23	31.7	30.7	31.1	30.9	30.0	3.2
9	38.5	31.3	38.1	37.3	37.8	37.6	36.8	2.5
10	32.4	23.8	35.5	30	31.1	30	30.5	3.5

Table B1.8 Concentration of *carbon dioxide (% vol/vol)* in the biogas sampled from shallow probes in Cell 3

SAMPLING POINT	SAMPLING DATE							
	7/9/01	10/9/01	17/9/01	21/9/01	28/9/01	29/10/01	MEAN	STD DEVIATION
1	45.3	48	47.4	47.4	47.3	47	47.1	0.8
2	43.4	44.7	44	44	44	44	44.0	0.4
3	41.9	43.6	42.7	42.7	42.6	42.3	42.6	0.5
4	41.7	42.9	42.7	42.7	42.6	42.5	42.5	0.4

5	42.5	43.7	44.7	44.7	44.7	42.4	43.8	1.0
6	43.4	43.6	43.5	43.7	43.5	43.6	43.6	0.1
7	46.2	46.6	46.9	46.8	46.6	46.7	46.6	0.2
8	46.4	40	45.2	46.5	46.6	45.3	45.0	2.3
9	44.5	41.7	45.6	45.1	45	45	44.5	1.3
10	42.9	36.1	44	41.1	41.1	41.1	41.1	2.5

Table B1.9 Concentration of *methane (% vol/vol)* in the biogas sampled from the gas wells in Cell 1 and Cell 2 for August 2001

DAY	**GAS EXTRACTION WELL**					
	GW1	GW2	GW3	GW4	GW5	GW6
1	35	38	41	47	46	49
2	49	51	52	53	47	54
3	45	49	51	50	45	52
6	49	50	52	48	45	50
7	44	46	48	49	46	50
8	45	46	50	50	44	50
9	39	40	43	45	39	50
10	37	39	40	45	44	50
11	40	44	45	45	40	50
12	37	39	41	45	40	49
13	49	50	50	51	49	51
14	38	40	43	45	44	49
15	39	40	43	45	40	49
16	39	40	41	45	40	49

20	50	54	55	50	42	50
21	44	45	50	46	45	50
22	39	40	42	48	48	50
23	49	50	55	50	47	50
24	44	48	50	50	47	50
27	50	51	51	49	46	50
28	40	40	45	49	44	50
29	40	41	41	44	41	49
30	35	39	35	40	46	45
31	39	40	44	46	41	50

Table B1.10 Concentration of *methane (% vol/vol)* in the biogas sampled from the gas wells in Cell 1 and Cell 2 for September 2001

DAY	**GAS EXTRACTION WELL**					
	GW1	GW2	GW3	GW4	GW5	GW6
1	42	39	40	46	39	49
2	49	39	54	43	42	42
3	36	40	40	45	41	50
4	35	35	35	40	35	48
5	35	40	42	45	41	50
6	25	37	39	45	39	45
7	34	37	40	45	40	50
8	35	39	41	45	42	50
9	37	40	45	47	45	50

10	35	39	40	45	40	50
11	36	39	40	46	38	50
12	35	30	37	40	39	45
13	40	49	40	50	50	50
14	39	43	45	50	40	50
15	40	41	45	50	47	54
16	38	42	45	47	41	50
17	39	42	45	50	43	50
18	38	42	40	49	42	49
19	38	40	40	45	40	51
20	40	40	40	47	40	50
21	38	41	45	50	42	53
22	40	47	45	45	49	50
23	40	40	45	49	45	50
24	40	43	45	48	45	35
25	37	40	40	45	40	51
26	41	40	57	50	45	54
27	34	25	30	40	35	50
28	39	41	48	46	44	50
29	39	43	40	45	41	50
30	35	40	46	48	45	50

Table B1.11 Concentration of *methane (% vol/vol)* in the biogas sampled from the gas wells in Cell 1 and Cell 2 for October 2001

DAY	GAS EXTRACTION WELL					
	GW1	GW2	GW3	GW4	GW5	GW6
1	40	44	47	50	45	53
2	37	40	45	45	40	52
3	40	40	39	33	41	50
4	40	43	49	50	46	53
5	40	44	45	50	45	54
6	35	40	40	45	40	50
7	36	40	44	50	41	50
8	38	40	45	48	43	50
9	39	43	45	50	45	54
10	40	40	46	50	43	53
11	40	43	49	50	48	52
12	28	40	40	40	40	49
13	42	39	47	50	45	51
14	40	40	47	45	43	50
15	40	43	47	50	45	55
16	40	43	47	50	45	55
17	40	43	49	50	47	53
18	40	40	45	48	44	50
19	40	40	45	49	40	50
20	40	40	47	50	42	52

22	40	40	41	50	45	50
23	40	40	47	50	45	50
24	40	40	44	48	44	51
25	40	40	50	50	42	55
26	40	43	50	52	45	50
29	40	42	50	50	44	53
30	40	41	47	50	48	44
31	45	44	51	52	49	55
MEAN	39.3	41.3	46.1	48.4	44.0	51.6
STD DEVIATION	2.7	1.6	3.1	3.8	2.4	2.3

APPENDIX C

Appendix C1 – Waste Stream Analysis for the Inner West Region and Waste Composition of Mariannhill Cell 1 and Cell 2

Appendix C2 – Landfill Gas Models (Physical-Chemical/Biochemical and LandGEM) applied to Cell 1

Appendix C3 – Landfill Gas Models (Physical-Chemical/Biochemical and LandGEM) applied to Cell 2

Table C1.1 Waste Composition for the Inner West Region (adapted from DMWS, 1998)

HOUSING DEVELOPMENT	MASS OF WASTE COMPONENT (kg/annum)							
	Hard Plastics	Soft Plastics	Glass	Tin/ Aluminum	Cardboard	Other Paper	Putrecibles	Other
Backyard Dwellings	23799	41647	17849	11899	47597	47597	362927	41647
Single Dwellings	30158	52777	22619	15079	60317	60317	459916	52777
Houses & Flats	2565035	3820261	3031279	2535567	3234201	3966658	16643532	2400286
Per Clus Dwell	67707	118488	50781	33854	135415	15415	1032537	118488
Per Sing Dwell	134691	235710	101019	67346	269383	269383	2054043	235710
Peri-Urban Cluster	2056	3598	1542	1028	4112	4112	31354	3598
Peri-Urb Sing	1722	3013	1291	861	3444	3444	26258	3013
Traditional Dwell	76	133	57	38	152	152	1156	133
Rows of Rooms	40419	70733	30314	20209	80837	80837	616384	70733
Township House	513223	1466351	513223	953128	953128	1026446	1246399	659858
TOTAL	3378886	5812711	3769974	3639009	4788586	5474361	22474506	3586243
% OF TOTAL	6.4	11.0	7.1	6.9	9.0	10.3	42.5	6.8

Table C1.2 Waste composition in Cell 1 (determined at the weighbridge)

WASTE COMPONENT	MASS OF WASTE COMPONENT OVER SIX MONTH PERIODS (TONS)					
	Jul-Dec 97	Jan-Jun 98	Jul-Dec 98	Jan-Apr 99	Cumulative	% of Total
Solid Waste	8357	10212	6870.2	5419.33	30858.54	39.93
Garden	1843	3064	3123.18	2998	11028.18	14.27
Rubble	1364	2408	1588.96	625.61	5986.57	7.75

Mixed Loads	457	442	364.99	319.33	1583.32	2.05
Cond. Foods	0	0	3.64	0.36	4	0.01
Sand etc.	7138	10927	5046.32	4086	27197.32	35.2
General - Rec.	0	0	0	0	0	0
Whole Tyres	30	75	123.64	64	292.64	0.38
Asphalt	0	0	0	0	0	0
Polystyrene	6	10	19.42	15.97	51.39	0.07
Light Waste	4	4	31.82	20.67	60.49	0.08
Sani-waste	26	26	0	0	52	0.07
Special Disp.	0	31	55.4	72.55	158.95	0.21
No Charge	0	0	0	0	0	0

Table C1.3 Waste composition in Cell 2 (determined at the weighbridge)

WASTE COMPONENT	MASS OF WASTE COMPONENT OVER SIX MONTH PERIODS (TONS)					
	Apr-Jun 99	Jul-Dec 99	Jan-Jun 00	Jul-Dec 00	Cumulative	% of Total
Solid Waste	2709.67	9767	11744	9747	33967.67	32.6
Garden	1499	6673	8802	7720	24694	23.7
Rubble	312.81	711	1089	2958	5070.81	4.87
Mixed Loads	159.67	485	548	626	1818.67	1.75
Cond. Foods	0.18	0	9	0	9.18	0.01
Sand etc.	2043	7025	8540	20099	37707	36.19
General - Rec.	0	0	0	0	0	0
Whole Tyres	32	112	88	104	336	0.32
Asphalt	0	5	5	0	10	0.01

Polystyrene	7.99	11	27	32	77.99	0.07
Light Waste	10.33	48	34	20	112.33	0.11
Sani-waste	0	0	21	8	29	0.03
Special Disp.	36.27	191	77	57	361.27	0.35
No Charge	0	0	0	0	0	0

The mass of ‘Solid Waste’ in Cell 1 and Cell 2 is separated into smaller components according to the relative percentages obtained from the WSA (Table C1.2), as is shown in Figures C1.1 and C1.2

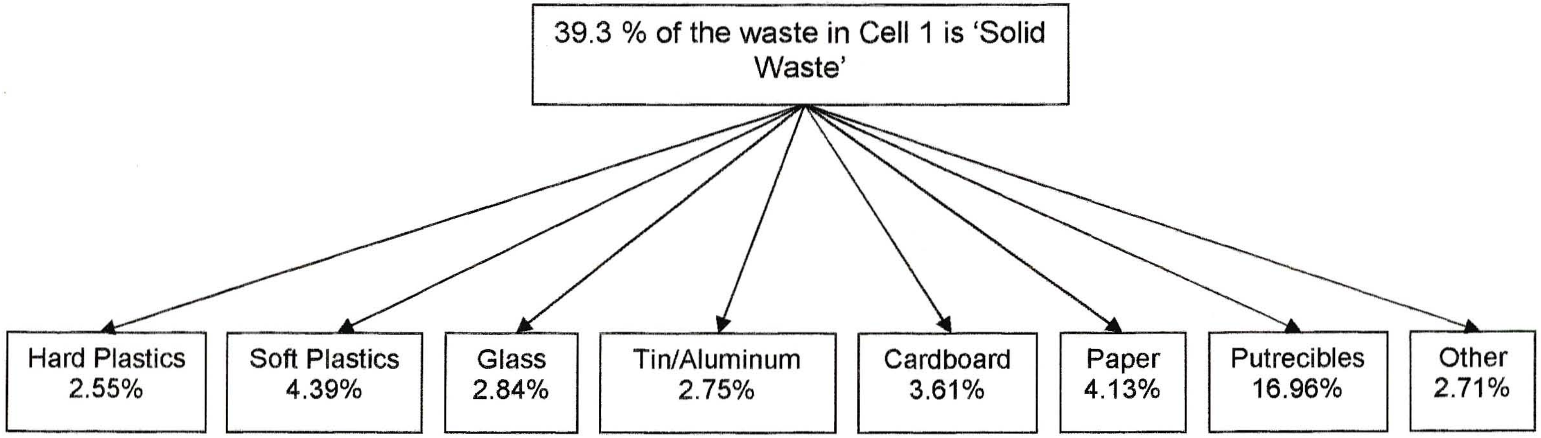

Figure C1.1 Breakdown of the ‘Solid Waste’ waste type in Cell 1

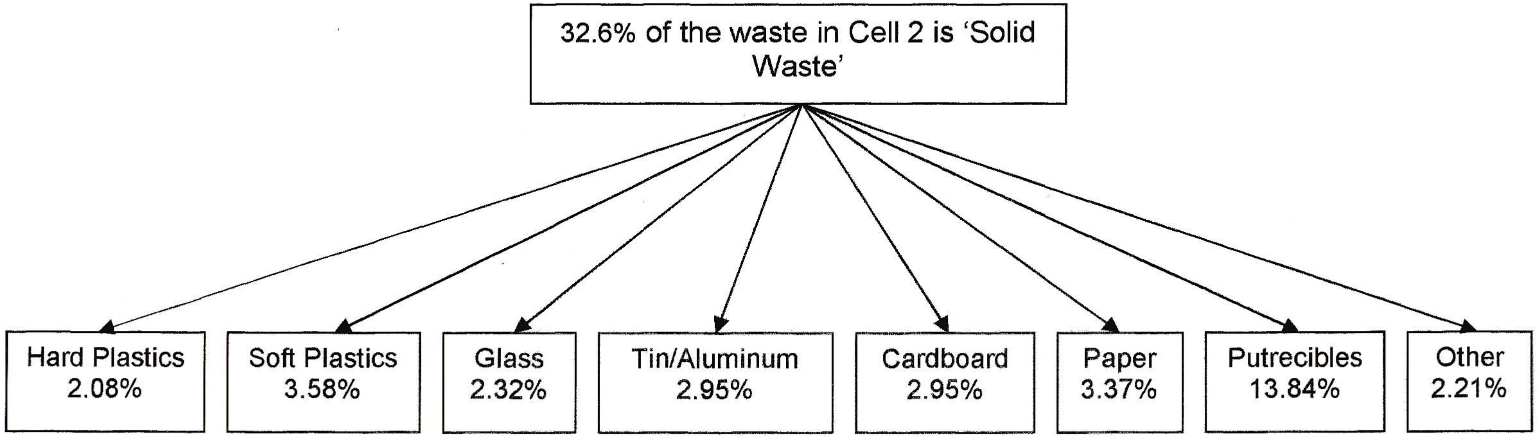

Figure C1.2 Breakdown of the 'Solid Waste' waste type in Cell 2

Table C1.4 Masses of the gas producing waste components in Cells 1 and 2.

	CELL 1				CELL 2			
	Putrescibles	Garden	Cardboard	Paper	Putrescibles	Garden	Cardboard	Paper
Mass (tons)	13103	11027	2792	3192	14424	24694	3073	3513
% of Total in Cell	16.96	14.27	3.61	4.13	13.84	23.70	2.95	3.37

Table C2.1 Relative masses of the gas producing components in Cell 1

WASTE COMPONENT	% OF TOTAL MASS IN CELL
(a) Easily Biodegradable	
1. Putrescibles	16.96
(b) Biodegradable	
2. Garden refuse	14.27
(c) Slowly Biodegradable	
3(a) Cardboard	3.61
3(b) Paper	4.13

Table C2.2 Cell 1 waste component properties

PROPERTY	WASTE COMPONENT			
	1	2	3(a)	3(b)
Ci	0.48	0.48	0.44	0.44
f_b	0.8	0.7	0.5	0.5
u_i	0.7	0.6	0.08	0.08
pi	0.1696	0.1427	0.0361	0.0413

Table C2.3 The amount of carbon in Cell 1 available for conversion to biogas

	FRACTION OF BIODEGRADABLE CARBON IN EACH WASTE COMPONENT (kg/kg_{MSW})			
	CO_b (1)	CO_b (2)	CO_b (3a)	CO_b (3b)
	0.0195	0.0192	0.0073	0.0084
Landfill Temperature (^0C)	45 ^0C	45 ^0C	45 ^0C	45 ^0C
Temperature correction factor	0.910	0.910	0.910	0.910
	FRACTION OF BIODEGRADABLE CARBON FOR EACH BIODEGRADABILITY FRACTION (kg/kg_{MSW})			
	CO_e(a)	CO_e(b)	CO_e(c)	CO_e (total)
	0.018	0.017	0.014	0.049

(a) Easily Biodegradable

(b) Biodegradable

(c) Slowly Biodegradable

Table C2.4 Effective generation constant (k_e) for each biodegradability fraction in Cell 1

BIODRADABILITY FRACTION	CORRECTION FACTORS		GENERATION CONSTANTS	
	α	β	k (yr^-1)	k_e (yr^-1)
(a)	0.80	0.9	0.693	0.499
(b)	0.80	0.9	0.139	0.100
(c)	0.80	0.9	0.069	0.050

Table C2.5 Predicted cumulative gas production rates for Cell 1 (Chemical-Physical/Biochemical Model)

TIME FROM OPENING OF CELL (years)	CUMULATIVE GAS PRODUCTION RATE (m^3/ton_{MSW})	TIME FROM OPENING OF CELL (years)	CUMULATIVE GAS PRODUCTION RATE (m^3/ton_{MSW})
0	0.000	26	82.709
1	17.442	27	83.294
2	29.401	28	83.840
3	37.921	29	84.349
4	44.253	30	84.825
5	49.165	31	85.270
6	53.130	32	85.686
7	56.445	33	86.076
8	59.295	34	86.441
9	61.797	35	86.782
10	64.030	36	87.103
11	66.046	37	87.403
12	67.879	38	87.685
13	69.557	39	87.950
14	71.099	40	88.198
15	72.520	41	88.432
16	73.832	42	88.651
17	75.045	43	88.858
18	76.169	44	89.052
19	77.211	45	89.235
20	78.178	46	89.408
21	79.076	47	89.570
22	79.910	48	89.723
23	80.687	49	89.868
24	81.409	50	90.004
25	82.082		

Table C2.6 Predicted Specific gas production rates for Cell 1 (Chemical-Physical/Biochemical Model)

TIME FROM OPENING OF CELL (years)	SPECIFIC GAS PRODUCTION RATE (m^3/ton_{MSW})	TIME FROM OPENING OF CELL (years)	SPECIFIC GAS PRODUCTION RATE (m^3/ton_{MSW})
0	21.157	26	0.605
1	14.273	27	0.565
2	9.978	28	0.527
3	7.266	29	0.492
4	5.523	30	0.460
5	4.378	31	0.430
6	3.602	32	0.403
7	3.058	33	0.377
8	2.660	34	0.353
9	2.357	35	0.331
10	2.117	36	0.310
11	1.920	37	0.291
12	1.752	38	0.273
13	1.607	39	0.256
14	1.479	40	0.241
15	1.364	41	0.226
16	1.261	42	0.213
17	1.167	43	0.200
18	1.082	44	0.189
19	1.003	45	0.178
20	0.931	46	0.167
21	0.865	47	0.158
22	0.805	48	0.149
23	0.749	49	0.140
24	0.697	50	0.132
25	0.649		

Table C2.7 Predicted total gas emissions from Cell 1 (Chemical-Physical/Biochemical Model)

Time (yrs)	**WASTE LAYER 1** Prod Rate (m^3/ton)	**WASTE LAYER 1** Waste in Place (tons)	**WASTE LAYER 1** Gas Volume (m^3)	**WASTE LAYER 2** Prod Rate (m^3/ton)	**WASTE LAYER 2** Waste in Place (tons)	**WASTE LAYER 2** Gas Volume (m^3)	**WASTE LAYER 3** Prod Rate (m^3/ton)	**WASTE LAYER 3** Waste in Place (tons)	**WASTE LAYER 3** Gas Volume (m^3)	**WASTE LAYER 4** Prod Rate (m^3/ton)	**WASTE LAYER 4** Waste in Place (tons)	**WASTE LAYER 4** Gas Volume (m^3)	TOTAL GAS PRODUCTION (m^3)
0	0.00	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0.00	19225	0	0.00	0	0	0	0	0	0	0	0	0
1	21.16	19225	406749	0.00	27199	0	0	0	0	0	0	0	406749
1.5	17.31	19225	332721	21.16	27199	575457	0.00	17228	0	0	0	0	908178
1.833	15.21	19225	292356	18.51	27199	503561	14.09	17228	242749	0	13622	0	1134925
2	14.27	19225	274389	17.307	27199	470724	21.16	17228	364489	7.07	13622	96259	137854[illegible]
2.33	12.63	19225	242785	15.21	27199	413617	18.51	17228	318951	21.16	13622	288201	1195936
2.5	11.88	19225	228316	14.27	27199	388198	17.31	17228	298152	19.74	13622	268942	1097115
3	9.98	19225	191823	11.88	27199	323015	14.27	17228	245881	16.19	13622	220583	913020
3.5	8.47	19225	162820	9.98	27199	271385	11.88	17228	204594	13.39	13622	182449	767197
4	7.27	19225	139679	8.47	27199	230353	9.98	17228	171893	11.18	13622	152302	651300
4.5	6.30	19225	121130	7.27	27199	197614	8.47	17228	145904	9.43	13622	128397	558822
5	5.52	19225	106180	6.30	27199	171371	7.27	17228	125167	8.03	13622	109375	484686
5.5	4.89	19225	94057	5.52	27199	150221	6.30	17228	108545	6.91	13622	94175	424935
6	4.38	19225	84158	4.89	27199	133070	5.52	17228	95148	6.02	13622	81969	376477
6.5	3.95	19225	76011	4.38	27199	119065	4.89	17228	84285	5.29	13622	72112	336903
7	3.60	19225	69248	3.95	27199	107538	4.38	17228	75414	4.71	13622	64101	304330
7.5	3.31	19225	63581	3.60	27199	97970	3.95	17228	68114	4.22	13622	57542	277287
8	3.06	19225	58786	3.31	27199	89953	3.60	17228	62053	3.83	13622	52129	254625
8.5	2.84	19225	54686	3.06	27199	83169	3.31	17228	56975	3.50	13622	47622	235446

9	2.66	19225	51144	2.84	27199	77368	3.06	17228	52678	3.22	**13622**	43833	219045
9.5	2.50	19225	48050	2.66	27199	72357	2.84	17228	49004	2.98	**13622**	40615	204872
10	2.36	19225	45321	2.50	27199	67980	2.66	17228	45830	2.78	**13622**	37854	192494
10.5	2.23	19225	42890	2.36	27199	64119	2.50	17228	43058	2.60	**13622**	35460	181572
11	2.12	19225	40703	2.23	27199	60679	2.36	17228	40613	2.45	**13622**	33362	171839
11.5	2.01	19225	38719	2.12	27199	57585	2.23	17228	38434	2.31	**13622**	31505	163084
12	1.92	19225	36905	2.01	27199	54778	2.12	17228	36474	2.19	**13622**	29845	155141
12.5	1.83	19225	35234	1.92	27199	52212	2.01	17228	34696	2.08	**13622**	28347	147878
13	1.75	19225	33687	1.83	27199	49849	1.92	17228	33070	1.98	**13622**	26985	141189
13.5	1.68	19225	32245	1.75	27199	47659	1.83	17228	31574	1.89	**13622**	25736	134991
14	1.61	19225	30896	1.68	27199	45620	1.75	17228	30187	1.80	**13622**	24583	129218
14.5	1.54	19225	29628	1.61	27199	43711	1.68	17228	28895	1.73	**13622**	23514	123814
15	1.48	19225	28433	1.54	27199	41917	1.61	17228	27686	1.65	**13622**	22515	118735
15.5	1.42	19225	27302	1.48	27199	40226	1.54	17228	26550	1.58	**13622**	21580	113947
16	1.36	19225	26231	1.42	27199	38626	1.48	17228	25479	1.52	**13622**	20700	109418
16.5	1.31	19225	25213	1.36	27199	37110	1.42	17228	24466	1.46	**13622**	19869	105125
17	1.26	19225	24244	1.31	27199	35670	1.36	17228	23505	1.40	**13622**	19082	101046
17.5	1.21	19225	23321	1.26	27199	34299	1.31	17228	22593	1.35	**13622**	18336	97165
18	1.17	19225	22440	1.21	27199	32993	1.26	17228	21725	1.29	**13622**	17627	93467
18.5	1.12	19225	21599	1.17	27199	31747	1.21	17228	20898	1.24	**13622**	16952	89938
19	1.08	19225	20794	1.12	27199	30557	1.17	17228	20108	1.20	**13622**	16308	86567
19.5	1.04	19225	20025	1.08	27199	29419	1.12	17228	19355	1.15	**13622**	15694	68799
20	1.00	19225	19289	1.04	27199	28331	1.08	17228	18634	1.11	**13622**	15107	66253

Table C2.8 Predicted total gas emissions from Cell 1 (LandGEM Model)

TIME (years)	TOTAL GAS PRODUCTION (m^3)
0	0
1	816000
2	1473400
3	1187000
4	956400
5	766400
6	620600
7	500000
8	402800
9	324600
10	261400
11	210600
12	169160
13	136720
14	110140
15	88620
16	71480
17	57600
18	46400
19	37380
20	30120

Table C2.9 Predicted methane emissions from Cell 1 (LandGEM Model output file)

```
=========================================================================
=======
                              Model Parameters
=========================================================================
=======
Lo: 46.22 m^3 / Mg ***** User Mode Selection
k : 0.2092 1/yr ***** User Mode Selection
NMOC : 0.00 ppmv ***** User Mode Selection
Methane: 50.0000 % volume
Carbon Dioxide: 50.0000 % volume
=========================================================================
=======
                             Landfill Parameters
=========================================================================
=======
Landfill type: No Co-Disposal
Year Opened: 1997    Current Year : 2002  Closure Year: 1999
Capacity: 77273 Mg Average Acceptance Rate Required from Current Year to
Closure Year : 0.00 Mg/year

=========================================================================
=======
                               Model Results
=========================================================================
=======
                                               Methane Emission Rate
Year      Refuse In Place (Mg)             (Mg/yr)          (Cubic m/yr)
=========================================================================
=======
1998          3.864E+04                   2.492E+02          3.736E+05
1999          7.727E+04                   4.515E+02          6.767E+05
2000          7.727E+04                   3.662E+02          5.490E+05
2001          7.727E+04                   2.971E+02          4.453E+05
2002          7.727E+04                   2.410E+02          3.613E+05
2003          7.727E+04                   1.955E+02          2.931E+05
2004          7.727E+04                   1.586E+02          2.377E+05
2005          7.727E+04                   1.287E+02          1.929E+05
2006          7.727E+04                   1.044E+02          1.565E+05
2007          7.727E+04                   8.468E+01          1.269E+05
2008          7.727E+04                   6.870E+01          1.030E+05
2009          7.727E+04                   5.573E+01          8.353E+04
2010          7.727E+04                   4.521E+01          6.776E+04
2011          7.727E+04                   3.667E+01          5.497E+04
2012          7.727E+04                   2.975E+01          4.459E+04
2013          7.727E+04                   2.414E+01          3.618E+04
2014          7.727E+04                   1.958E+01          2.935E+04
2015          7.727E+04                   1.588E+01          2.381E+04
2016          7.727E+04                   1.289E+01          1.931E+04
2017          7.727E+04                   1.045E+01          1.567E+04
2018          7.727E+04                   8.480E+00          1.271E+04
2019          7.727E+04                   6.879E+00          1.031E+04
2020          7.727E+04                   5.580E+00          8.365E+03
2021          7.727E+04                   4.527E+00          6.786E+03
2022          7.727E+04                   3.673E+00          5.505E+03
2023          7.727E+04                   2.979E+00          4.466E+03
```

2024	7.727E+04	2.417E+00	3.623E+03
2025	7.727E+04	1.961E+00	2.939E+03
2026	7.727E+04	1.591E+00	2.384E+03
2027	7.727E+04	1.290E+00	1.934E+03
2028	7.727E+04	1.047E+00	1.569E+03
2029	7.727E+04	8.491E-01	1.273E+03
2030	7.727E+04	6.889E-01	1.033E+03
2031	7.727E+04	5.588E-01	8.376E+02
2032	7.727E+04	4.533E-01	6.795E+02
2033	7.727E+04	3.678E-01	5.512E+02
2034	7.727E+04	2.983E-01	4.472E+02
2035	7.727E+04	2.420E-01	3.628E+02
2036	7.727E+04	1.963E-01	2.943E+02
2037	7.727E+04	1.593E-01	2.387E+02
2038	7.727E+04	1.292E-01	1.937E+02
2039	7.727E+04	1.048E-01	1.571E+02
2040	7.727E+04	8.503E-02	1.275E+02
2041	7.727E+04	6.898E-02	1.034E+02
2042	7.727E+04	5.596E-02	8.388E+01
2043	7.727E+04	4.540E-02	6.805E+01
2044	7.727E+04	3.683E-02	5.520E+01
2045	7.727E+04	2.988E-02	4.478E+01
2046	7.727E+04	2.424E-02	3.633E+01
2047	7.727E+04	1.966E-02	2.947E+01
2048	7.727E+04	1.595E-02	2.391E+01
2049	7.727E+04	1.294E-02	1.939E+01
2050	7.727E+04	1.050E-02	1.573E+01
2051	7.727E+04	8.515E-03	1.276E+01
2052	7.727E+04	6.908E-03	1.035E+01
2053	7.727E+04	5.604E-03	8.400E+00
2054	7.727E+04	4.546E-03	6.814E+00
2055	7.727E+04	3.688E-03	5.528E+00
2056	7.727E+04	2.992E-03	4.484E+00
2057	7.727E+04	2.427E-03	3.638E+00
2058	7.727E+04	1.969E-03	2.951E+00
2059	7.727E+04	1.597E-03	2.394E+00
2060	7.727E+04	1.296E-03	1.942E+00
2061	7.727E+04	1.051E-03	1.576E+00
2062	7.727E+04	8.527E-04	1.278E+00
2063	7.727E+04	6.917E-04	1.037E+00
2064	7.727E+04	5.611E-04	8.411E-01
2065	7.727E+04	4.552E-04	6.823E-01
2066	7.727E+04	3.693E-04	5.535E-01
2067	7.727E+04	2.996E-04	4.490E-01
2068	7.727E+04	2.430E-04	3.643E-01
2069	7.727E+04	1.972E-04	2.955E-01
2070	7.727E+04	1.599E-04	2.397E-01
2071	7.727E+04	1.297E-04	1.945E-01
2072	7.727E+04	1.053E-04	1.578E-01
2073	7.727E+04	8.539E-05	1.280E-01
2074	7.727E+04	6.927E-05	1.038E-01
2075	7.727E+04	5.619E-05	8.423E-02
2076	7.727E+04	4.559E-05	6.833E-02
2077	7.727E+04	3.698E-05	5.543E-02
2078	7.727E+04	3.000E-05	4.497E-02
2079	7.727E+04	2.434E-05	3.648E-02
2080	7.727E+04	1.974E-05	2.959E-02

2081	7.727E+04	1.602E-05	2.401E-02
2082	7.727E+04	1.299E-05	1.947E-02
2083	7.727E+04	1.054E-05	1.580E-02
2084	7.727E+04	8.550E-06	1.282E-02
2085	7.727E+04	6.936E-06	1.040E-02
2086	7.727E+04	5.627E-06	8.434E-03
2087	7.727E+04	4.565E-06	6.842E-03
2088	7.727E+04	3.703E-06	5.551E-03
2089	7.727E+04	3.004E-06	4.503E-03
2090	7.727E+04	2.437E-06	3.653E-03
2091	7.727E+04	1.977E-06	2.963E-03
2092	7.727E+04	1.604E-06	2.404E-03
2093	7.727E+04	1.301E-06	1.950E-03
2094	7.727E+04	1.055E-06	1.582E-03
2095	7.727E+04	8.562E-07	1.283E-03
2096	7.727E+04	6.946E-07	1.041E-03
2097	7.727E+04	5.635E-07	8.446E-04
2098	7.727E+04	4.571E-07	6.852E-04
2099	7.727E+04	3.708E-07	5.558E-04
2100	7.727E+04	3.008E-07	4.509E-04
2101	7.727E+04	2.440E-07	3.658E-04
2102	7.727E+04	1.980E-07	2.967E-04
2103	7.727E+04	1.606E-07	2.407E-04
2104	7.727E+04	1.303E-07	1.953E-04
2105	7.727E+04	1.057E-07	1.584E-04
2106	7.727E+04	8.574E-08	1.285E-04
2107	7.727E+04	6.956E-08	1.043E-04
2108	7.727E+04	5.643E-08	8.458E-05
2109	7.727E+04	4.578E-08	6.861E-05
2110	7.727E+04	3.713E-08	5.566E-05
2111	7.727E+04	3.012E-08	4.515E-05
2112	7.727E+04	2.444E-08	3.663E-05
2113	7.727E+04	1.982E-08	2.972E-05
2114	7.727E+04	1.608E-08	2.411E-05
2115	7.727E+04	1.305E-08	1.956E-05
2116	7.727E+04	1.058E-08	1.586E-05
2117	7.727E+04	8.586E-09	1.287E-05
2118	7.727E+04	6.965E-09	1.044E-05
2119	7.727E+04	5.650E-09	8.470E-06
2120	7.727E+04	4.584E-09	6.871E-06
2121	7.727E+04	3.719E-09	5.574E-06
2122	7.727E+04	3.017E-09	4.522E-06
2123	7.727E+04	2.447E-09	3.668E-06
2124	7.727E+04	1.985E-09	2.976E-06
2125	7.727E+04	1.610E-09	2.414E-06
2126	7.727E+04	1.306E-09	1.958E-06
2127	7.727E+04	1.060E-09	1.589E-06
2128	7.727E+04	8.598E-10	1.289E-06
2129	7.727E+04	6.975E-10	1.045E-06
2130	7.727E+04	5.658E-10	8.481E-07
2131	7.727E+04	4.590E-10	6.880E-07
2132	7.727E+04	3.724E-10	5.582E-07
2133	7.727E+04	3.021E-10	4.528E-07
2134	7.727E+04	2.451E-10	3.673E-07
2135	7.727E+04	1.988E-10	2.980E-07
2136	7.727E+04	1.613E-10	2.417E-07
2137	7.727E+04	1.308E-10	1.961E-07

2138	7.727E+04	1.061E-10	1.591E-07
2139	7.727E+04	8.610E-11	1.291E-07
2140	7.727E+04	6.985E-11	1.047E-07
2141	7.727E+04	5.666E-11	8.493E-08
2142	7.727E+04	4.597E-11	6.890E-08
2143	7.727E+04	3.729E-11	5.589E-08
2144	7.727E+04	3.025E-11	4.534E-08
2145	7.727E+04	2.454E-11	3.678E-08
2146	7.727E+04	1.991E-11	2.984E-08
2147	7.727E+04	1.615E-11	2.421E-08
2148	7.727E+04	1.310E-11	1.964E-08
2149	7.727E+04	1.063E-11	1.593E-08
2150	7.727E+04	8.622E-12	1.292E-08
2151	7.727E+04	6.994E-12	1.048E-08
2152	7.727E+04	5.674E-12	8.505E-09
2153	7.727E+04	4.603E-12	6.899E-09
2154	7.727E+04	3.734E-12	5.597E-09
2155	7.727E+04	3.029E-12	4.541E-09
2156	7.727E+04	2.457E-12	3.683E-09
2157	7.727E+04	1.994E-12	2.988E-09
2158	7.727E+04	1.617E-12	2.424E-09
2159	7.727E+04	1.312E-12	1.966E-09
2160	7.727E+04	1.064E-12	1.595E-09
2161	7.727E+04	8.634E-13	1.294E-09
2162	7.727E+04	7.004E-13	1.050E-09
2163	7.727E+04	5.682E-13	8.517E-10
2164	7.727E+04	4.609E-13	6.909E-10
2165	7.727E+04	3.739E-13	5.605E-10
2166	7.727E+04	3.033E-13	4.547E-10
2167	7.727E+04	2.461E-13	3.689E-10
2168	7.727E+04	1.996E-13	2.992E-10
2169	7.727E+04	1.619E-13	2.427E-10
2170	7.727E+04	1.314E-13	1.969E-10
2171	7.727E+04	1.066E-13	1.597E-10
2172	7.727E+04	8.646E-14	1.296E-10
2173	7.727E+04	7.014E-14	1.051E-10
2174	7.727E+04	5.690E-14	8.528E-11
2175	7.727E+04	4.616E-14	6.919E-11
2176	7.727E+04	3.744E-14	5.613E-11
2177	7.727E+04	3.038E-14	4.553E-11
2178	7.727E+04	2.464E-14	3.694E-11
2179	7.727E+04	1.999E-14	2.996E-11
2180	7.727E+04	1.622E-14	2.431E-11
2181	7.727E+04	1.316E-14	1.972E-11
2182	7.727E+04	1.067E-14	1.600E-11
2183	7.727E+04	8.658E-15	1.298E-11
2184	7.727E+04	7.023E-15	1.053E-11
2185	7.727E+04	5.698E-15	8.540E-12
2186	7.727E+04	4.622E-15	6.928E-12
2187	7.727E+04	3.750E-15	5.620E-12
2188	7.727E+04	3.042E-15	4.559E-12
2189	7.727E+04	2.468E-15	3.699E-12
2190	7.727E+04	2.002E-15	3.001E-12
2191	7.727E+04	1.624E-15	2.434E-12
2192	7.727E+04	1.317E-15	1.975E-12
2193	7.727E+04	1.069E-15	1.602E-12
2194	7.727E+04	8.670E-16	1.300E-12

```
2195          7.727E+04                     7.033E-16            1.054E-12
2196          7.727E+04                     5.706E-16            8.552E-13
2197          7.727E+04                     4.629E-16            6.938E-13
2198          7.727E+04                     3.755E-16            5.628E-13
2199          7.727E+04                     3.046E-16            4.566E-13
2200          7.727E+04                     2.471E-16            3.704E-13
2201          7.727E+04                     2.005E-16            3.005E-13
```

Table C2.10 Predicted Carbon dioxide emissions from Cell 1 (LandGEM Model output file)

```
=========================================================================
=======
                          Model Parameters
=========================================================================
=======
Lo: 46.22 m^3 / Mg ***** User Mode Selection
k: 0.2092 1/yr ***** User Mode Selection
NMOC: 0.00 ppmv ***** User Mode Selection
Methane: 50.0000 % volume
Carbon Dioxide: 50.0000 % volume
=========================================================================
=======
                         Landfill Parameters
=========================================================================
=======
Landfill type: No Co-Disposal
Year Opened: 1997    Current Year : 2002   Closure Year: 1999
Capacity: 77273 Mg
Average Acceptance Rate Required from current Year to Closure Year : 0.00
Mg/year
=========================================================================
=======
                           Model Results
=========================================================================
=======
                                             Carbon Dioxide Emission Rate
Year     Refuse In Place (Mg)               (Mg/yr)          (Cubic m/yr)
=========================================================================
=======
1998          3.864E+04                     6.839E+02            3.736E+05
1999          7.727E+04                     1.239E+03            6.767E+05
2000          7.727E+04                     1.005E+03            5.490E+05
2001          7.727E+04                     8.152E+02            4.453E+05
2002          7.727E+04                     6.613E+02            3.613E+05
2003          7.727E+04                     5.365E+02            2.931E+05
2004          7.727E+04                     4.352E+02            2.377E+05
2005          7.727E+04                     3.530E+02            1.929E+05
2006          7.727E+04                     2.864E+02            1.565E+05
2007          7.727E+04                     2.323E+02            1.269E+05
2008          7.727E+04                     1.885E+02            1.030E+05
2009          7.727E+04                     1.529E+02            8.353E+04
2010          7.727E+04                     1.240E+02            6.776E+04
2011          7.727E+04                     1.006E+02            5.497E+04
2012          7.727E+04                     8.163E+01            4.459E+04
2013          7.727E+04                     6.622E+01            3.618E+04
2014          7.727E+04                     5.372E+01            2.935E+04
```

2015	7.727E+04	4.358E+01	2.381E+04
2016	7.727E+04	3.535E+01	1.931E+04
2017	7.727E+04	2.868E+01	1.567E+04
2018	7.727E+04	2.327E+01	1.271E+04
2019	7.727E+04	1.887E+01	1.031E+04
2020	7.727E+04	1.531E+01	8.365E+03
2021	7.727E+04	1.242E+01	6.786E+03
2022	7.727E+04	1.008E+01	5.505E+03
2023	7.727E+04	8.174E+00	4.466E+03
2024	7.727E+04	6.631E+00	3.623E+03
2025	7.727E+04	5.380E+00	2.939E+03
2026	7.727E+04	4.364E+00	2.384E+03
2027	7.727E+04	3.540E+00	1.934E+03
2028	7.727E+04	2.872E+00	1.569E+03
2029	7.727E+04	2.330E+00	1.273E+03
2030	7.727E+04	1.890E+00	1.033E+03
2031	7.727E+04	1.533E+00	8.376E+02
2032	7.727E+04	1.244E+00	6.795E+02
2033	7.727E+04	1.009E+00	5.512E+02
2034	7.727E+04	8.186E-01	4.472E+02
2035	7.727E+04	6.641E-01	3.628E+02
2036	7.727E+04	5.387E-01	2.943E+02
2037	7.727E+04	4.370E-01	2.387E+02
2038	7.727E+04	3.545E-01	1.937E+02
2039	7.727E+04	2.876E-01	1.571E+02
2040	7.727E+04	2.333E-01	1.275E+02
2041	7.727E+04	1.893E-01	1.034E+02
2042	7.727E+04	1.535E-01	8.388E+01
2043	7.727E+04	1.246E-01	6.805E+01
2044	7.727E+04	1.010E-01	5.520E+01
2045	7.727E+04	8.197E-02	4.478E+01
2046	7.727E+04	6.650E-02	3.633E+01
2047	7.727E+04	5.394E-02	2.947E+01
2048	7.727E+04	4.376E-02	2.391E+01
2049	7.727E+04	3.550E-02	1.939E+01
2050	7.727E+04	2.880E-02	1.573E+01
2051	7.727E+04	2.336E-02	1.276E+01
2052	7.727E+04	1.895E-02	1.035E+01
2053	7.727E+04	1.538E-02	8.400E+00
2054	7.727E+04	1.247E-02	6.814E+00
2055	7.727E+04	1.012E-02	5.528E+00
2056	7.727E+04	8.208E-03	4.484E+00
2057	7.727E+04	6.659E-03	3.638E+00
2058	7.727E+04	5.402E-03	2.951E+00
2059	7.727E+04	4.382E-03	2.394E+00
2060	7.727E+04	3.555E-03	1.942E+00
2061	7.727E+04	2.884E-03	1.576E+00
2062	7.727E+04	2.340E-03	1.278E+00
2063	7.727E+04	1.898E-03	1.037E+00
2064	7.727E+04	1.540E-03	8.411E-01
2065	7.727E+04	1.249E-03	6.823E-01
2066	7.727E+04	1.013E-03	5.535E-01
2067	7.727E+04	8.220E-04	4.490E-01
2068	7.727E+04	6.668E-04	3.643E-01
2069	7.727E+04	5.409E-04	2.955E-01
2070	7.727E+04	4.388E-04	2.397E-01
2071	7.727E+04	3.560E-04	1.945E-01

2072	7.727E+04	2.888E-04	1.578E-01
2073	7.727E+04	2.343E-04	1.280E-01
2074	7.727E+04	1.901E-04	1.038E-01
2075	7.727E+04	1.542E-04	8.423E-02
2076	7.727E+04	1.251E-04	6.833E-02
2077	7.727E+04	1.015E-04	5.543E-02
2078	7.727E+04	8.231E-05	4.497E-02
2079	7.727E+04	6.677E-05	3.648E-02
2080	7.727E+04	5.417E-05	2.959E-02
2081	7.727E+04	4.394E-05	2.401E-02
2082	7.727E+04	3.565E-05	1.947E-02
2083	7.727E+04	2.892E-05	1.580E-02
2084	7.727E+04	2.346E-05	1.282E-02
2085	7.727E+04	1.903E-05	1.040E-02
2086	7.727E+04	1.544E-05	8.434E-03
2087	7.727E+04	1.252E-05	6.842E-03
2088	7.727E+04	1.016E-05	5.551E-03
2089	7.727E+04	8.243E-06	4.503E-03
2090	7.727E+04	6.687E-06	3.653E-03
2091	7.727E+04	5.424E-06	2.963E-03
2092	7.727E+04	4.401E-06	2.404E-03
2093	7.727E+04	3.570E-06	1.950E-03
2094	7.727E+04	2.896E-06	1.582E-03
2095	7.727E+04	2.349E-06	1.283E-03
2096	7.727E+04	1.906E-06	1.041E-03
2097	7.727E+04	1.546E-06	8.446E-04
2098	7.727E+04	1.254E-06	6.852E-04
2099	7.727E+04	1.017E-06	5.558E-04
2100	7.727E+04	8.254E-07	4.509E-04
2101	7.727E+04	6.696E-07	3.658E-04
2102	7.727E+04	5.432E-07	2.967E-04
2103	7.727E+04	4.407E-07	2.407E-04
2104	7.727E+04	3.575E-07	1.953E-04
2105	7.727E+04	2.900E-07	1.584E-04
2106	7.727E+04	2.353E-07	1.285E-04
2107	7.727E+04	1.908E-07	1.043E-04
2108	7.727E+04	1.548E-07	8.458E-05
2109	7.727E+04	1.256E-07	6.861E-05
2110	7.727E+04	1.019E-07	5.566E-05
2111	7.727E+04	8.265E-08	4.515E-05
2112	7.727E+04	6.705E-08	3.663E-05
2113	7.727E+04	5.440E-08	2.972E-05
2114	7.727E+04	4.413E-08	2.411E-05
2115	7.727E+04	3.580E-08	1.956E-05
2116	7.727E+04	2.904E-08	1.586E-05
2117	7.727E+04	2.356E-08	1.287E-05
2118	7.727E+04	1.911E-08	1.044E-05
2119	7.727E+04	1.550E-08	8.470E-06
2120	7.727E+04	1.258E-08	6.871E-06
2121	7.727E+04	1.020E-08	5.574E-06
2122	7.727E+04	8.277E-09	4.522E-06
2123	7.727E+04	6.715E-09	3.668E-06
2124	7.727E+04	5.447E-09	2.976E-06
2125	7.727E+04	4.419E-09	2.414E-06
2126	7.727E+04	3.585E-09	1.958E-06
2127	7.727E+04	2.908E-09	1.589E-06
2128	7.727E+04	2.359E-09	1.289E-06

2129	7.727E+04	1.914E-09	1.045E-06
2130	7.727E+04	1.553E-09	8.481E-07
2131	7.727E+04	1.259E-09	6.880E-07
2132	7.727E+04	1.022E-09	5.582E-07
2133	7.727E+04	8.288E-10	4.528E-07
2134	7.727E+04	6.724E-10	3.673E-07
2135	7.727E+04	5.455E-10	2.980E-07
2136	7.727E+04	4.425E-10	2.417E-07
2137	7.727E+04	3.590E-10	1.961E-07
2138	7.727E+04	2.912E-10	1.591E-07
2139	7.727E+04	2.362E-10	1.291E-07
2140	7.727E+04	1.916E-10	1.047E-07
2141	7.727E+04	1.555E-10	8.493E-08
2142	7.727E+04	1.261E-10	6.890E-08
2143	7.727E+04	1.023E-10	5.589E-08
2144	7.727E+04	8.300E-11	4.534E-08
2145	7.727E+04	6.733E-11	3.678E-08
2146	7.727E+04	5.462E-11	2.984E-08
2147	7.727E+04	4.431E-11	2.421E-08
2148	7.727E+04	3.595E-11	1.964E-08
2149	7.727E+04	2.916E-11	1.593E-08
2150	7.727E+04	2.366E-11	1.292E-08
2151	7.727E+04	1.919E-11	1.048E-08
2152	7.727E+04	1.557E-11	8.505E-09
2153	7.727E+04	1.263E-11	6.899E-09
2154	7.727E+04	1.025E-11	5.597E-09
2155	7.727E+04	8.311E-12	4.541E-09
2156	7.727E+04	6.742E-12	3.683E-09
2157	7.727E+04	5.470E-12	2.988E-09
2158	7.727E+04	4.437E-12	2.424E-09
2159	7.727E+04	3.600E-12	1.966E-09
2160	7.727E+04	2.920E-12	1.595E-09
2161	7.727E+04	2.369E-12	1.294E-09
2162	7.727E+04	1.922E-12	1.050E-09
2163	7.727E+04	1.559E-12	8.517E-10
2164	7.727E+04	1.265E-12	6.909E-10
2165	7.727E+04	1.026E-12	5.605E-10
2166	7.727E+04	8.323E-13	4.547E-10
2167	7.727E+04	6.752E-13	3.689E-10
2168	7.727E+04	5.477E-13	2.992E-10
2169	7.727E+04	4.443E-13	2.427E-10
2170	7.727E+04	3.605E-13	1.969E-10
2171	7.727E+04	2.924E-13	1.597E-10
2172	7.727E+04	2.372E-13	1.296E-10
2173	7.727E+04	1.924E-13	1.051E-10
2174	7.727E+04	1.561E-13	8.528E-11
2175	7.727E+04	1.266E-13	6.919E-11
2176	7.727E+04	1.027E-13	5.613E-11
2177	7.727E+04	8.334E-14	4.553E-11
2178	7.727E+04	6.761E-14	3.694E-11
2179	7.727E+04	5.485E-14	2.996E-11
2180	7.727E+04	4.450E-14	2.431E-11
2181	7.727E+04	3.610E-14	1.972E-11
2182	7.727E+04	2.928E-14	1.600E-11
2183	7.727E+04	2.375E-14	1.298E-11
2184	7.727E+04	1.927E-14	1.053E-11
2185	7.727E+04	1.563E-14	8.540E-12

2186	7.727E+04	1.268E-14	6.928E-12
2187	7.727E+04	1.029E-14	5.620E-12
2188	7.727E+04	8.346E-15	4.559E-12
2189	7.727E+04	6.771E-15	3.699E-12
2190	7.727E+04	5.493E-15	3.001E-12
2191	7.727E+04	4.456E-15	2.434E-12
2192	7.727E+04	3.615E-15	1.975E-12
2193	7.727E+04	2.932E-15	1.602E-12
2194	7.727E+04	2.379E-15	1.300E-12
2195	7.727E+04	1.930E-15	1.054E-12
2196	7.727E+04	1.565E-15	8.552E-13
2197	7.727E+04	1.270E-15	6.938E-13
2198	7.727E+04	1.030E-15	5.628E-13
2199	7.727E+04	8.358E-16	4.566E-13
2200	7.727E+04	6.780E-16	3.704E-13
2201	7.727E+04	5.500E-16	3.005E-13

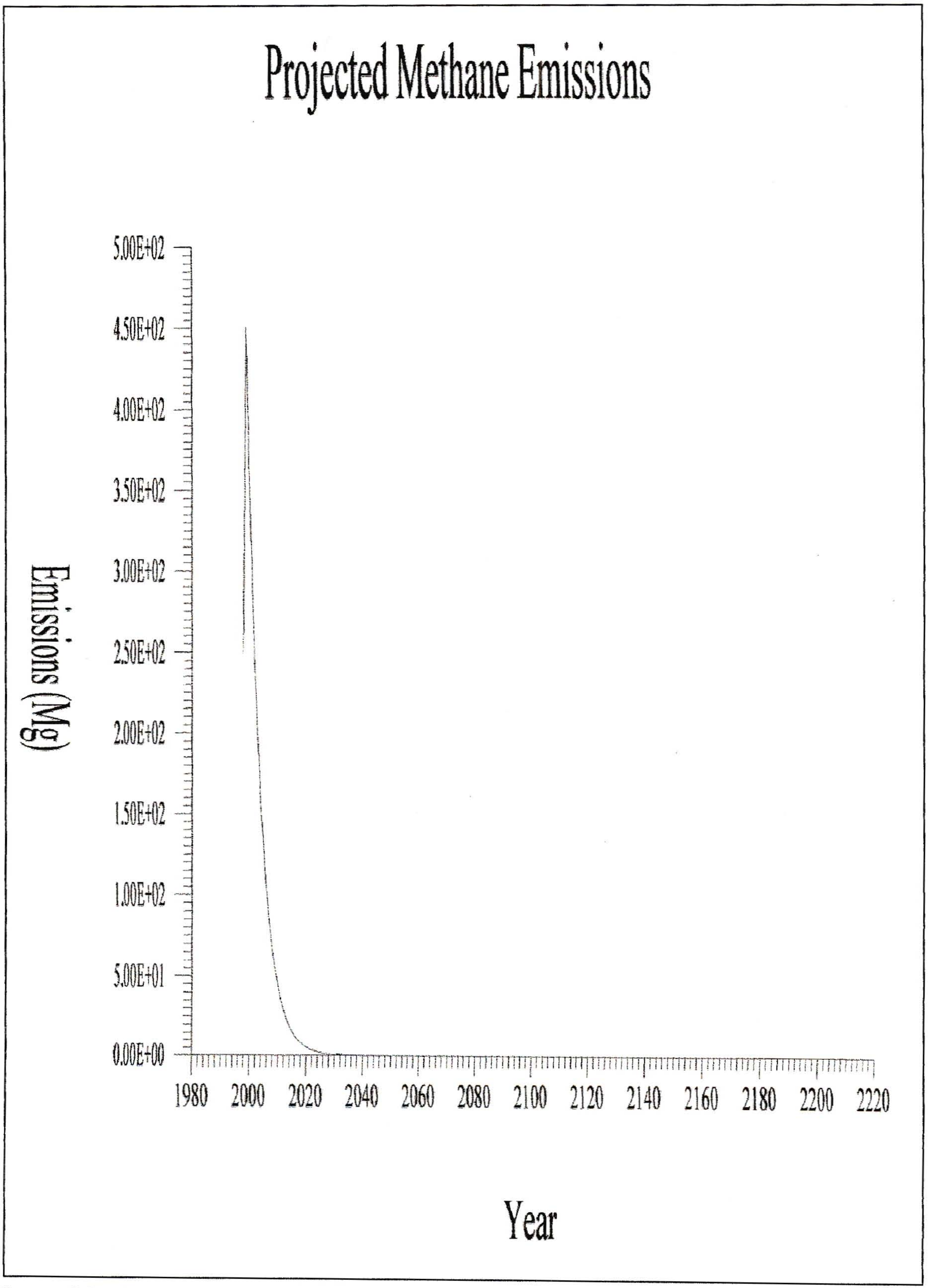

Figure C2.1 Projected methane emissions for Cell 1 (LandGEM Model output)

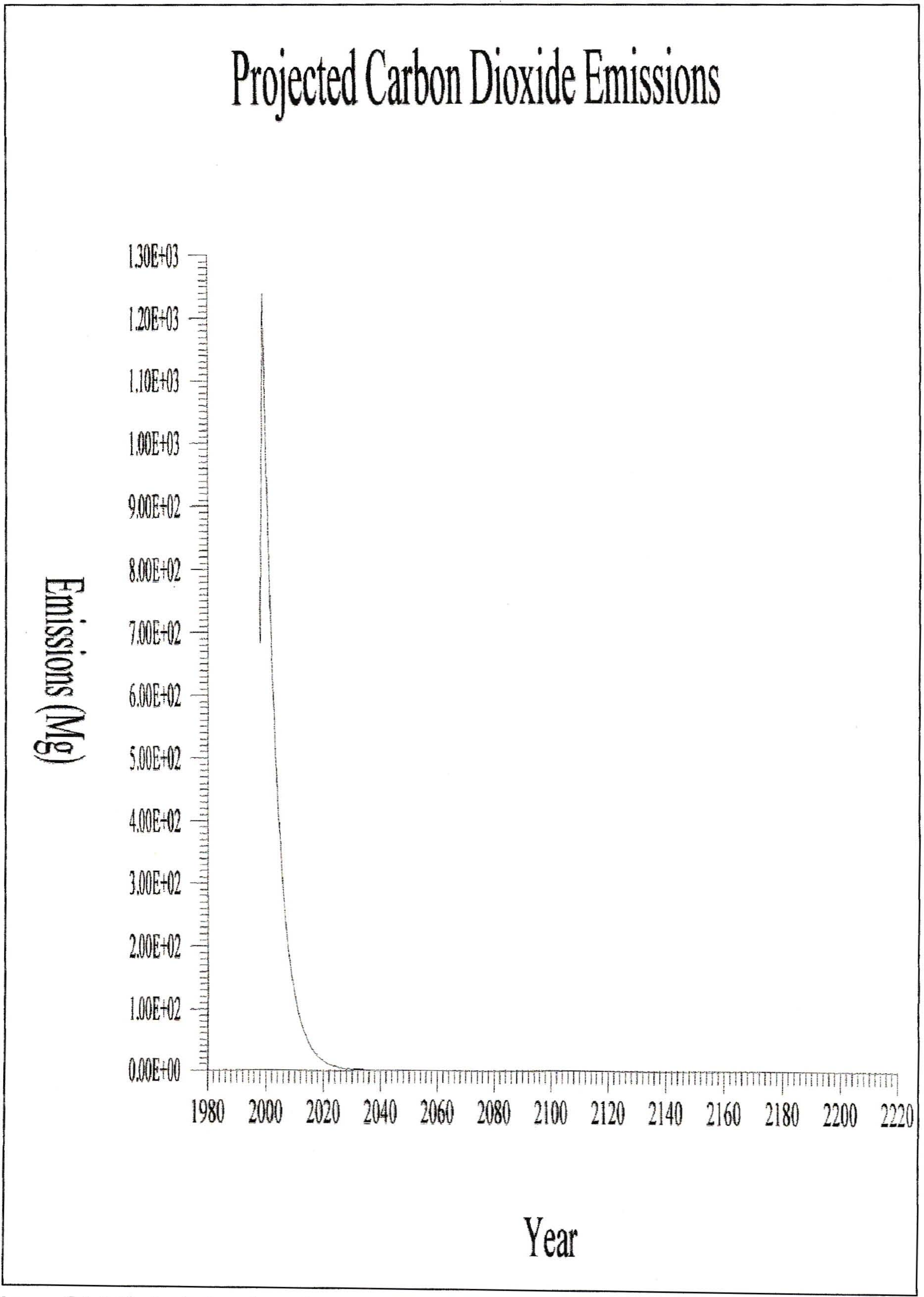

Figure C2.2 Projected carbon dioxide emissions for Cell 1 (LandGEM Model output)

Table C3.1 Relative masses of the gas producing components in Cell 2

WASTE COMPONENT	% OF TOTAL MASS IN CELL
(a) Easily Biodegradable	
1. Putrescibles	13.84
(b) Biodegradable	
2. Garden refuse	23.70
(c) Slowly Biodegradable	
3(a) Cardboard	2.95
3(b) Paper	3.37

Table C3.2 Cell 2 waste component properties

PROPERTY	WASTE COMPONENT			
	1	2	3(a)	3(b)
Ci	0.48	0.48	0.44	0.44
f_b	0.8	0.7	0.5	0.5
u	0.7	0.6	0.08	0.08
p	0.1384	0.237	0.0295	0.0337

Table C3.3 The amount of carbon in Cell 2 available for conversion to biogas

	FRACTION OF BIODEGRADABLE CARBON IN EACH WASTE COMPONENT (kg/kg$_{MSW}$)			
	CO_b (1)	CO_b (2)	CO_b (3a)	CO_b (3b)
	0.01594	0.03185	0.00597	0.00682
Landfill Temperature (^{0}C)	45 ^{0}C	45 ^{0}C	45 ^{0}C	45 ^{0}C
Temperature correction factor	0.910	0.910	0.910	0.910
	FRACTION OF BIODEGRADABLE CARBON FOR EACH BIODEGRADABILITY FRACTION (kg/kg$_{MSW}$)			
	CO_e(a)	CO_e(b)	CO_e(c)	CO_e (total)
	0.01451	0.02899	0.01164	0.05514

(a) Easily Biodegradable

(b) Biodegradable

(c) Slowly Biodegradable

Table C3.4 Effective generation constant (k_e) for each biodegradability fraction in Cell 2

BIODERAD ABILITY FRACTION	CORRECTION FACTORS		GENERATION CONSTANTS	
	α	β	k (yr^-1)	k_e (yr^-1)
(a)	0.80	0.9	0.693	0.499
(b)	0.80	0.9	0.139	0.100
(c)	0.80	0.9	0.069	0.050

Table C3.5 Predicted cumulative gas production rates for Cell 2 (Chemical-Physical/Biochemical Model)

TIME FROM OPENING OF CELL (years)	CUMULATIVE GAS PRODUCTION (m^3/ton_{MSW})	TIME FROM OPENING OF CELL (years)	CUMULATIVE GAS PRODUCTION (m^3/ton_{MSW})
0	0.000	26	93.004
1	16.857	27	93.676
2	28.990	28	94.297
3	38.090	29	94.872
4	45.200	30	95.405
5	50.967	31	95.898
6	55.794	32	96.356
7	59.938	33	96.780
8	63.565	34	97.175
9	66.786	35	97.541
10	69.674	36	97.881
11	72.283	37	98.198
12	74.652	38	98.493
13	76.811	39	98.767
14	78.784	40	99.023
15	80.590	41	99.262
16	82.245	42	99.485
17	83.764	43	99.692
18	85.160	44	99.887
19	86.444	45	100.068
20	87.625	46	100.238
21	88.712	47	100.397
22	89.714	48	100.546
23	90.638	49	100.685
24	91.490	50	100.816
25	92.277		

Table C3.6 Predicted specific gas production rates for Cell 2 (Chemical-Physical/Biochemical Model)

TIME FROM OPENING OF CELL (years)	**SPECIFIC GAS PRODUCTION RATE ($m^3/ton_{MSW}.year$)**	**TIME FROM OPENING OF CELL (years)**	**SPECIFIC GAS PRODUCTION RATE ($m^3/ton_{MSW}year$)**
0	20.022	26	2.062
1	16.745	27	1.972
2	14.141	28	1.886
3	12.064	29	1.805
4	10.399	30	1.728
5	9.058	31	1.655
6	7.971	32	1.585
7	7.084	33	1.519
8	6.355	34	1.456
9	5.750	35	1.395
10	5.244	36	1.338
11	4.817	37	1.283
12	4.452	38	1.231
13	4.137	39	1.181
14	3.864	40	1.133
15	3.623	41	1.087
16	3.409	42	1.043
17	3.217	43	1.002
18	3.044	44	0.962
19	2.886	45	0.924
20	2.741	46	0.887
21	2.608	47	0.819
22	2.484	48	0.756
23	2.368	49	0.699
24	2.260	50	0.646
25	2.158		

Table C3.7 Predicted Total gas emissions from Cell 2 (Chemical-Physical/Biochemical Model)

	WASTE LAYER 1			WASTE LAYER 2			WASTE LAYER 3			WASTE LAYER 4			
Time (yrs)	Prod Rate (m^3/ton)	Waste in Place (tons)	Gas Volume (m^3)	Prod Rate (m^3/ton)	Waste in Place (tons)	Gas Volume (m^3)	Prod Rate (m^3/ton)	Waste in Place (tons)	Gas Volume (m^3)	Prod Rate (m^3/ton)	Waste in Place (tons)	Gas Volume (m^3)	TOTA GAS PROD CTIO (m^3
0	0	0	0	0	0	0	0.00	0	0	0.00	0	0	0
0.17	5.080	6811	34601	0.00	0	0	0.00	0	0	0.00	0	0	3460
0.67	20.022	6811	136369	0.00	25028	0	0.00	0	0	0.00	0	0	13636
1.17	16.745	6811	114051	20.02	25028	501115	0.00	30984	0	0.00	0	0	61516
1.67	14.141	6811	96316	16.75	25028	419103	20.02	30984	620367	0.00	41371	0	11357
2.17	12.064	6811	82167	14.14	25028	353931	16.75	30984	518839	20.02	41371	828337	17832
2.67	10.399	6811	70828	12.06	25028	301938	14.14	30984	438157	16.75	41371	692773	15036
3.17	9.058	6811	61693	10.40	25028	260271	12.06	30984	373791	14.14	41371	585044	12807
3.67	7.971	6811	54290	9.06	25028	226703	10.40	30984	322209	12.06	41371	499100	11023
4.17	7.084	6811	48248	7.97	25028	199497	9.06	30984	280653	10.40	41371	430225	95862
4.67	6.355	6811	43281	7.08	25028	177297	7.97	30984	246973	9.06	41371	374738	84228
5.17	5.750	6811	39162	6.35	25028	159043	7.08	30984	219489	7.97	41371	329767	74746
5.67	5.244	6811	35716	5.75	25028	143908	6.35	30984	196891	7.08	41371	293070	66958
6.17	4.817	6811	32805	5.24	25028	131244	5.75	30984	178154	6.35	41371	262896	60509
6.67	4.452	6811	30321	4.82	25028	120548	5.24	30984	162477	5.75	41371	237877	55122
7.17	4.137	6811	28180	4.45	25028	111421	4.82	30984	149235	5.24	41371	216946	50578
7.67	3.864	6811	26316	4.14	25028	103553	4.45	30984	137936	4.82	41371	199264	46706
8.17	3.623	6811	24676	3.86	25028	96702	4.14	30984	128196	4.45	41371	184177	43375
8.67	3.409	6811	23219	3.62	25028	90675	3.86	30984	119714	4.14	41371	171172	40478
9.17	3.217	6811	21913	3.41	25028	85322	3.62	30984	112253	3.86	41371	159847	37933

9.67	3.044	6811	20733	3.22	25028	80523	3.41	30984	105626	3.62	41371	149885	35676
10.17	2.886	6811	19657	3.04	25028	76186	3.22	30984	99686	3.41	41371	141036	33656
10.67	2.741	6811	18671	2.89	25028	72234	3.04	30984	94316	3.22	41371	133104	31832
11.17	2.608	6811	17760	2.74	25028	68609	2.89	30984	89424	3.04	41371	125934	30172
11.67	2.484	6811	16915	2.61	25028	65263	2.74	30984	84936	2.89	41371	119402	28651
12.17	2.368	6811	16128	2.48	25028	62159	2.61	30984	80794	2.74	41371	113410	27249
12.67	2.260	6811	15390	2.37	25028	59264	2.48	30984	76951	2.61	41371	107880	25948
13.17	2.158	6811	14698	2.26	25028	56555	2.37	30984	73368	2.48	41371	102748	24736
13.67	2.062	6811	14045	2.16	25028	54010	2.26	30984	70013	2.37	41371	97963	23603
14.17	1.972	6811	13429	2.06	25028	51613	2.16	30984	66863	2.26	41371	93485	22538
14.67	1.886	6811	12846	1.97	25028	49349	2.06	30984	63895	2.16	41371	89278	21536
15.17	1.805	6811	12294	1.89	25028	47207	1.97	30984	61093	2.06	41371	85315	20590
15.67	1.728	6811	11769	1.81	25028	45176	1.89	30984	58441	1.97	41371	81573	19695
16.17	1.655	6811	11271	1.73	25028	43249	1.81	30984	55927	1.89	41371	78032	18847
16.67	1.585	6811	10796	1.65	25028	41416	1.73	30984	53541	1.81	41371	74676	18042
17.17	1.519	6811	10345	1.59	25028	39673	1.65	30984	51272	1.73	41371	71489	17278
17.67	1.456	6811	9914	1.52	25028	38013	1.59	30984	49115	1.65	41371	68461	16550
18.17	1.395	6811	9504	1.46	25028	36432	1.52	30984	47060	1.59	41371	65580	15857
18.67	1.338	6811	9112	1.40	25028	34924	1.46	30984	45102	1.52	41371	62836	15197
19.17	1.283	6811	8739	1.34	25028	33485	1.40	30984	43234	1.46	41371	60221	14567
19.67	1.231	6811	8382	1.28	25028	32111	1.34	30984	41453	1.40	41371	57728	13967
20.17	1.181	6811	8041	1.23	25028	30800	1.28	30984	39753	1.34	41371	55350	13394
20	1.00	19225	19289	1.04	27199	28331	1.08	17228	18634	1.11	13621.8	15107	6625

Table C3.8 Predicted total gas emissions from Cell 2 (LandGEM Model)

TIME (years)	TOTAL GAS PRODUCTION (m^3)
0	0
1	1121400
2	2032000
3	1648200
4	1337400
5	1085200
6	880400
7	714400
8	579600
9	470400
10	381600
11	309600
12	251200
13	203800
14	165420
15	134220
16	108900
17	88360
18	71700
19	58080
20	47200

Table C3.9 Methane emissions from Cell 2 (LandGEM Model output file)

```
=========================================================================
=======
                                Model Parameters
=========================================================================
=======
Lo : 51.50 m^3 / Mg ***** User Mode Selection
k : 0.2090 1/yr ***** User Mode Selection
NMOC : 4000.00 ppmv ***** User Mode Selection
Methane : 50.0000 % volume Carbon Dioxide : 50.0000 % volume
=========================================================================
=======
                              Landfill Parameters
=========================================================================
=======
Landfill type: No Co-Disposal
Year Opened: 1999    Current Year : 2002  Closure Year: 2000
Capacity: 104194 Mg
Average Acceptance Rate Required from Current Year to Closure Year: 0.00
Mg/year
=========================================================================
=======
                                 Model Results
=========================================================================
=======
                                              Methane Emission Rate
Year     Refuse In Place (Mg)              (Mg/yr)          (Cubic m/yr)
=========================================================================
=======
2000         5.210E+04                    3.741E+02          5.607E+05
2001         1.042E+05                    6.776E+02          1.016E+06
2002         1.042E+05                    5.498E+02          8.241E+05
2003         1.042E+05                    4.461E+02          6.687E+05
2004         1.042E+05                    3.620E+02          5.426E+05
2005         1.042E+05                    2.937E+02          4.402E+05
2006         1.042E+05                    2.383E+02          3.572E+05
2007         1.042E+05                    1.934E+02          2.898E+05
2008         1.042E+05                    1.569E+02          2.352E+05
2009         1.042E+05                    1.273E+02          1.908E+05
2010         1.042E+05                    1.033E+02          1.548E+05
2011         1.042E+05                    8.381E+01          1.256E+05
2012         1.042E+05                    6.800E+01          1.019E+05
2013         1.042E+05                    5.518E+01          8.271E+04
2014         1.042E+05                    4.477E+01          6.711E+04
2015         1.042E+05                    3.633E+01          5.445E+04
2016         1.042E+05                    2.948E+01          4.418E+04
2017         1.042E+05                    2.392E+01          3.585E+04
2018         1.042E+05                    1.941E+01          2.909E+04
2019         1.042E+05                    1.575E+01          2.360E+04
2020         1.042E+05                    1.278E+01          1.915E+04
2021         1.042E+05                    1.037E+01          1.554E+04
2022         1.042E+05                    8.411E+00          1.261E+04
2023         1.042E+05                    6.825E+00          1.023E+04
2024         1.042E+05                    5.538E+00          8.300E+03
2025         1.042E+05                    4.493E+00          6.735E+03
2026         1.042E+05                    3.646E+00          5.465E+03
```

2027	1.042E+05	2.958E+00	4.434E+03
2028	1.042E+05	2.400E+00	3.598E+03
2029	1.042E+05	1.948E+00	2.919E+03
2030	1.042E+05	1.580E+00	2.369E+03
2031	1.042E+05	1.282E+00	1.922E+03
2032	1.042E+05	1.040E+00	1.559E+03
2033	1.042E+05	8.441E-01	1.265E+03
2034	1.042E+05	6.849E-01	1.027E+03
2035	1.042E+05	5.558E-01	8.330E+02
2036	1.042E+05	4.509E-01	6.759E+02
2037	1.042E+05	3.659E-01	5.484E+02
2038	1.042E+05	2.969E-01	4.450E+02
2039	1.042E+05	2.409E-01	3.611E+02
2040	1.042E+05	1.955E-01	2.930E+02
2041	1.042E+05	1.586E-01	2.377E+02
2042	1.042E+05	1.287E-01	1.929E+02
2043	1.042E+05	1.044E-01	1.565E+02
2044	1.042E+05	8.472E-02	1.270E+02
2045	1.042E+05	6.874E-02	1.030E+02
2046	1.042E+05	5.577E-02	8.360E+01
2047	1.042E+05	4.526E-02	6.783E+01
2048	1.042E+05	3.672E-02	5.504E+01
2049	1.042E+05	2.979E-02	4.466E+01
2050	1.042E+05	2.418E-02	3.624E+01
2051	1.042E+05	1.962E-02	2.940E+01
2052	1.042E+05	1.592E-02	2.386E+01
2053	1.042E+05	1.291E-02	1.936E+01
2054	1.042E+05	1.048E-02	1.571E+01
2055	1.042E+05	8.502E-03	1.274E+01
2056	1.042E+05	6.899E-03	1.034E+01
2057	1.042E+05	5.597E-03	8.390E+00
2058	1.042E+05	4.542E-03	6.808E+00
2059	1.042E+05	3.685E-03	5.524E+00
2060	1.042E+05	2.990E-03	4.482E+00
2061	1.042E+05	2.426E-03	3.637E+00
2062	1.042E+05	1.969E-03	2.951E+00
2063	1.042E+05	1.597E-03	2.394E+00
2064	1.042E+05	1.296E-03	1.943E+00
2065	1.042E+05	1.052E-03	1.576E+00
2066	1.042E+05	8.533E-04	1.279E+00
2067	1.042E+05	6.923E-04	1.038E+00
2068	1.042E+05	5.618E-04	8.420E-01
2069	1.042E+05	4.558E-04	6.832E-01
2070	1.042E+05	3.698E-04	5.544E-01
2071	1.042E+05	3.001E-04	4.498E-01
2072	1.042E+05	2.435E-04	3.650E-01
2073	1.042E+05	1.976E-04	2.961E-01
2074	1.042E+05	1.603E-04	2.403E-01
2075	1.042E+05	1.301E-04	1.950E-01
2076	1.042E+05	1.055E-04	1.582E-01
2077	1.042E+05	8.563E-05	1.284E-01
2078	1.042E+05	6.948E-05	1.041E-01
2079	1.042E+05	5.638E-05	8.451E-02
2080	1.042E+05	4.574E-05	6.857E-02
2081	1.042E+05	3.712E-05	5.564E-02
2082	1.042E+05	3.012E-05	4.514E-02
2083	1.042E+05	2.444E-05	3.663E-02

2084	1.042E+05	1.983E-05	2.972E-02
2085	1.042E+05	1.609E-05	2.411E-02
2086	1.042E+05	1.305E-05	1.957E-02
2087	1.042E+05	1.059E-05	1.588E-02
2088	1.042E+05	8.594E-06	1.288E-02
2089	1.042E+05	6.973E-06	1.045E-02
2090	1.042E+05	5.658E-06	8.481E-03
2091	1.042E+05	4.591E-06	6.881E-03
2092	1.042E+05	3.725E-06	5.584E-03
2093	1.042E+05	3.022E-06	4.530E-03
2094	1.042E+05	2.452E-06	3.676E-03
2095	1.042E+05	1.990E-06	2.983E-03
2096	1.042E+05	1.615E-06	2.420E-03
2097	1.042E+05	1.310E-06	1.964E-03
2098	1.042E+05	1.063E-06	1.593E-03
2099	1.042E+05	8.625E-07	1.293E-03
2100	1.042E+05	6.998E-07	1.049E-03
2101	1.042E+05	5.678E-07	8.511E-04
2102	1.042E+05	4.607E-07	6.906E-04
2103	1.042E+05	3.738E-07	5.604E-04
2104	1.042E+05	3.033E-07	4.547E-04
2105	1.042E+05	2.461E-07	3.689E-04
2106	1.042E+05	1.997E-07	2.993E-04
2107	1.042E+05	1.620E-07	2.429E-04
2108	1.042E+05	1.315E-07	1.971E-04
2109	1.042E+05	1.067E-07	1.599E-04
2110	1.042E+05	8.656E-08	1.297E-04
2111	1.042E+05	7.023E-08	1.053E-04
2112	1.042E+05	5.699E-08	8.542E-05
2113	1.042E+05	4.624E-08	6.931E-05
2114	1.042E+05	3.752E-08	5.624E-05
2115	1.042E+05	3.044E-08	4.563E-05
2116	1.042E+05	2.470E-08	3.702E-05
2117	1.042E+05	2.004E-08	3.004E-05
2118	1.042E+05	1.626E-08	2.438E-05
2119	1.042E+05	1.319E-08	1.978E-05
2120	1.042E+05	1.071E-08	1.605E-05
2121	1.042E+05	8.687E-09	1.302E-05
2122	1.042E+05	7.049E-09	1.057E-05
2123	1.042E+05	5.719E-09	8.573E-06
2124	1.042E+05	4.641E-09	6.956E-06
2125	1.042E+05	3.765E-09	5.644E-06
2126	1.042E+05	3.055E-09	4.579E-06
2127	1.042E+05	2.479E-09	3.716E-06
2128	1.042E+05	2.011E-09	3.015E-06
2129	1.042E+05	1.632E-09	2.446E-06
2130	1.042E+05	1.324E-09	1.985E-06
2131	1.042E+05	1.074E-09	1.611E-06
2132	1.042E+05	8.718E-10	1.307E-06
2133	1.042E+05	7.074E-10	1.060E-06
2134	1.042E+05	5.740E-10	8.603E-07
2135	1.042E+05	4.657E-10	6.981E-07
2136	1.042E+05	3.779E-10	5.664E-07
2137	1.042E+05	3.066E-10	4.596E-07
2138	1.042E+05	2.488E-10	3.729E-07
2139	1.042E+05	2.019E-10	3.026E-07
2140	1.042E+05	1.638E-10	2.455E-07

2141	1.042E+05	1.329E-10	1.992E-07
2142	1.042E+05	1.078E-10	1.616E-07
2143	1.042E+05	8.750E-11	1.311E-07
2144	1.042E+05	7.099E-11	1.064E-07
2145	1.042E+05	5.760E-11	8.634E-08
2146	1.042E+05	4.674E-11	7.006E-08
2147	1.042E+05	3.792E-11	5.685E-08
2148	1.042E+05	3.077E-11	4.612E-08
2149	1.042E+05	2.497E-11	3.742E-08
2150	1.042E+05	2.026E-11	3.037E-08
2151	1.042E+05	1.644E-11	2.464E-08
2152	1.042E+05	1.334E-11	1.999E-08
2153	1.042E+05	1.082E-11	1.622E-08
2154	1.042E+05	8.781E-12	1.316E-08
2155	1.042E+05	7.125E-12	1.068E-08
2156	1.042E+05	5.781E-12	8.665E-09
2157	1.042E+05	4.691E-12	7.031E-09
2158	1.042E+05	3.806E-12	5.705E-09
2159	1.042E+05	3.088E-12	4.629E-09
2160	1.042E+05	2.506E-12	3.756E-09
2161	1.042E+05	2.033E-12	3.048E-09
2162	1.042E+05	1.650E-12	2.473E-09
2163	1.042E+05	1.339E-12	2.006E-09
2164	1.042E+05	1.086E-12	1.628E-09
2165	1.042E+05	8.812E-13	1.321E-09
2166	1.042E+05	7.150E-13	1.072E-09
2167	1.042E+05	5.802E-13	8.696E-10
2168	1.042E+05	4.708E-13	7.056E-10
2169	1.042E+05	3.820E-13	5.725E-10
2170	1.042E+05	3.099E-13	4.646E-10
2171	1.042E+05	2.515E-13	3.769E-10
2172	1.042E+05	2.040E-13	3.058E-10
2173	1.042E+05	1.656E-13	2.482E-10
2174	1.042E+05	1.343E-13	2.014E-10
2175	1.042E+05	1.090E-13	1.634E-10
2176	1.042E+05	8.844E-14	1.326E-10
2177	1.042E+05	7.176E-14	1.076E-10
2178	1.042E+05	5.823E-14	8.728E-11
2179	1.042E+05	4.724E-14	7.082E-11
2180	1.042E+05	3.833E-14	5.746E-11
2181	1.042E+05	3.110E-14	4.662E-11
2182	1.042E+05	2.524E-14	3.783E-11
2183	1.042E+05	2.048E-14	3.069E-11
2184	1.042E+05	1.662E-14	2.491E-11
2185	1.042E+05	1.348E-14	2.021E-11
2186	1.042E+05	1.094E-14	1.640E-11
2187	1.042E+05	8.876E-15	1.330E-11
2188	1.042E+05	7.202E-15	1.080E-11
2189	1.042E+05	5.844E-15	8.759E-12
2190	1.042E+05	4.741E-15	7.107E-12
2191	1.042E+05	3.847E-15	5.767E-12
2192	1.042E+05	3.122E-15	4.679E-12
2193	1.042E+05	2.533E-15	3.797E-12
2194	1.042E+05	2.055E-15	3.080E-12
2195	1.042E+05	1.668E-15	2.499E-12
2196	1.042E+05	1.353E-15	2.028E-12
2197	1.042E+05	1.098E-15	1.646E-12

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2198         1.042E+05                   8.908E-16          1.335E-12
2199         1.042E+05                   7.228E-16          1.083E-12
2200         1.042E+05                   5.865E-16          8.790E-13
2201         1.042E+05                   4.758E-16          7.133E-13
```

Table C3.10 Carbon dioxide emissions from Cell 2 (LandGEM Model output file)

```
=========================================================================
=======
                                Model Parameters
=========================================================================
=======
Lo: 51.50 m^3 / Mg ***** User Mode Selection
k: 0.2090 1/yr ***** User Mode Selection
NMOC: 4000.00 ppmv ***** User Mode Selection
Methane: 50.0000 % volume
Carbon Dioxide: 50.0000 % volume
=========================================================================
=======
                              Landfill Parameters
=========================================================================
=======
Landfill type: No Co-Disposal
Year Opened: 1999    Current Year : 2002  Closure Year: 2000
Capacity: 104194 Mg
Average Acceptance Rate Required from Current Year to Closure Year: 0.00
Mg/year
=========================================================================
=======
                                 Model Results
=========================================================================
=======
                                          Carbon Dioxide Emission Rate
Year     Refuse In Place (Mg)            (Mg/yr)          (Cubic m/yr)
=========================================================================
=======
2000         5.210E+04                   1.026E+03          5.607E+05
2001         1.042E+05                   1.859E+03          1.016E+06
2002         1.042E+05                   1.509E+03          8.241E+05
2003         1.042E+05                   1.224E+03          6.687E+05
2004         1.042E+05                   9.932E+02          5.426E+05
2005         1.042E+05                   8.058E+02          4.402E+05
2006         1.042E+05                   6.539E+02          3.572E+05
2007         1.042E+05                   5.305E+02          2.898E+05
2008         1.042E+05                   4.305E+02          2.352E+05
2009         1.042E+05                   3.493E+02          1.908E+05
2010         1.042E+05                   2.834E+02          1.548E+05
2011         1.042E+05                   2.300E+02          1.256E+05
2012         1.042E+05                   1.866E+02          1.019E+05
2013         1.042E+05                   1.514E+02          8.271E+04
2014         1.042E+05                   1.228E+02          6.711E+04
2015         1.042E+05                   9.967E+01          5.445E+04
2016         1.042E+05                   8.087E+01          4.418E+04
2017         1.042E+05                   6.562E+01          3.585E+04
2018         1.042E+05                   5.324E+01          2.909E+04
2019         1.042E+05                   4.320E+01          2.360E+04
2020         1.042E+05                   3.505E+01          1.915E+04
```

2021	1.042E+05	2.844E+01	1.554E+04
2022	1.042E+05	2.308E+01	1.261E+04
2023	1.042E+05	1.873E+01	1.023E+04
2024	1.042E+05	1.519E+01	8.300E+03
2025	1.042E+05	1.233E+01	6.735E+03
2026	1.042E+05	1.000E+01	5.465E+03
2027	1.042E+05	8.116E+00	4.434E+03
2028	1.042E+05	6.586E+00	3.598E+03
2029	1.042E+05	5.344E+00	2.919E+03
2030	1.042E+05	4.336E+00	2.369E+03
2031	1.042E+05	3.518E+00	1.922E+03
2032	1.042E+05	2.854E+00	1.559E+03
2033	1.042E+05	2.316E+00	1.265E+03
2034	1.042E+05	1.879E+00	1.027E+03
2035	1.042E+05	1.525E+00	8.330E+02
2036	1.042E+05	1.237E+00	6.759E+02
2037	1.042E+05	1.004E+00	5.484E+02
2038	1.042E+05	8.146E-01	4.450E+02
2039	1.042E+05	6.609E-01	3.611E+02
2040	1.042E+05	5.363E-01	2.930E+02
2041	1.042E+05	4.351E-01	2.377E+02
2042	1.042E+05	3.531E-01	1.929E+02
2043	1.042E+05	2.865E-01	1.565E+02
2044	1.042E+05	2.324E-01	1.270E+02
2045	1.042E+05	1.886E-01	1.030E+02
2046	1.042E+05	1.530E-01	8.360E+01
2047	1.042E+05	1.242E-01	6.783E+01
2048	1.042E+05	1.008E-01	5.504E+01
2049	1.042E+05	8.175E-02	4.466E+01
2050	1.042E+05	6.633E-02	3.624E+01
2051	1.042E+05	5.382E-02	2.940E+01
2052	1.042E+05	4.367E-02	2.386E+01
2053	1.042E+05	3.543E-02	1.936E+01
2054	1.042E+05	2.875E-02	1.571E+01
2055	1.042E+05	2.333E-02	1.274E+01
2056	1.042E+05	1.893E-02	1.034E+01
2057	1.042E+05	1.536E-02	8.390E+00
2058	1.042E+05	1.246E-02	6.808E+00
2059	1.042E+05	1.011E-02	5.524E+00
2060	1.042E+05	8.204E-03	4.482E+00
2061	1.042E+05	6.657E-03	3.637E+00
2062	1.042E+05	5.401E-03	2.951E+00
2063	1.042E+05	4.383E-03	2.394E+00
2064	1.042E+05	3.556E-03	1.943E+00
2065	1.042E+05	2.885E-03	1.576E+00
2066	1.042E+05	2.341E-03	1.279E+00
2067	1.042E+05	1.900E-03	1.038E+00
2068	1.042E+05	1.541E-03	8.420E-01
2069	1.042E+05	1.251E-03	6.832E-01
2070	1.042E+05	1.015E-03	5.544E-01
2071	1.042E+05	8.234E-04	4.498E-01
2072	1.042E+05	6.681E-04	3.650E-01
2073	1.042E+05	5.421E-04	2.961E-01
2074	1.042E+05	4.398E-04	2.403E-01
2075	1.042E+05	3.569E-04	1.950E-01
2076	1.042E+05	2.896E-04	1.582E-01
2077	1.042E+05	2.350E-04	1.284E-01

2078	1.042E+05	1.906E-04	1.041E-01
2079	1.042E+05	1.547E-04	8.451E-02
2080	1.042E+05	1.255E-04	6.857E-02
2081	1.042E+05	1.018E-04	5.564E-02
2082	1.042E+05	8.263E-05	4.514E-02
2083	1.042E+05	6.705E-05	3.663E-02
2084	1.042E+05	5.440E-05	2.972E-02
2085	1.042E+05	4.414E-05	2.411E-02
2086	1.042E+05	3.582E-05	1.957E-02
2087	1.042E+05	2.906E-05	1.588E-02
2088	1.042E+05	2.358E-05	1.288E-02
2089	1.042E+05	1.913E-05	1.045E-02
2090	1.042E+05	1.552E-05	8.481E-03
2091	1.042E+05	1.260E-05	6.881E-03
2092	1.042E+05	1.022E-05	5.584E-03
2093	1.042E+05	8.293E-06	4.530E-03
2094	1.042E+05	6.729E-06	3.676E-03
2095	1.042E+05	5.460E-06	2.983E-03
2096	1.042E+05	4.430E-06	2.420E-03
2097	1.042E+05	3.595E-06	1.964E-03
2098	1.042E+05	2.917E-06	1.593E-03
2099	1.042E+05	2.366E-06	1.293E-03
2100	1.042E+05	1.920E-06	1.049E-03
2101	1.042E+05	1.558E-06	8.511E-04
2102	1.042E+05	1.264E-06	6.906E-04
2103	1.042E+05	1.026E-06	5.604E-04
2104	1.042E+05	8.323E-07	4.547E-04
2105	1.042E+05	6.753E-07	3.689E-04
2106	1.042E+05	5.479E-07	2.993E-04
2107	1.042E+05	4.446E-07	2.429E-04
2108	1.042E+05	3.607E-07	1.971E-04
2109	1.042E+05	2.927E-07	1.599E-04
2110	1.042E+05	2.375E-07	1.297E-04
2111	1.042E+05	1.927E-07	1.053E-04
2112	1.042E+05	1.564E-07	8.542E-05
2113	1.042E+05	1.269E-07	6.931E-05
2114	1.042E+05	1.029E-07	5.624E-05
2115	1.042E+05	8.353E-08	4.563E-05
2116	1.042E+05	6.777E-08	3.702E-05
2117	1.042E+05	5.499E-08	3.004E-05
2118	1.042E+05	4.462E-08	2.438E-05
2119	1.042E+05	3.620E-08	1.978E-05
2120	1.042E+05	2.938E-08	1.605E-05
2121	1.042E+05	2.384E-08	1.302E-05
2122	1.042E+05	1.934E-08	1.057E-05
2123	1.042E+05	1.569E-08	8.573E-06
2124	1.042E+05	1.273E-08	6.956E-06
2125	1.042E+05	1.033E-08	5.644E-06
2126	1.042E+05	8.383E-09	4.579E-06
2127	1.042E+05	6.802E-09	3.716E-06
2128	1.042E+05	5.519E-09	3.015E-06
2129	1.042E+05	4.478E-09	2.446E-06
2130	1.042E+05	3.633E-09	1.985E-06
2131	1.042E+05	2.948E-09	1.611E-06
2132	1.042E+05	2.392E-09	1.307E-06
2133	1.042E+05	1.941E-09	1.060E-06
2134	1.042E+05	1.575E-09	8.603E-07

2135	1.042E+05	1.278E-09	6.981E-07
2136	1.042E+05	1.037E-09	5.664E-07
2137	1.042E+05	8.413E-10	4.596E-07
2138	1.042E+05	6.826E-10	3.729E-07
2139	1.042E+05	5.539E-10	3.026E-07
2140	1.042E+05	4.494E-10	2.455E-07
2141	1.042E+05	3.646E-10	1.992E-07
2142	1.042E+05	2.959E-10	1.616E-07
2143	1.042E+05	2.401E-10	1.311E-07
2144	1.042E+05	1.948E-10	1.064E-07
2145	1.042E+05	1.581E-10	8.634E-08
2146	1.042E+05	1.282E-10	7.006E-08
2147	1.042E+05	1.041E-10	5.685E-08
2148	1.042E+05	8.443E-11	4.612E-08
2149	1.042E+05	6.851E-11	3.742E-08
2150	1.042E+05	5.559E-11	3.037E-08
2151	1.042E+05	4.510E-11	2.464E-08
2152	1.042E+05	3.660E-11	1.999E-08
2153	1.042E+05	2.969E-11	1.622E-08
2154	1.042E+05	2.409E-11	1.316E-08
2155	1.042E+05	1.955E-11	1.068E-08
2156	1.042E+05	1.586E-11	8.665E-09
2157	1.042E+05	1.287E-11	7.031E-09
2158	1.042E+05	1.044E-11	5.705E-09
2159	1.042E+05	8.473E-12	4.629E-09
2160	1.042E+05	6.875E-12	3.756E-09
2161	1.042E+05	5.578E-12	3.048E-09
2162	1.042E+05	4.526E-12	2.473E-09
2163	1.042E+05	3.673E-12	2.006E-09
2164	1.042E+05	2.980E-12	1.628E-09
2165	1.042E+05	2.418E-12	1.321E-09
2166	1.042E+05	1.962E-12	1.072E-09
2167	1.042E+05	1.592E-12	8.696E-10
2168	1.042E+05	1.292E-12	7.056E-10
2169	1.042E+05	1.048E-12	5.725E-10
2170	1.042E+05	8.504E-13	4.646E-10
2171	1.042E+05	6.900E-13	3.769E-10
2172	1.042E+05	5.599E-13	3.058E-10
2173	1.042E+05	4.543E-13	2.482E-10
2174	1.042E+05	3.686E-13	2.014E-10
2175	1.042E+05	2.991E-13	1.634E-10
2176	1.042E+05	2.427E-13	1.326E-10
2177	1.042E+05	1.969E-13	1.076E-10
2178	1.042E+05	1.598E-13	8.728E-11
2179	1.042E+05	1.296E-13	7.082E-11
2180	1.042E+05	1.052E-13	5.746E-11
2181	1.042E+05	8.534E-14	4.662E-11
2182	1.042E+05	6.925E-14	3.783E-11
2183	1.042E+05	5.619E-14	3.069E-11
2184	1.042E+05	4.559E-14	2.491E-11
2185	1.042E+05	3.699E-14	2.021E-11
2186	1.042E+05	3.001E-14	1.640E-11
2187	1.042E+05	2.435E-14	1.330E-11
2188	1.042E+05	1.976E-14	1.080E-11
2189	1.042E+05	1.603E-14	8.759E-12
2190	1.042E+05	1.301E-14	7.107E-12
2191	1.042E+05	1.056E-14	5.767E-12

2192	1.042E+05	8.565E-15	4.679E-12
2193	1.042E+05	6.950E-15	3.797E-12
2194	1.042E+05	5.639E-15	3.080E-12
2195	1.042E+05	4.575E-15	2.499E-12
2196	1.042E+05	3.712E-15	2.028E-12
2197	1.042E+05	3.012E-15	1.646E-12
2198	1.042E+05	2.444E-15	1.335E-12
2199	1.042E+05	1.983E-15	1.083E-12
2200	1.042E+05	1.609E-15	8.790E-13
2201	1.042E+05	1.306E-15	7.133E-13

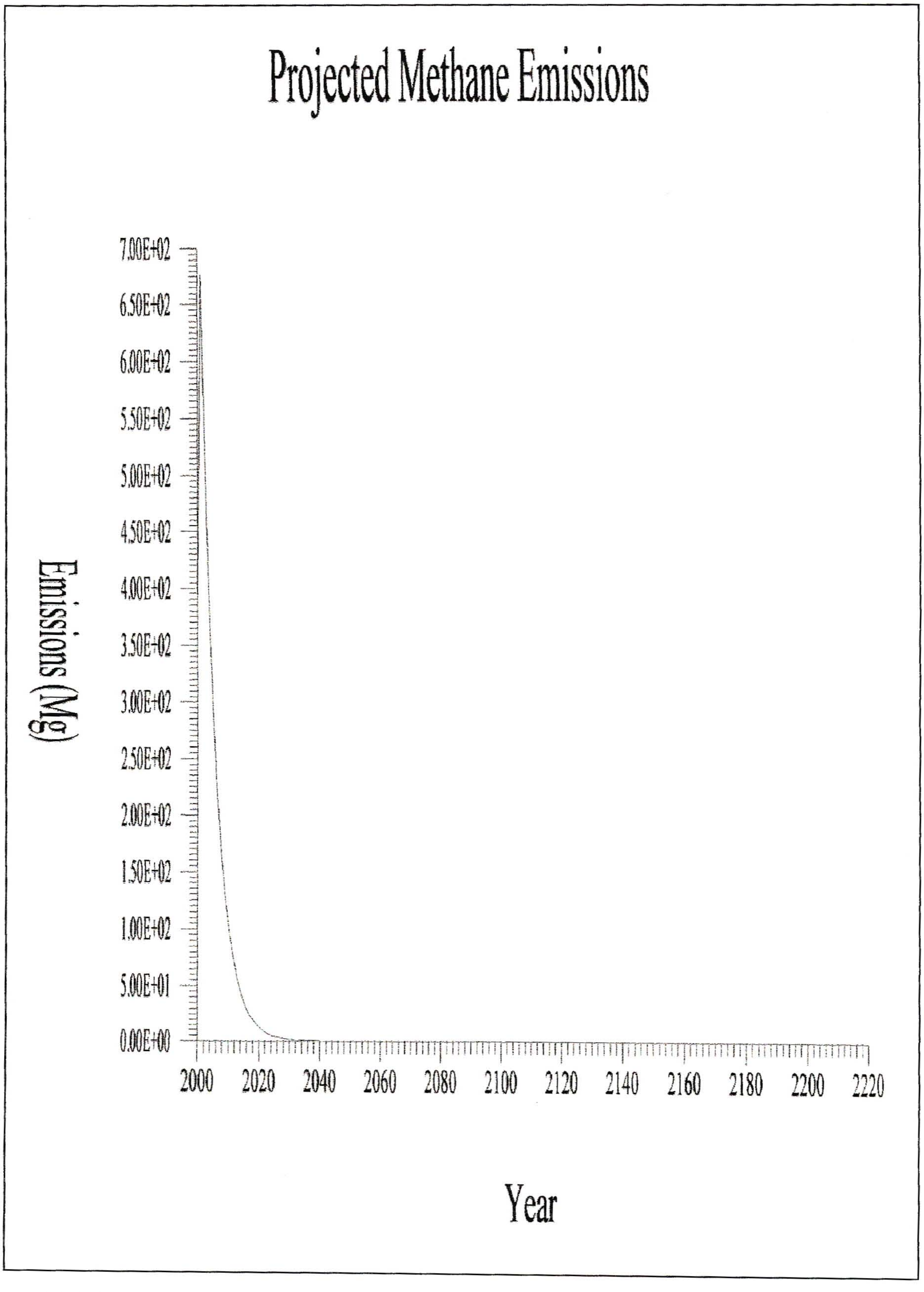


Figure C3.1 Projected methane emissions for Cell 2 (LandGEM Model output)

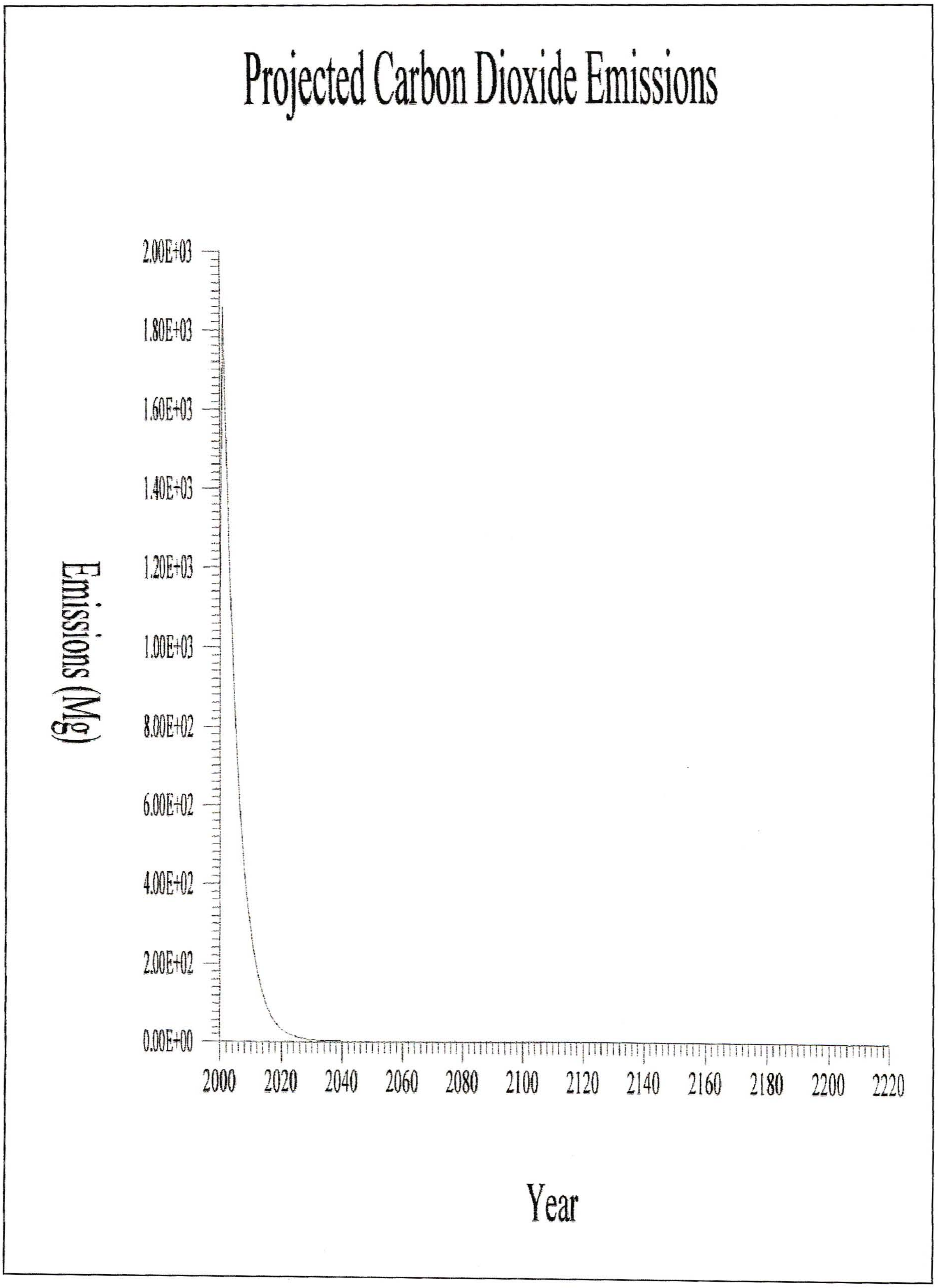
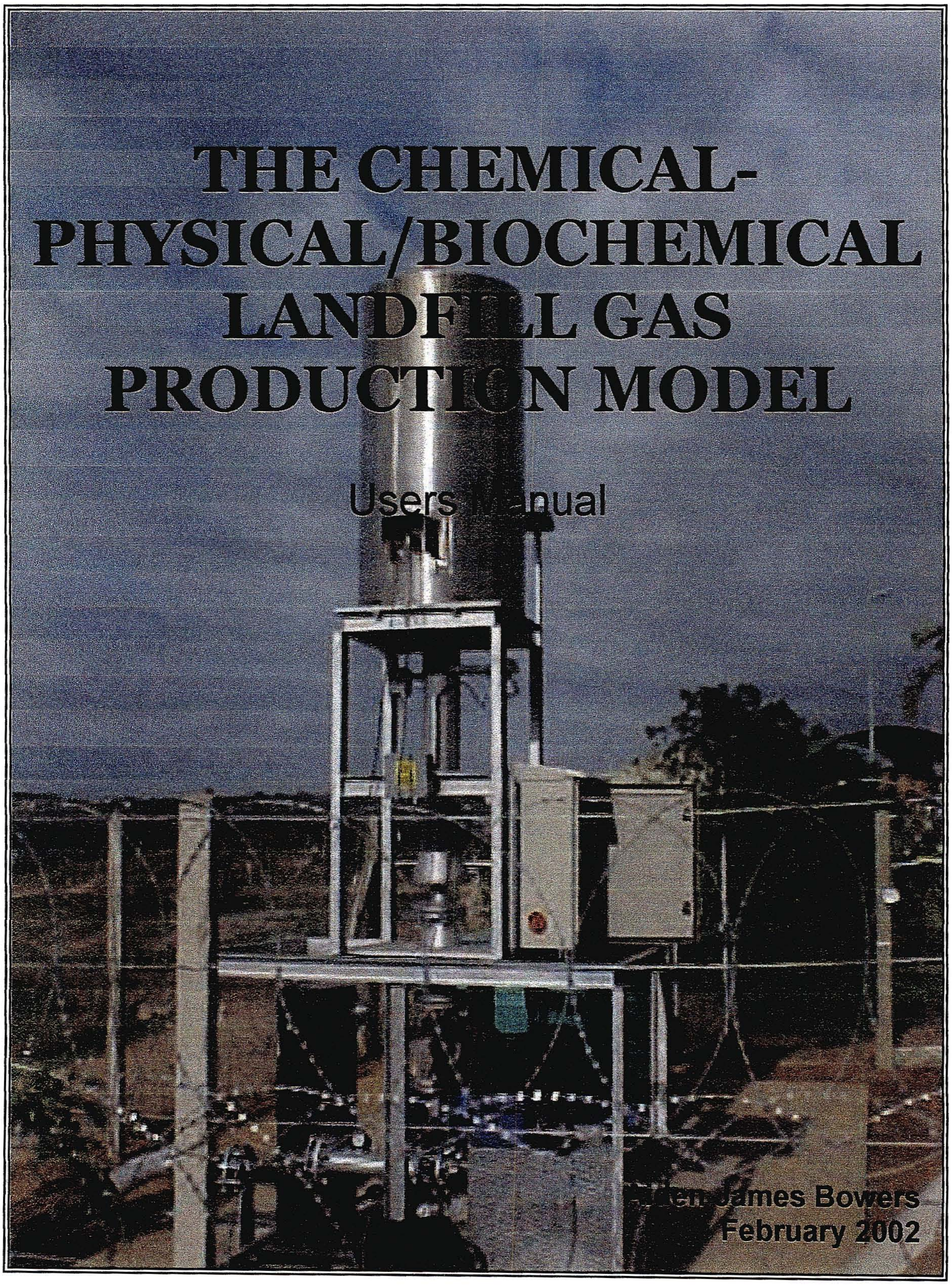


Figure C3.2 Projected carbon dioxide emissions for Cell 2 (LandGEM Model output)

APPENDIX D

Appendix D1 – The Chemical-Physical/Biochemical Landfill Gas Production Model Users Manual



THE CHEMICAL-PHYSICAL/BIOCHEMICAL LANDFILL GAS PRODUCTION MODEL

Users Manual

Allen James Bowers
February 2002

CONTENTS

1. INTRODUCTION

Landfill gas models that are able to predict the yield and production rate of biogas generated are necessary in terms of evaluating potential gas migration and related problems; and for the installation of a gas management system. A relatively simple, easy-to-use gas production model is a useful tool for the landfill manager in assessing likely gas emissions from waste cells or the landfill as a whole.

The Chemical-Physical/Biochemical Landfill Gas Production model is based on work by Muntoni et al (1995) and Cossu et al (1996a). The model is comprehensive and may be used in cases where site-specific conditions are known and in cases where site-specific data is lacking. The model presented in this manual relates specifically to landfills located in sub-tropical climates, where waste degradation rates are expected to be relatively high. It has been programmed in Microsoft Excel^{TM}, providing the user with a clear, simple interface from which landfill gas emissions may be predicted.

This users manual includes:

- background information on landfill gas generating processes in a landfill and landfill gas control
- an overview of the Chemical-Physical/Biochemical Model
- an overview of the programmed model
- a detailed example calculation

2. LANDFILL GAS

Landfill gas (biogas) is the generic term given to describe the gaseous components generated through microbial degradation and/or by chemical reaction/volatilisation consequent to the disposal of waste in landfill sites. Typically, landfill gas consists of methane and carbon dioxide as major components in a wide range and combination of concentrations. Landfill gas may also contain numerous minor (trace) components, of which over 300 have been identified (Couth, 2001). The methane in landfill gas can cause fires, explosion, asphyxiation, damage to vegetation, and it is a potent greenhouse gas. Carbon dioxide can cause asphyxiation, is toxic to vegetation, and has corrosive properties. The trace components may cause health risks, odour nuisances and groundwater pollution and have corrosive properties.

2.1 Landfill Gas Production

The generation of landfill gas is a complex process, predominated by anaerobic digestion. Biochemical processes degrade primarily cellulose and other similar materials, releasing methane and carbon dioxide as final products of waste decomposition. In a typical landfill, biogas consists of 60 – 65 % methane and 35 – 40% carbon dioxide relatively soon after the waste is placed (within one to three years). The developments in landfill gas composition can be separated into eight idealised phases (Christensen et al, 1996). Figure 1 illustrates the changes in gas composition as the landfilled wastes degrade. The various phases are described in Table 1.

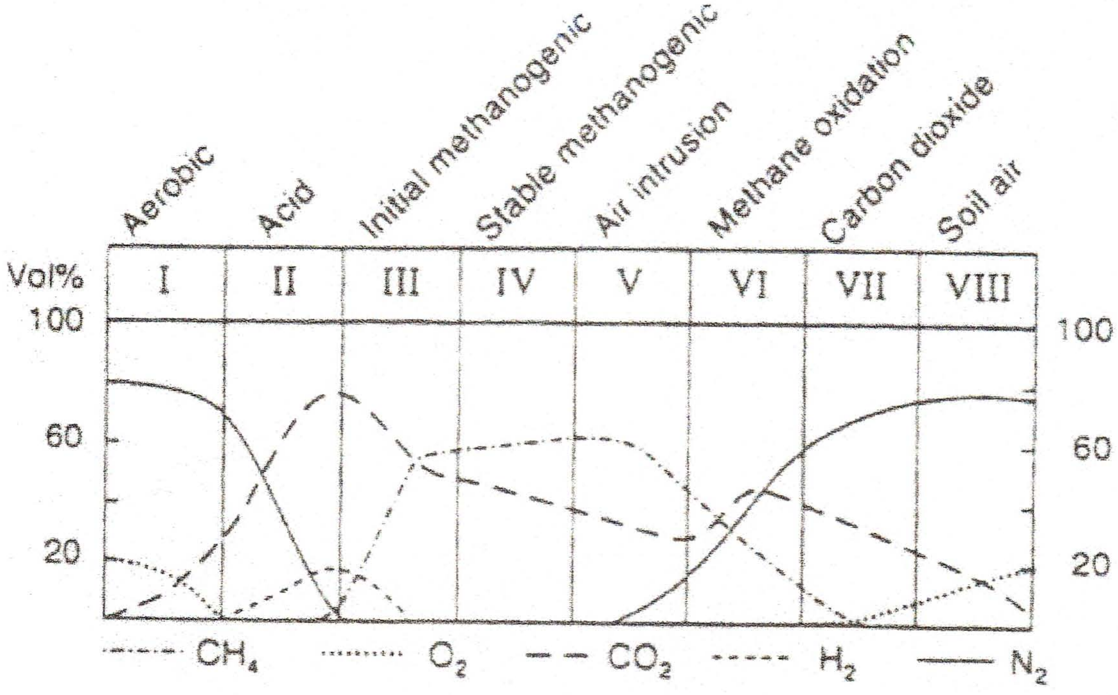


Figure 4.1 Developments in gas composition in a landfill cell (Christensen et al, 1996)

Table 1 Phases of landfill gas generation (adapted from Couth, 2000)

PHASE	DESCRIPTION
1. Aerobic	A short aerobic phase by composting of easily degradable organic matter to carbon dioxide
2. Acid	Fermentative and acidogenic bacteria produce, under anaerobic conditions, volatile fatty acids, CO_2 and H_2. The presence of these gases reduces the content of N_2
3. Initial methanogenic	In a second anaerobic phase, methanogenic bacteria start to grow producing CH_4, while CO_2 and H_2 decrease.
4. Stable methanogenic	The stable methanogenic phase is characterised by 50-60% CH_4 and low concentrations of H_2. The latter being oxidised by CO_2 to CH_4.
5. Air Intrusion	Air starts to intrude into the outer part of landfill body reducing the formation of CH_4. The lower rates lead to a relatively more significant washout of CO_2 and a relative increase in CH_4 content in the gas.
6. Methane oxidation	Methane produced in the centre of the waste is oxidised to CO_2 as it migrates through the outer part of the landfill body. N_2 is now present in significant concentrations in the gas
7. Carbon dioxide	Methane formation is now negligible and intruding air now oxidises solid organic carbon (and reduced inorganic species) yielding CO_2.
8. Soil air	The rates of the processes now approach the rates found in an active soil and the landfill gas starts to resemble soil air

2.2 Landfill Gas Characteristics

The typical concentrations of methane and carbon dioxide given in section 2.1 remain relatively constant over the life of the landfill, though higher methane concentrations may be observed in older landfills (Rettenberger and Stegmann, 1996). The composition of the gas will change when oxygen enters the landfill, which may occur during active gas extraction when air is sucked into the fill.

Landfill gas typically contains a volumetric ratio of CH_4/CO_2 of 1.2 to 1.5 (Wilhelm, 1993). The volatile organic compounds (VOC) generally account for less than 1% of landfill gas by volume. Carbon dioxide is heavier than air, having a density (relative to air) of 1.53, whilst methane is lighter than air, having a density (relative to air) of 0.55. Landfill gas will thus be lighter than air when methane is in excess of 54% (0.54*0.55 + 0.46*1.53 = 1.0008), and heavier than air when it is less than 54% (Massacci, 1996). Generally, landfill gas will be heavier than air however, as it is actually a mixture saturated by water vapour. Couth (2001) reports that in England and Wales landfill gas tends to rise due to the difference in temperature of the gas and the ambient air. Table 4.3 gives the characteristics of the bulk components of landfill gas.

Table 4.3 Characteristics of Landfill Gas Components (Couth, 2001)

COMPONENT	DENSITY g/L	ODOUR	COLOUR	FLAMMABLE	COMMENT
Methane (CH_4)	0.71	Odourless	Colourless	Yes	Very low solubility in liquid at STP. Important greenhouse gas
Carbon Dioxide (CO_2)	1.98	Odourless	Colourless	No	Slightly acidic at high concentrations. Very soluble in water, forming corrosive liquid with low pH
Hydrogen Sulphide (H_2S)	1.53	Rotten eggs	Colourless	Yes	-
Hydrogen (H_2)	0.09	Odourless	Colourless	Yes	-
Oxygen (O_2)	1.42	Odourless	Colourless	No	-
Nitrogen (N_2)	1.25	Odourless	Colourless	No	-

In addition to the methane and carbon dioxide, landfill gas will also contain numerous trace components. The composition of the landfilled wastes will determine the type and concentration of the trace components, although these may change due to chemical and biological processes that take place in the landfill.

Trace components may cause damage to technical equipment (especially that used for landfill gas extraction) and have an adverse impact on the environment, atmosphere and on the health of humans and animals (Rettenberger and Stegmann, 1996).

2.3 Landfill gas Control

The migration of landfill gas into the surrounding environment through the surface of the landfill and adjacent gas permeable pathways is the factor most in need of control. The gas control systems commonly used to prevent this migration include impervious barriers, passive venting and active gas pumping. The majority of newly engineered landfills have barrier systems installed to prevent leachate migration into the environment, thereby ensuring that gaseous emissions are also contained. Passive venting techniques consist of simple venting trenches backfilled with coarse material to create a zone of relatively high gas permeability to be preferentially used by the gas (Gendebien et al, 1992). Commonly, vent trenches are sealed in a row and the gas is collected with a series of vent stacks. The use of venting trenches is generally limited to relatively shallow landfills however.

The active pumping of gas from the landfill is a more sophisticated, but more efficient, system of controlling gas. These systems involve the extraction of gas from the waste body under a slight vacuum by use of a pumping station containing an extraction unit. Gas control systems are a requirement in South Africa in areas where high gas generation rates may pose an environmental risk. The development of attenuation landfills in South Africa before the enforced legislative requirements has resulted in very few landfills having barrier systems to prevent off-site migration of landfill gas, and highlighted the need for active gas extraction as the only feasible method to control emissions. In addition to preventing gas migration, active gas extraction via vertically driven wells in the waste body facilitates the collection of leachate, which would have otherwise migrated into the surrounding environment.

3. OVERVIEW OF THE CHEMICAL-PHYSICAL/BIOCHEMICAL MODEL

The production of biogas is considered in two sub-models in this multi-phase modeling method, as proposed by Muntoni et al (1995). The first sub-model describes the influence of several chemical-physical parameters (content of biodegradable organic carbon, moisture content, temperature, density and particle size) on the conversion of organic carbon to biogas. The second sub-model describes the kinetics of biogas production considering the biodegradation rates of three categories of organic matter, viz. easily biodegradable, biodegradable and slowly biodegradable matter. The results from the chemical-physical sub-model provides the input for the biochemical sub-model and allows the forecast of specific and absolute biogas production for separate cells and for the landfill as a whole (Muntoni et al, 1995).

The chemical-physical submodel calculates for each cell and for each waste component (e.g. putrescibles, cardboard, garden refuse) the quantity of biodegradable carbon based on the composition and the chemical-physical characteristics of the waste. Equation 1 describes the relationship between these characteristics.

$$(CO_b)_{i,j} = [(OC)_i \, (f_b)_i \, (1 - u_i) \, p_i]_j \qquad \textbf{EQ 1}$$

Where:

i = 1..n index of waste component

j = 1...n index of cell

$(CO_b)_{i,j}$ = Amount of organic carbon that may be converted to biogas (kg_C/kg_{MSW})

(OC_i) = Biodegradable organic carbon in waste mass ($kg_C/kg_{kg\ dry\ component}$)

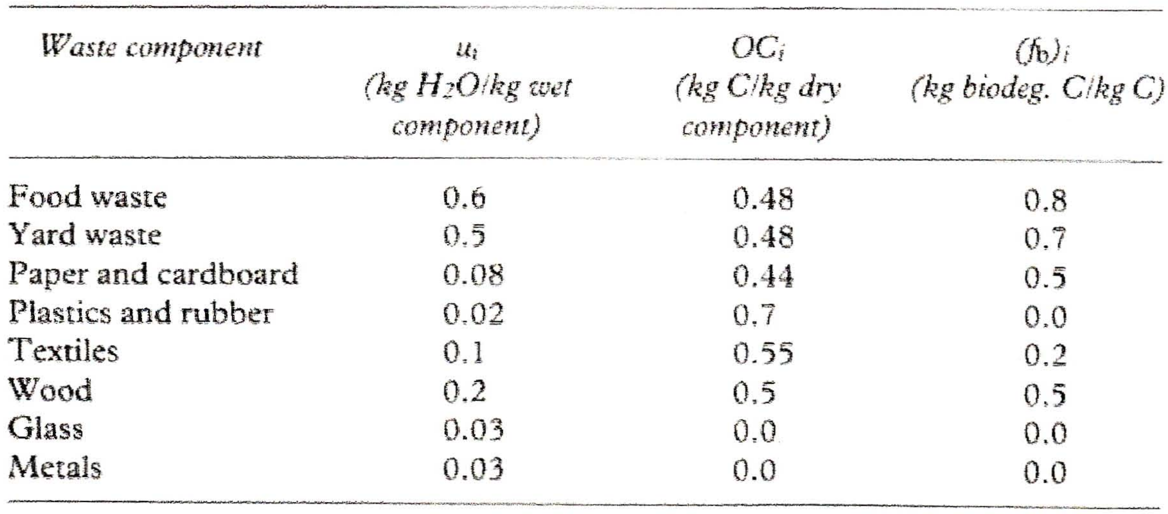
$(f_b)_i$ = Biodegradable fraction of organic carbon ($kg_{biodegradable\ C}/kg_C$)

u_i = Water content of the waste component (kg_{H2O}/kg)

p_i = Humid weight (kg/kg_{MSW})

Determining site-specific values for the waste component characteristics (C_i, u,) and the ratio of biodegradable carbon to total carbon (f_b) is difficult in practice. Cossu et al (1996) reported typical parameter values for various waste components. Table 2 presents the typical values. The humid weight (p_i) represents the portion of the waste body that is composed of the ith waste component, i.e. the ratio of the mass of the ith waste component to the total mass of the waste body. This may be determined from either weighbridge data (if available), or by estimating the relative proportion of the waste components.

Table 2 Typical Parameter values for the moisture content (u_i); biodegradable organic carbon in waste mass (OC_i); and biodegradable fraction of organic carbon in different waste components (from Cossu et al, 1996)



Waste component	u_i *(kg H_2O/kg wet component)*	OC_i *(kg C/kg dry component)*	$(f_b)_i$ *(kg biodeg. C/kg C)*
Food waste	0.6	0.48	0.8
Yard waste	0.5	0.48	0.7
Paper and cardboard	0.08	0.44	0.5
Plastics and rubber	0.02	0.7	0.0
Textiles	0.1	0.55	0.2
Wood	0.2	0.5	0.5
Glass	0.03	0.0	0.0
Metals	0.03	0.0	0.0

The amount of carbon that may be converted to biogas is also an increasing function of temperature. Tabasaran (1982) provides a correlation, which is shown in Equation 2.

$$CO_e = CO_b\,(0.28 + 0.014\,T) \quad \textbf{EQ 2}$$

Where:

CO_e = Amount of biodegradable carbon that may be converted to biogas ($kg_C/kg_{wet\ MSW}$)

CO_b = Amount of biodegradable carbon available in the waste ($kg_C/kg_{wet\ MSW}$)

T = Landfill Temperature (^{0}C)

The landfill temperature generally may range between 20 and 60 ^{0}C, depending primarily on climatic conditions. Landfill temperatures in the United Kingdom generally range between 16 and 40 ^{0}C (Couth, 2001; Christensen and Kjeldsen, 1989). Houi et al (1997) found that temperatures in the landfill were extremely varied, with temperatures in the uppermost layers ranging between 29 and 37^{0}C, in the middle layers between 50 and

60^0C and in the lower layers between 38 and 50^0C. The likely range of landfill temperatures in South African landfills is between 35 and 50 ^{0}C.

The output of the chemical-physical sub-model is given by a mass of biodegradable carbon that may be converted to biogas for each MSW component and for each cell.
The biochemical sub-model is based on a first-order kinetic model, which describes the rate of substrate (biodegradable carbon) consumption, as is shown in Equation 3. Each waste type has an associated biodegradation rate. This model assumes that there are three general fractions of biodegradable matter in the waste mass into which the various waste types fall, viz. easily biodegradable, biodegradable and slowly biodegradable matter. Each waste component must therefore be placed into one of three fractions of biodegradable matter. If more than one waste type is considered as easily biodegradable, the masses of biodegradable carbon are added. The same approach applies for the other two fractions. Table 3 reports typical waste types that are found in landfilled waste, and their respective biodegradability.

Table 3 Different waste types and their respective biodegradability

WASTE COMPONENT	BIODEGRADABILITY
Food waste	Easily Biodegradable
Putrescibles	Easily Biodegradable
Garden Refuse (wet)	Biodegradable
Garden Refuse (dry)	Slowly Biodegradable
Paper and Cardboard	Slowly Biodegradable
Plastics and Rubber	Non-Biodegradable
Textiles	Slowly Biodegradable
Wood	Slowly Biodegradable
Glass	Non-Biodegradable
Metals	Non-Biodegradable

$$\frac{d.(CO_g(t))}{(CO_e)_{h,j} - (CO_g(t))_{h,j}} = k_h .dt \qquad \textbf{EQ 3}$$

Where:

h = 1,..,3 general biodegradable fraction index

j = 1,..,n Cell number index

$(CO_g)_{i,j}$ = Carbon converted to biogas ($kg_c/kg_{wet\ MSW}$)

$(CO_b)_{i,j}$ = Carbon available for conversion to biogas at time $t = 0$ ($kg_c/kg_{wet\ MSW}$)

k_h = Biodegradability coefficient for the h^{th} waste fraction ($year^{-1}$)

t = Time (years)

k_h is a global reaction coefficient representing both the hydrolysis reaction and the biochemical transformations that lead to the production of biogas. It can be estimated for different fractions as a function of their half-life ($t_{1/2}$), as is shown in Equation 4. The half-life is the time over which the gas generation equals half of the estimated yield (Cossu et al, 1996).

$$k_h = \ln 2/(t_{1/2}) \qquad \textbf{EQ 4}$$

The half-lives for the three biodegradable fractions are largely influenced by climatic conditions. Waste in landfills that are situated in cool, dry climates will take longer to degrade than waste in landfills in hot humid climates. Table 4 presents typical half-lives for the three biodegradable fractions.

Table 4 Typical half-lives for the three biodegradable fractions

HALF-TIME	CLIMATIC CONDITIONS
(a) Easily Biodegradable	
1 – 2 years	Moist climate (e.g. Durban)
2 – 4 years	Moderate climate (e.g. Cape Town)
4 – 5 years	Dry climate (e.g. Johannesburg)
(b) Biodegradable	
5 – 6 years	Moist
6 – 8 years	Moderate
9 – 10 years	Dry
(c) Slowly Biodegradable	
10 – 15 years	Moist
12 – 20 years	Moderate
15 – 25 years	Dry

The rate of waste degradation is also dependent on the moisture conditions in the landfill and the total reactive surface of solid fraction. Two corrective factors are introduced at this stage:

- The first factor (α) takes into account the moisture conditions in a landfill. The biodegradable organic fractions in MSW usually have sufficient moisture to prevent inhibition of bacterial activity. The moisture content however is generally smaller than the field capacity, depending on the degree of compaction. . It is assumed in the model that the biodegradation rate is a maximum if the waste is saturated. Under normal conditions, the waste is unsaturated and is the limiting factor. The factor (α) is given by equation 5:

$$\alpha = \left(\frac{u}{u_s}\right) \qquad \textbf{EQ 5}$$

Where:

$\forall$ = Landfill moisture coefficient

u = Moisture content (%)

u_s = Saturation moisture content (%)

Landfilled waste is not homogeneous, and hence moisture conditions within the waste body are highly variable. A value for α is usually estimated, taking into consideration climatic conditions (e.g. wetter climate, more moisture in landfill) and whether there are significant quantities of leachate being generated. Recommended values for α generally lie between 0.5 and 0.9 (i.e. waste is between 50% and 90% saturated).

- The second corrective factor (β) is applied to account for the reactive surface area of the solid fraction, which depends on the density and waste size. Determining the ratio of reactive to maximum reactive surface is difficult in practice, and hence a value of 0.9 may be assumed.

The three global reaction coefficients (k_h) are multiplied by these two factors, yielding an 'effective' reaction coefficient ($k_{h,e}$), as shown in Equation 6.

$$k_{h,e} = \alpha.\beta.k_h \qquad \textbf{EQ 6}$$

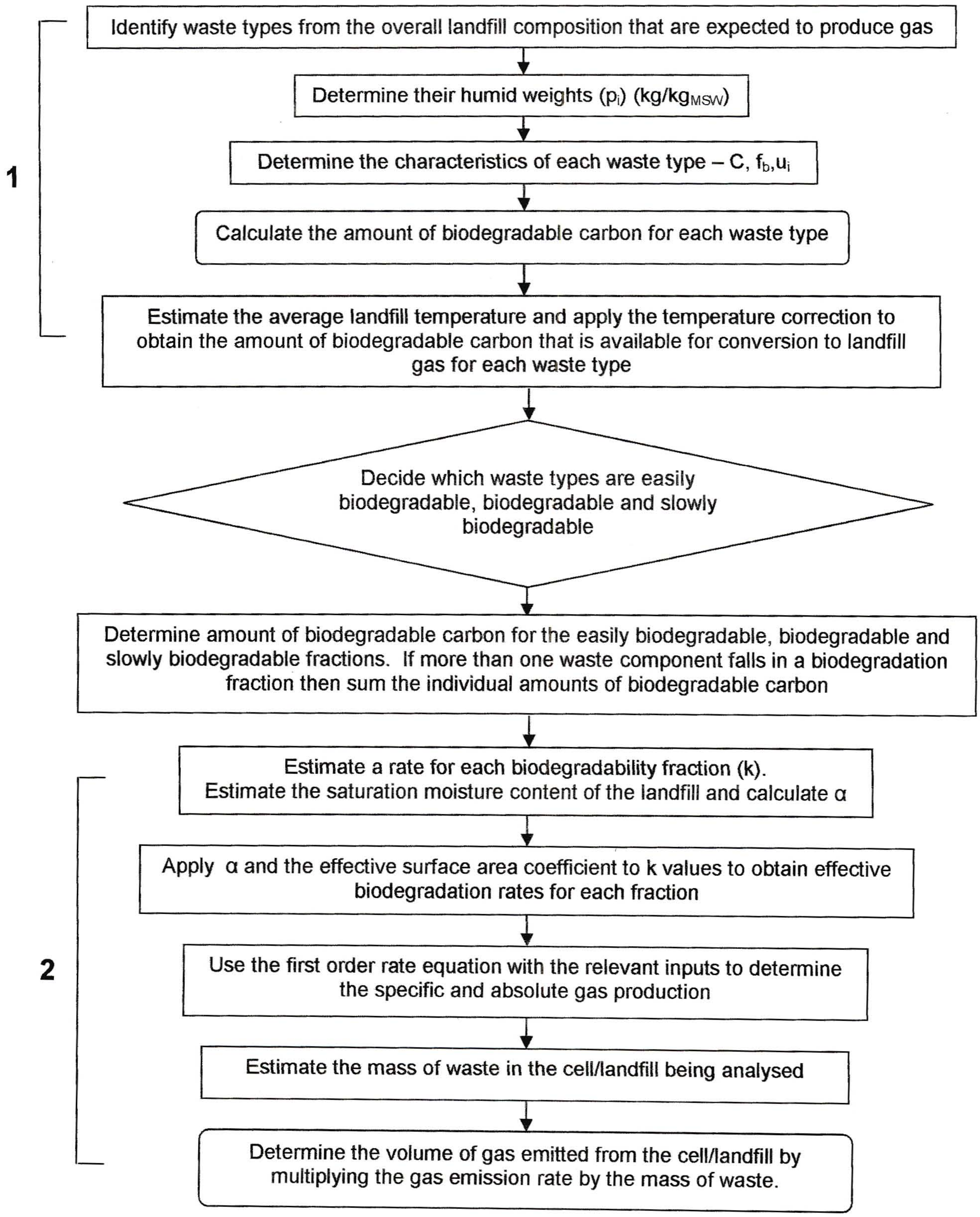
It can be shown that 1.868 m^3 of biogas can be produced from the biodegradation of one kilogram of organic carbon (Cossu et al, 1996). The cumulative biogas production at time t is given by Equation 7.

$$G_t = \sum_{h,j} 1.186(CO_e)_{h,j}(1 - e^{-K_{he,j}t}) \qquad (m^3/ton_{MSW} \cdot year) \qquad \textbf{EQ 7}$$

The specific gas production is given by Equation 6.

$$g = - dG/dt = \sum_{h,j} 1.868(CO_e)_{h,j}K_{he,j}e^{-K_{he,j}t} \qquad (m^3/ton_{MSW} \cdot year) \qquad \textbf{EQ 8}$$

Figure 2 presents a summary of the model.



Identify waste types from the overall landfill composition that are expected to produce gas

Determine their humid weights (p_i) (kg/kg$_{MSW}$)

Determine the characteristics of each waste type – C, f_b,u_i

Calculate the amount of biodegradable carbon for each waste type

Estimate the average landfill temperature and apply the temperature correction to obtain the amount of biodegradable carbon that is available for conversion to landfill gas for each waste type

Decide which waste types are easily biodegradable, biodegradable and slowly biodegradable

Determine amount of biodegradable carbon for the easily biodegradable, biodegradable and slowly biodegradable fractions. If more than one waste component falls in a biodegradation fraction then sum the individual amounts of biodegradable carbon

Estimate a rate for each biodegradability fraction (k).
Estimate the saturation moisture content of the landfill and calculate α

Apply α and the effective surface area coefficient to k values to obtain effective biodegradation rates for each fraction

Use the first order rate equation with the relevant inputs to determine the specific and absolute gas production

Estimate the mass of waste in the cell/landfill being analysed

Determine the volume of gas emitted from the cell/landfill by multiplying the gas emission rate by the mass of waste.

Figure 2 Overview of the model, showing the progression from 1) The Chemical-Physical Model to 2) The Biochemical Model.

4. THE CHEMICAL-PHYSICAL/BIOCHEMICAL MODEL PROGRAM

The program develops in four environments, which are clearly integrated in a main menu screen, as described below:

- *Instructions Environment* – the program presents a general overview of the model and its objectives. A series of pop-up menus guides the user through the general process that the model follows.

- *Inputs Environment* – the second part of the program requires the user to input all the model parameters. Firstly, the user must have knowledge of the waste composition in the landfill. This data can be estimated from a Waste Stream Analysis (WSA) or obtained from weighbridge records. The gas producing waste components must be identified and their relative masses calculated (humid weight). The user must then decide which components are easily biodegradable, biodegradable and slowly biodegradable. The model allows a maximum of four different waste components per biodegradation fraction.

  The name of each component must then be entered for the easily biodegradable category. The parameter values (humid weight, carbon content, biodegradable fraction of carbon, moisture content) for the respective components must then be entered. Once all the inputs for the easily biodegradable fraction have been entered, the model asks the user for the general characteristics of the fraction. These include the biodegradation half time (in years), the landfill moisture coefficient (α) and the effective surface area reaction coefficient (β). The program then calculates the biodegradation constant (k) and the effective biodegradation constant (k_e)

  The biodegradable and slowly biodegradable fractions follow the same sequence as for the easily biodegradable category.

  Once the parameters related to the various waste components have been entered, the user returns to the main menu. The next step requires the user to enter the waste volumes in the cell/ landfill being analysed in six monthly intervals.

The user returns to the main menu, where the program requires that the average landfill temperature be entered. Following this, the key inputs may be inspected, and manually change if necessary. The inputs may also be set to zero if the user wishes to restart the model.

- *View Inputs* – All the input parameters are neatly presented, allowing for a final inspection of the entered data.
- *View Outputs* – The program runs the model using the inputs, and presents 3 graphical results – the specific gas production, cumulative gas production and the total gas emissions from the cell/landfill in question. Tabulated results for the total gas emissions are also presented.

The model is user-friendly, and additional software other than Microsoft Excel^{TM} is not required. Parameter values can be easily updated; thereby allowing the landfill manager to update predicted emissions as more waste is placed in the cell/landfill.

5. APPLYING THE MODEL – EXAMPLE

This section presents a gas production calculation using the programmed model, with input data from a typical landfill in Kwa-Zulu Natal, South Africa. This area experiences a warm, relatively wet climate.

Table 5 presents the typical weighbridge records for a Municipal Solid Waste (MSW) landfill site, which may be available to the model user. The waste was placed over a period of one and a half years in a lined landfill cell. The objective is to predict the volume of gas that will be produced by this waste body.

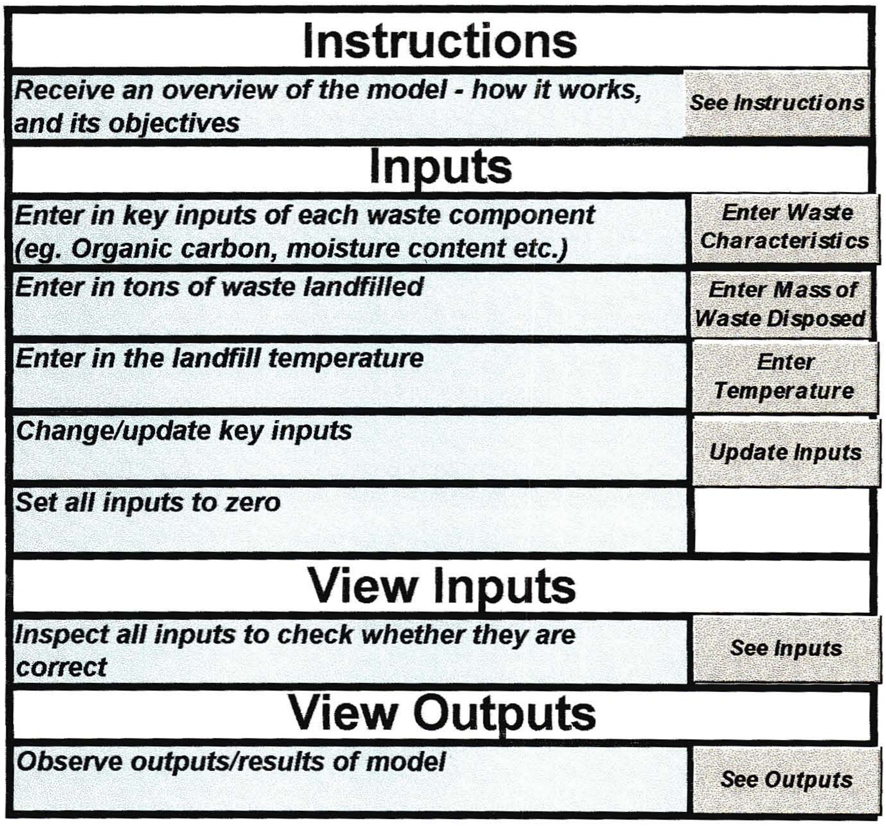
When the program is opened in Microsoft Excel^{TM}, the user is presented with the main menu screen, which is shown in Figure 3.

Table 5 Typical waste types (and masses) received at a Municipal Solid Waste Landfill Site

WASTE TYPE	**MASS OF WASTE IN CELL (TONS)**				
	Jul-Dec 97	Jan-Jun 98	Jul-Dec 98	Cumulative Mass	% total mass
Solid Waste	8357	10212	6870.2	25439.2	39.97
Garden Refuse	1843	3064	3123.18	8030.18	12.62
Rubble	1364	2408	1588.96	5360.96	8.42
Mixed Loads	457	442	364.99	1263.99	1.99
Cond. Foods	0	0	3.64	3.64	0.01
Paper	1024	845	764	2633	4.14
Sand etc.	7138	10927	5046.32	23111.32	36.31
General - Rec.	0	0	0	0	0.00
Whole Tyres	30	75	123.64	228.64	0.36
Asphalt	0	0	0	0	0.00
Polystyrene	6	10	19.42	35.42	0.06
Light Waste	4	4	31.82	39.82	0.06
Sani-waste	26	26	0	52	0.08
Special Disp.	0	31	55.4	86.4	0.14
No Charge	0	0	0	0	0.00
TOTALS	19225	27199	17227.57	63651.57	100.00

The 'see instructions' icon is chosen firstly, and the user is introduced to the program via pop-up screens. It provides the user with a general overview of the model, and it's objectives. The pop-up screens read as follows:

This is a simple landfill gas production model that aims to achieve two things
1. Calculate the rate of gas emission over time
2. Calculate the total gas emissions over time
To calculate these emissions the user must enter in the necessary data
This data includes:
1. The waste components and their characteristics
2. The waste dumped over time
3. The expected temperature of the landfill
Begin by pressing the 'Enter Waste Characteristics' button



Instructions

Receive an overview of the model - how it works, and its objectives — See Instructions

Inputs

Enter in key inputs of each waste component (eg. Organic carbon, moisture content etc.) — Enter Waste Characteristics

Enter in tons of waste landfilled — Enter Mass of Waste Disposed

Enter in the landfill temperature — Enter Temperature

Change/update key inputs — Update Inputs

Set all inputs to zero

View Inputs

Inspect all inputs to check whether they are correct — See Inputs

View Outputs

Observe outputs/results of model — See Outputs

Figure 3 Main menu screen

The first step is to decide which waste components will produce gas, and whether they are easily biodegradable, biodegradable or slowly biodegradable. From Table 5, three gas-generating waste components may be identified, namely *Solid Waste, Garden Refuse* and *Paper.*

It may immediately be identified that *Garden Refuse* and *Paper* are biodegradable and slowly biodegradable respectively. Identifying which category 'Solid Waste' falls into requires some care. If it is assumed that *Solid Waste* implies waste collected by collection vehicles (i.e. household wastes), then it seems reasonable that a relatively large proportion will be food waste. It is therefore assumed that *Solid Waste* is easily biodegradable

The 'enter waste characteristics' icon is now chosen, which takes the user to a screen where all the inputs for the model are stored. A series of pop-up screens asks the user to enter the relevant information for each waste component in each of three biodegradability fractions.

The number of waste components in the category must be entered. In this example, there is one easily biodegradable, one biodegradable and one slowly biodegradable waste component.

The waste components related to the easily biodegradable fraction are required first. The input sequence is as follows:

1. The number of waste components in the category must be entered. In this example, there is one easily biodegradable waste component (*Solid Waste*).
2. The name of the waste component must be entered.
3. The model now requires the humid weight. This may be obtained from Table 5. *Solid Waste* accounts for 39.97% of the mass of waste in the cell. This is a humid weight of 0.3997 kg/kg_{MSW}.
4. The organic carbon content (OC) is now required. Consulting table 2, food waste has a value of 0.48 kg_C/kg_{MSW}. As discussed earlier, not all of the *Solid Waste* comprised food waste. The user must approximate the carbon content. In this example, a value of 0.4 kg_C/kg_{MSW} has been chosen.
5. The fraction of the carbon that is biodegradable (f_b) must now be entered. Consulting Table 2, it can be seen that f_b for food waste is 0.8 $kg_{biodegradable\ C}/kg_C$. In this example, it is assumed that the only biodegradable waste in *Solid Waste* is food waste, and hence the aforementioned value is chosen.
6. The moisture content of the waste component is now required. Food waste has a typical moisture content of 0.6 $kg_{H2)}/kg_{MSW}$. This value has been chosen since food waste is the only biodegradable component of *Solid Waste.*
7. Information relating to the easily biodegradable fraction is now required. Firstly, the landfill moisture factor α must be entered. A value of 0.7 has been chosen in this example (it is assumed that the waste is 70% saturated).
8. The reactive surface coefficient, β, is now required. A value of 0.9 has been chosen.
9. The biodegradation half-life ($t_{1/2}$) must now be chosen. Since the landfill is located in Kwa-Zulu Natal, which has a warm, humid climate, the biodegradation rate is expected to be high. A half-life of 1 year has been chosen. The model automatically calculates the biodegradation constant (k) and applies the correction factors to obtain the effective biodegradation constant (k_e).

The inputs for the easily biodegradable fraction are now complete. The waste characteristics for the biodegradable fraction must now be entered:

1. The number of waste components in the category must be entered. In this example, there is one biodegradable waste component (*Garden Refuse*).
2. The name of the waste component is now entered.
3. The model now requires the humid weight. This may be obtained from Table 5. *Garden Refuse* accounts for 12.62% of the mass of waste in the cell. This is a humid weight of 0.1262 kg/kg_{MSW}.
4. The organic carbon content (OC) is now required. Consulting table 2, yard waste has a value of 0.48 kg_C/kg_{MS} (it is assumed that garden refuse and yard waste are the same).
5. The fraction of the carbon that is biodegradable (f_b) must now be chosen. Consulting Table 2, it can be seen that f_b for yard waste is 0.7 $kg_{biodegradable\ C}/kg_C$.
6. The moisture content of the waste component is now required. Yard waste has a moisture content of 0.5 $kg_{H2)}/kg_{MSW}$.
7. Information relating to the easily biodegradable fraction is now required. Firstly, the landfill moisture factor α must be entered. A value of 0.7 has been chosen in this example (it is assumed that the waste is 70% saturated).
8. The reactive surface coefficient, β, is now required. A value of 0.9 has been chosen.
9. The biodegradation half-life ($t_{1/2}$) must now be chosen. Since the landfill is located in Kwa-Zulu Natal, which has a warm, humid climate, the biodegradation rate is expected to be high. A half-life of 5 years has been chosen.

The inputs for the biodegradable fraction are now complete. The waste characteristics for the slowly biodegradable fraction must now be entered:

1. The number of waste components in the category must be entered. In this example, there is one slowly biodegradable waste component (*Paper*).
2. The name of the waste component is now entered.
3. The model now requires the humid weight. This may be obtained from Table 5. *Paper* accounts for 4.14% of the mass of waste in the cell. This is a humid weight of 0.0414 kg/kg_{MSW}.

4. The organic carbon content (OC) is now required. Consulting table 2, paper has a value of 0.44 kg_C/kg_{MS} (it is assumed that garden refuse and yard waste are the same).
5. The fraction of the carbon that is biodegradable (f_b) must now be chosen. Consulting Table 2, it can be seen that f_b paper is 0.5 $kg_{biodegradable\ C}/kg_C$.
6. The moisture content of the waste component is now required. Paper has a moisture content of 0.08 $kg_{H2)}/kg_{MSW}$.
7. Information relating to the easily biodegradable fraction is now required. Firstly, the landfill moisture factor α must be entered. A value of 0.7 has been chosen in this example (it is assumed that the waste is 70% saturated).
8. The reactive surface coefficient, β, is now required. A value of 0.9 has been chosen.
9. The biodegradation half-life ($t_{1/2}$) must now be chosen. Since the landfill is located in Kwa-Zulu Natal, which has a warm, humid climate, the biodegradation rate is expected to be high. A half-life of 10 years has been chosen.

All the characteristics of the waste have now been entered. Returning to the main menu, the 'enter waste dumped' icon is chosen. The mass of waste that has been placed in the landfill or landfill cell is now required in six monthly intervals. Table 6 shows the mass of waste placed (obtained from table 5) for the three six month intervals.

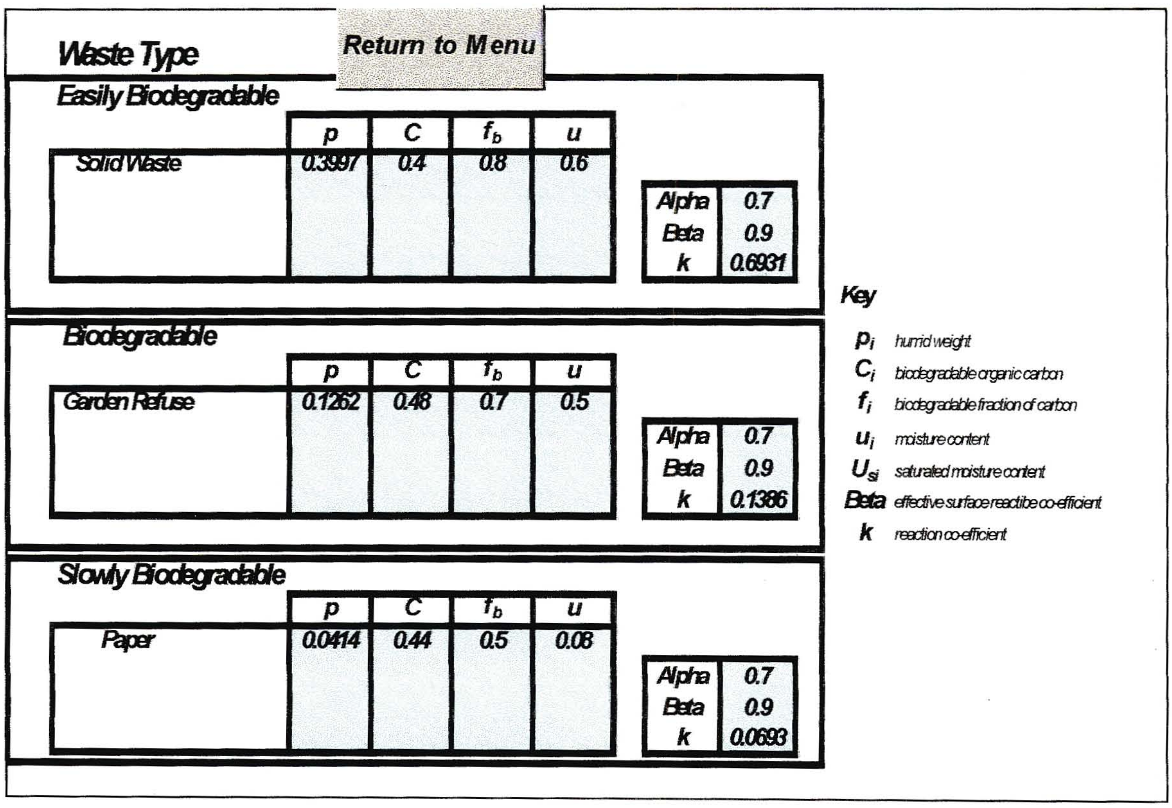
Table 6 Mass of waste disposed in the landfill cell

Time Period (months)	***Waste Disposed (tons)***
0-6 months	19225
6-12 months	27199
12-18 months	17227.57
18-24 months	
24-30 months	

Returning to the main menu, the 'enter temperature' is chosen. The average landfill temperature must now be entered. A temperature of 45 ^0C has been chosen for this example. This is considered representative of the relatively warm conditions experienced in Kwa-Zulu Natal.

Returning to the main menu, the user can choose the 'see inputs' icon, and inspect the entered data. If there has been an error in the inputs entered, they may manually edited by choosing the 'update key inputs' icon. Table 7 shows all the inputs as they appear in the 'see inputs' screen.

Table 7 Input data



Waste Type

Easily Biodegradable

	p	C	f_b	u
Solid Waste	0.3997	0.4	0.8	0.6

Alpha	0.7
Beta	0.9
k	0.6931

Biodegradable

	p	C	f_b	u
Garden Refuse	0.1262	0.48	0.7	0.5

Alpha	0.7
Beta	0.9
k	0.1386

Slowly Biodegradable

	p	C	f_b	u
Paper	0.0414	0.44	0.5	0.08

Alpha	0.7
Beta	0.9
k	0.0693

Key

p_i	humid weight
C_i	biodegradable organic carbon
f_i	biodegradable fraction of carbon
u_i	moisture content
U_{si}	saturated moisture content
Beta	effective surface reactibe co-efficient
k	reaction co-efficient

The program is now ready to calculate the gas emissions from the landfill cell. The 'see outputs' icon is chosen, and the user is sent to an output menu screen, which is shown in table 7. The user may choose to view the cumulative and specific gas production rates, as well as the total gas emissions from the cell. Figures 4, 5 and 6 show the three model outputs respectively.

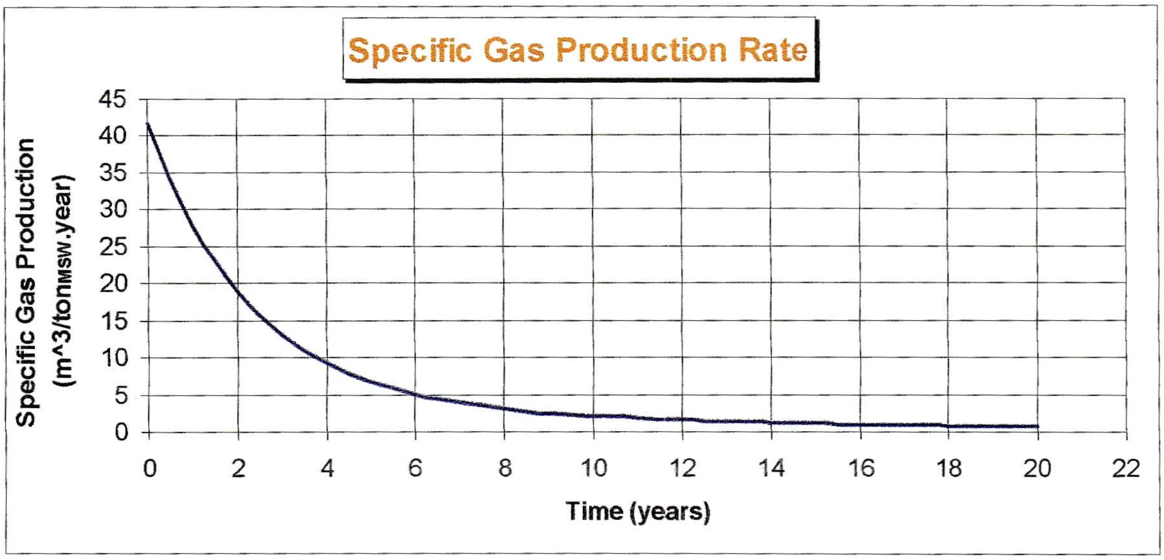


Figure 4 The specific gas production rate

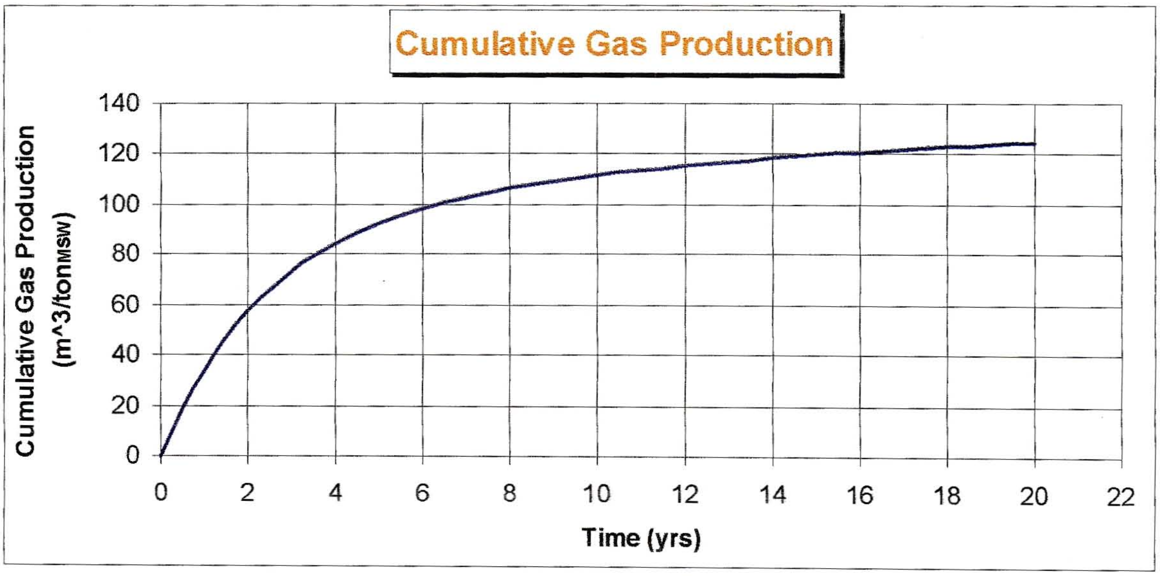


Figure 5 The specific gas production rate

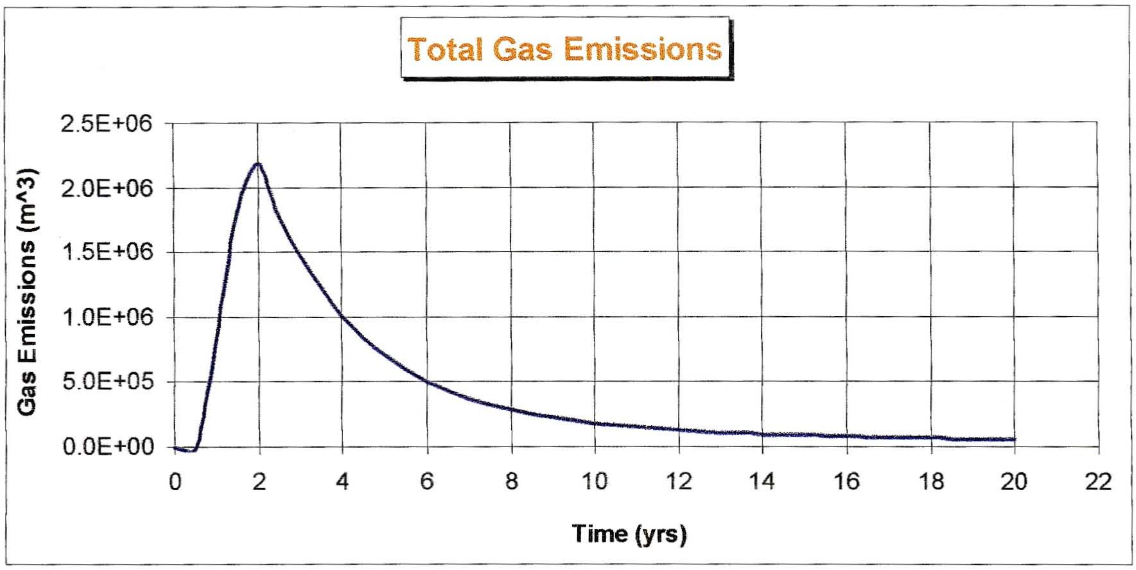


Figure 6 The specific gas production rate

6. SUMMARY

This programmed model allows the landfill manager to predict, in a relatively quick and simple way, the emissions from a landfill cell or a landfill as a whole. Although many of inputs required by the model have to be estimated, the simplicity of the program allows the user to run the model several times with different values for the input parameters. In this way, the user may run the model using a range of possible parameter values, thereby obtaining the maximum and minimum expected emissions i.e. an emissions envelope. This would then inform the landfill manager as to the possible risks associated with the biogas emissions. If the model reveals potentially harmful emission volumes, the manager could then apply the model with a more detailed analysis of the waste stream and waste characteristics, providing an accurate estimation of the biogas emissions.

The manager can then decide which gas control measure is required (e.g. gas extraction, passive venting). In the cases where gas extraction is necessary, the predicted gas emissions may be used to size the extraction system.

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APPENDIX E

Appendix E1 – Results of the Surface Emissions Analysis Using the Test Bed

Table E1.1 Results of the eleven SAC sampling runs

Date	14 September 2001	**dc/dt**	0.875 ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	313.4 mg/min.m^2

Time step	Conc of CO_2 in SAC (% vol/vol)	Conc of CO_2 in SAC (ml/l)
0	0.225	2.25
1	0	0
2	0.252	2.52
4	0.859	8.59
8	0.176	1.76
16	0.066	0.66
32	3.532	35.32

SAC sampling run two

Date	14 September 2001	**dc/dt**	0.141 ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	50.52 mg/min.m^2

Time step	Conc of CO_2 in SAC (%)	Conc of CO_2 in SAC (ml/l)
0	0	0
1	0	0
2	0	0
4	0	0
8	0.185	1.85
16	0.06	0.6
32	0.525	5.25

SAC sampling run three

Date	26 September 2001	**dc/dt**	0.684 ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	245.12 mg/min.m^2

Time step	Conc of CO_2 in SAC (%)	Conc of CO_2 in SAC (ml/l)
0	0.182	1.82
1	0.059	0.59
2	0.137	1.37
4	0.128	1.28
8	0.479	4.79
16	1.261	12.61
32	2.142	21.42

SAC sampling run four

Date	26 September 2001	**dc/dt**	0.7924 ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	283.89 mg/min.m^2

Time step	Conc of CO$_2$ in SAC (%)	Conc of CO$_2$ in SAC (ml/l)
0	0.086	0.86
1	0.249	2.49
2	0.304	3.04
4	0.326	3.26
8	0.226	2.26
16	2.228	22.28
32	2.142	21.42

SAC sampling run five

Date	4 October 2001	**dc/dt**	0.698ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	250.07 mg/min.m^2

Time step	Conc of CO$_2$ in SAC (%)	Conc of CO$_2$ in SAC (ml/l)
0	0.198	1.98
1	0.125	1.25
2	0.416	4.16
4	0.191	1.91
8	0.099	0.99
16	0.055	0.55
32	2.873	28.73

SAC sampling run six

Date	4 October 2001	**dc/dt**	0.698ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	72.37 mg/min.m^2

Time step	Conc of CO$_2$ in SAC (%)	Conc of CO$_2$ in SAC (ml/l)
0	0.091	0.91
1	0.39	3.9
2	0.05	0.5
4	0.058	0.58
8	0.072	0.72
16	0.192	1.92
32	0.844	8.44

SAC sampling run seven

Date	26 October 2001	**dc/dt**	0.267ml.l^{-1}
Actual flux	2498 mg/min.m^2	**Measured flux**	95.66 mg/min.m^2

Time step	**Conc of CO$_2$ in SAC (%)**	**Conc of CO$_2$ in SAC (ml/l)**
0	0.042	0.42
1	0.051	0.51
2	0.082	0.82
4	0.138	1.38
8	0.189	1.89
16	0.04	0.4
32	1.048	10.48

SAC sampling run eight

Date	6 September 2001	**dc/dt**	0.0571 ml.l^{-1}
Actual flux	6243 mg/min.m^2	**Measured flux**	20.46 mg/min.m^2

Time step	**Conc of CO$_2$ in SAC (%)**	**Conc of CO$_2$ in SAC (ml/l)**
0	0.06	0.6
1	0	0
2	0.158	1.58
4	0.324	3.24
8	0	0
16	0.197	1.97
32	0.28	2.8

SAC sampling run nine

Date	6 September 2001	**dc/dt**	0.3401 ml.l^{-1}
Actual flux	6243 mg/min.m^2	**Measured flux**	121.85 mg/min.m^2

Time step	**Conc of CO$_2$ in SAC (%)**	**Conc of CO$_2$ in SAC (ml/l)**
0	0	0
1	0.065	0.65
2	0.12	1.2
4	0	0
8	0.412	4.12
16	0.506	5.06
32	1.103	11.03

SAC sampling run ten

Date	7 September 2001	**dc/dt**	0.893 $ml.l^{-1}$
Actual flux	6243 $mg/min.m^2$	**Measured flux**	319.93 $mg/min.m^2$

Time step	Conc of CO_2 in SAC (%)	Conc of CO_2 in SAC (ml/l)
0	0.84	0.84
1	15.77	15.77
2	0.82	0.82
4	0.89	0.89
8	0.91	0.91
16	16.37	16.37
32	32.31	32.31

SAC sampling run eleven

Date	4 October 2001	**dc/dt**	0.2018 $ml.l^{-1}$
Actual flux	6243 $mg/min.m^2$	**Measured flux**	72.30 $mg/min.m^2$

Time step	Conc of CO_2 in SAC (%)	Conc of CO_2 in SAC (ml/l)
0	0.091	0.91
1	0.39	3.9
2	0.05	0.5
4	0.058	0.58
8	0.072	0.72
16	0.192	1.92
32	0.844	8.44

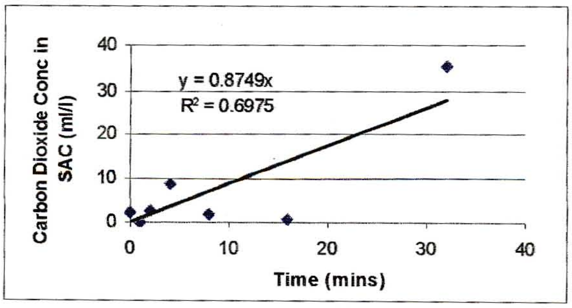

Figure F1.1(a) Concentration profile of CO_2 in SAC for the first sampling run

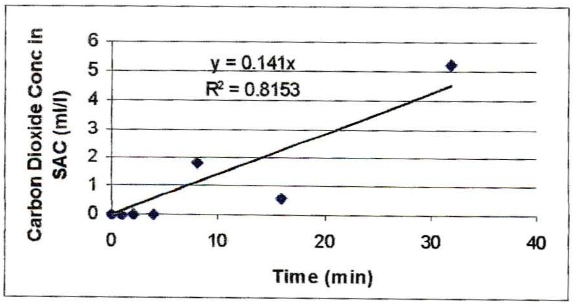

Figure F1.1(b) Concentration profile of CO_2 in SAC for the second sampling run

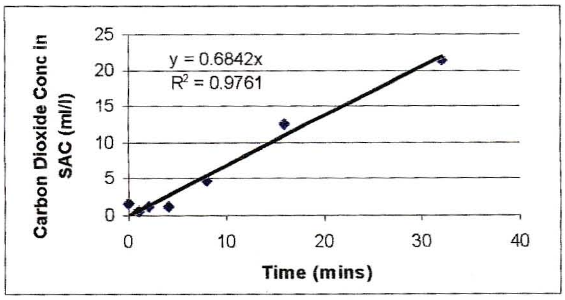

Figure F1.3 (C) Concentration profile of CO_2 in SAC for the third sampling run

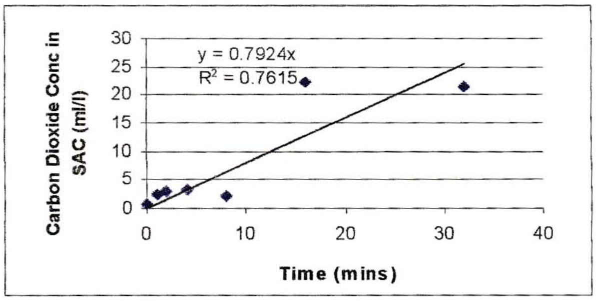

Figure F1.1(d) Concentration profile of CO_2 in SAC for the fourth sampling run

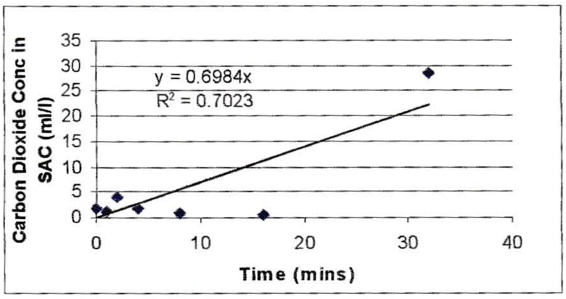

Figure F1.1(d) Concentration profile of CO_2 in SAC for the fifth sampling run

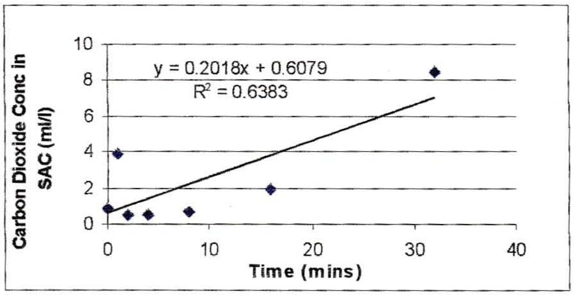

Figure F1.1(e) Concentration profile of CO_2 in SAC for the sixth sampling run

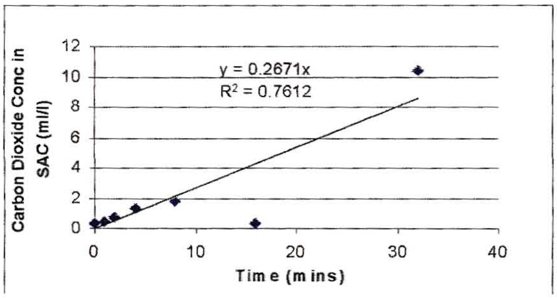

Figure F1.1(f) Concentration profile of CO_2 in SAC for the seventh sampling run

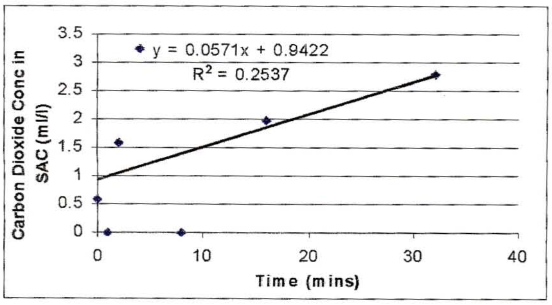

Figure F1.1(g) Concentration profile of CO_2 in SAC for the eighth sampling run

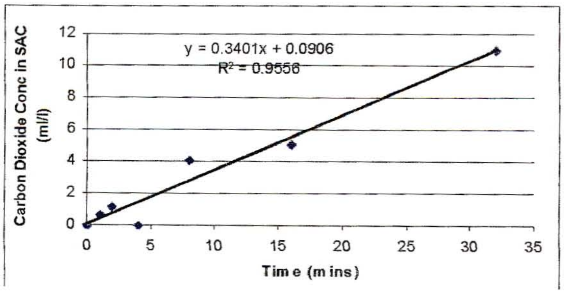

Figure F1.1(h) Concentration profile of CO_2 in SAC for the ninth sampling run

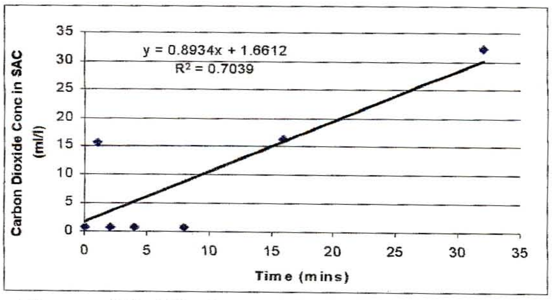

Figure F1.1(i) Concentration profile of CO_2 in SAC for the tenth sampling run

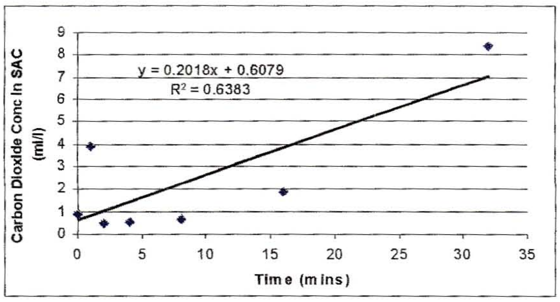

Figure F1.1(k) Concentration profile of CO_2 in SAC for the eleventh sampling run