The Controlled Landfill Bioreactor: A Sustainable Waste Management Option for the 21st Century ?

The Mid Auchencarroch Experimental Landfill

A thesis submitted in fulfilment of
the requirements for the degree of
Doctor of Philosophy

Crispin Wingfield-Hayes
Water and Environmental Management Unit
Department of Civil Engineering

December 1997

THE UNIVERSITY OF STRATHCLYDE IN GLASGOW

THESIS
CONTAINS
CD/DVD

Declaration of Author's Copyright

Disclaimer

With reference to the experimental work reported in the latter part of this thesis, the opinions expressed are those of the author alone, and do not necessarily represent the views of the Environment Agency, the British Government or EnviroCentre Ltd.

Environmental data on the production of this thesis

The original bound copies of this thesis are printed on *Repeat Laser* paper, made in Scotland from 100% de-inked post-consumer waste. During manufacture, oxygen is used as the bleaching agent, and no optical brightening agents are added. The paper cannot be classified as Elementally, or Totally Chlorine Free as the chlorine status of the recycled feedstock cannot be guaranteed.

Information about the environmental credentials of the printing medium was not forthcoming from Hewlett-Packard.

The document is printed on one side of the paper only, in accordance with University Regulation 20.4.7, which specifically precludes text being printed on both sides.

The appendix to this thesis is presented in software format. The alternative, submission of a large amount of experimental data in print, would otherwise occupy many hundred sheets of paper.

DEDICATION

This thesis is dedicated to the memory of my dear mum, Henrietta.

ACKNOWLEDGEMENTS

The author's involvement with this research, and indeed with this degree, would not have occurred without the leadership and guidance of Professor George Fleming; and the author is indebted to him for this. My sincere thanks go to Professor Fleming for the feedback and advice that arises from his intense interest in this field, and for the training which he has provided during his supervision.

The author would like to thank Dr David Buchanan for his supervision during this period of study, and in particular his helpful advice on the processing of data, hydrological aspects of landfill, and assistance on preparation of the software appendix.

The experimental work described in this thesis, was facilitated by a research contract won by EnviroCentre Ltd. The author worked as part of a team with EnviroCentre staff, and in particular with Claire Keenan during the initial part of the project, and with Dave Cooke during the latter part. Sitework during the monitoring and maintenance phase was carried out mainly with Duar Fleming and Liam Macrae.

The experimental work was funded by a number of bodies; the Department of the Environment, the Department of Trade and Industry, G & A Munn & Son (Landfill) Ltd, the Scottish Office, the National Rivers Authority and subsequently the Environment Agency. Louise de Rome at ETSU managed the project for the funding partners.

George and Agnes Munn, owners and operators of the landfill site, were key partners in enabling the research project. They also provided warm hospitality and welcome hot meals during site visits. The staff on the landfill site also made a major contribution to the construction of the experimental facility.

Many of the staff of the Department of Civil Engineering have played an important supporting role in accomplishing this research; from advice on interpretation of results, to fabrication of apparatus.

Characterisation of the three waste streams used in the experimental work was carried out with student Vicky McSherry of the Department of Geography, University of Strathclyde.

The author would like to express many thanks to all the above.

This period of study was funded through a Bicentenary Studentship from the University of Strathclyde. EnviroCentre Ltd were the commercial sponsors of the studentship. The author would like to express genuine gratitude to both these bodies for enabling him to conduct this work.

The author would also like to specifically thank the Environment Agency for funding conference attendance to present this work.

ABSTRACT

In the twilight of the 20th Century, it has been realised that development cannot continue in an unsustainable manner. The way that resources are utilised within society plays an important role in Sustainable Development.

Waste Management is the discipline that deals with the material resources when society no longer has a use for them. Sustainable waste management regenerates resources from waste, because disposal of these resources is not sustainable.

However, the reality is that disposal to landfill will be the fate of the majority of waste for the foreseeable future, in the UK and many parts of the world. Therefore, the development of techniques to reduce the disbenefits of disposal to landfill are justified.

The experimental work in this thesis describes research into methods of bringing disposal to landfill closer to the principles of sustainability.

The Mid Auchencarroch Experimental Landfill is a field scale facility, constructed in order to assess a number of techniques that promote moves towards more sustainable landfill. The experiment centres on municipal solid waste in a enhanced bioreactor mode of landfill operation. The techniques evaluated are; pretreatment of waste, leachate recirculation and co-disposal with inert material. Results from the first two years of monitoring show that a combination of manipulations could move the process of landfill very much closer to the goals of sustainability, achieving in just over one generation what it may take several hundred years to achieve in conventional landfill.

Keywords: landfill, bioreactor, sustainable, waste management, methane

Concise Table Of Contents

DETAILED TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

How Society can develop in a sustainable manner is one of the key questions in the twilight of the 20th Century. The principles of Sustainable Development are now widely accepted, if not acted upon. Their scope influences all aspects of human activity.

In its crudest form, Sustainable Development is about considering the long term. Sustainable Development requires a change, an evolution in the way society operates. The flow of resources is one of the key fields in which our material hungry society is unsustainable. Waste management is the discipline that is concerned with resources once society no longer requires them.

The fate of most of these unwanted resources is disposal. In the UK, disposal to landfill is still the most prevalent method; 70% of controlled waste and 90% of household waste is landfilled (Great Britain, 1996a). In Scotland, landfill is especially dominant, being the fate of 96.5% of controlled wastes (Great Britain. Scottish Office, 1996).

The government is committed to reducing the amount of controlled waste going to landfill from 70% to 60% by 2005 (Great Britain, 1996b). It aims to achieve this by series of measures including encouraging recycling, and taxing the disposal of waste to landfill. However, landfill will remain a vital part of the UK waste strategy, indeed the government states that "At present it is not possible to foresee circumstances in which landfill will ever become unnecessary." It adds "The volumes of waste going to landfill are likely to remain large for years to come." (Great Britain. DoE / WO, 1995)

Thus the issue arises that if landfill is to continue as a waste management practice, techniques of operation need to be developed that mitigate the environmental disbenefits associated with it, and enhance the process of biochemical stabilisation so that a legacy is not left for future generations.

1.2 Research Objectives

This research aims to assess what level of control can be exercised over the landfill process and determine the contribution that this could make to sustainable development. The specific objectives of the study are:

- Investigate the concept of 'sustainable waste management'.
- Establish the parameters in which landfill may be sustainable.
- Place landfill within the context of other waste management options.
- Determine the efficacy of a number of waste manipulation techniques in moving landfill towards sustainability.
- Show that shallow landfill is suitable for operation as a controlled bioreactor.
- Develop and utilise 'appropriate technology' for methods of operating a landfill as a controlled bioreactor.
- Determine whether the controlled landfill bioreactor *is* a sustainable waste management option for the 21st Century.

1.3 Scope

The experimental work contained herein is essentially about manipulating the landfill environment. Therefore, many issues that are important to the operation of commercial landfill, from regulation to containment engineering, are not addressed, unless they have a particular bearing on the question of sustainable landfill.

The part of the literature review that directly supports the experimental work reflects this limitation on the scope of the work.

1.4 A Priori Assumptions of Experimental Work

1.4.1 Feasibility of Shallow Landfill

Landfill has traditionally followed mineral extraction. The motivation was largely due to the post-war pressures of food production. Landfill was an integral part of the process of restoration of quarry voids to agricultural land (Harris,RC 1992).

Thermal Loss

Due to the size and depth of a quarry void, the landfilled body of waste is massive, and hence the surface area to volume ratio is low. The size of the wastemass and its surface area to volume ratio are both key factors for thermal loss from the wastemass. The significance of thermal loss is that the rate of degradation - microbial activity - is controlled by temperature. Thermal loss has not been considered a problem in conventional landfill, as typically the landfilled wastemass has been able to maintain a temperature significantly above ambient conditions.

The supply of quarry voids has diminished in many areas of high population. However these are the major locations for production of waste. This situation has been created by the geographical mismatch between mineral use and mineral source (Great Britain. DoE, 1994a). It is therefore accepted that above ground landfill, also known as landraise, is going to become more widespread (Harris,RC 1992). For aesthetic reasons, landraise is typically shallower than conventional landfill. The wastemass is more exposed and shallower, and so thermal loss becomes significant.

In 'small scale shallow landfill' thermal loss is be more significant as the wastemass is a even smaller. Nevertheless, small scale shallow landfill is a technique widespread in rural areas; for example, in Scotland 55% of licensed landfills have less than 5000 tonnes annual input (Great Britain. Scottish Office, 1996). It is also potentially a technique that is transferable to the developing world.

Permeability of Wastemass

Though there are potentially significant disadvantages of a thin wastemass, there are significant advantages. Perhaps the most important of these, in terms of creating a 'sustainable landfill', is permeability. The lower layers of a deep landfill have been shown to have a permeability similar to the containment system (Beaven and Powrie, 1995). Yet, to flush pollutants from the wastemass requires liquid to be passed through the wastemass at a rate that is higher than these low permeabilities allow. Thus, shallow landfill is proposed as a more suitable model on which to create a 'sustainable landfill'.

To summarise; shallow landfill is widespread. It is set to become more prevalent for reasons of planning and geology. However the question of feasibility remains, as thermal loss may allow the temperature of the wastemass to reduce, to the extent that methanogenic activity is insignificant.

A Priori Assumption 1

Shallow landfill of municipal solid waste is feasible in terms of establishing and maintaining a suitable environment for methanogenic degradation to occur at significant rates.

1.4.2 Control over Landfill Processes

As a result of the Rio Declaration on Environment and Development, the government produced plans on sustainable waste management, with a stated aim being to "promote more sustainable landfill techniques" (Great Britain. DoE/WO, 1995). One of the key principles of sustainability is that the activity of the present generation should not be detrimental to the development and environment of future generations (UNCED, 1992).

Within the context of the waste management industry, this is interpreted as landfilled waste stabilising to *final stage quality* in a period of 30 years (Harris, Knox and Walker, 1994). This is a considerably shorter time than the several hundred years that might usually be associated with landfill (Knox,K 1990). The *flushing bioreactor* has been put forward by the Government and leading environmental consultants (Great Britain. DoE, 1995b)[1] as the method of achieving this aim. The experimental element of this project, partly funded by the Government, is a test bed for the flushing bioreactor and its control as an enhanced degradation system.

A Priori Assumption 2

It is possible to control and enhance landfill gas production, and flush potential pollutants from the wastemass, by manipulating the whole process of landfill.

A Priori Assumption 3

It is possible to expedite the degradation, stabilisation and flushing of the wastemass, to the extent that final stage quality is achieved within a 30 year timeframe.

---

[1] Prepared for DoE by Aspinwall & Co Ltd, Shrewsbury, SY4 2HH

1.4.3 Experimental Treatments

In a recent review of landfill microbiology research (Archer, Reynolds and Blakey, 1995), it was made evident that, although much landfill research had been conducted in laboratory lysimeters, they do not approximate well to conditions in the field.

This project aims to bridge the gap between laboratory lysimeters and full scale commercial landfill. It attempts to achieve this by the use of field scale experimental cells. Each cell contains nearly 4000 tonnes of waste compared with the few kilograms usually associated with laboratory lysimeters. Each cell is a small containment landfill, which has been designed and constructed with monitoring and control as prime requirements.

The project deals exclusively with municipal solid waste (MSW) and inert waste. It does not attempt to address the specific problems associated with commercial, industrial, special, or hazardous wastes.

Three manipulations of the landfill process have been adopted:

- Manipulation of waste input: Co-disposal of inert waste with MSW
- Manipulation of waste prior to landfill by processing: Pretreatment
- Manipulation of landfill environment after capping: Recirculation of leachate

These manipulations were appropriate in terms of the state of landfill technology, and the prevailing political climate. Four experimental cells were used to examine the effects of a combination of these three treatments.

1.5 Structure of Thesis

Chapter 1 introduces the field in which the study has been made. It has established the objectives, scope and a priori assumptions of the research.

Chapter 2 opens the discussion about Sustainable Development. It discusses the historical precedent and how it developed into the principles that we know today. The chapter goes on to discuss how the issue of sustainability is being dealt with today, with reference mainly to measures being taken in the UK and EU. The relevance of waste management in terms of resource utilisation and climate change is established.

Chapter 3 continues with the theme of sustainability, looking at the Cycle of Resources in Society, and how product design and material selection have an immensely significant role to play in enabling the waste management industry to recycle rather than dispose. Methods of comparing materials and manufacturing processes on grounds of environmental cost are discussed, together with case study of PVC as a material.

Chapter 4 considers the various waste management options and their relative benefits. In addition to main stream techniques, some of the more obscure and promising techniques are discussed.

Chapter 5 examines the technology of landfill and anaerobic degradation, together with the pretreatment of waste. In a review of landfill test cell projects, recent work and experiences relevant to this research are detailed.

Chapter 6 describes the concepts surrounding the experimental landfill, the design considerations and the methodology used to establish the experiment. It also contains a description of the waste streams used in the experiment.

Chapter 7 describes the construction of the experimental test cells.

Chapter 8 contains the methodology of monitoring the experiment, and descriptions of various trials that have been conducted on the landfill test cells.

Chapter 9 presents the data collected to date and discusses the primary analysis that has been conducted.

Chapter 10 presents and discusses secondary analysis of data, considering water balance, quality of gas flow data, mass carbon balance and the progress to stabilisation of the wastemass.

Chapter 11 contains conclusions and recommendations emanating from the research.

Glossary. A glossary of terms is provided to assist in this multi-disciplinary field.

Software Appendix. The appendix for this work is submitted on CD-ROM. An explanation of the contents, and methods of use are provided.

2 SUSTAINABILITY

sustain, *vt* to hold up; to bear; to support, to provide for, to maintain, to sanction, to keep going; to keep up, to support life of; to prolong. - *n* **sustainability**

Source: Chambers Concise Dictionary, 1991

2.1 Historical Background

Sustainability is not a new concept, ancient cultures survived because, by definition, they lived in a sustainable manner. Those that utilised their food, water and fuel resources in a unsustainable way usually perished. Of course war and disease also played their part in the success of a society, but in the long term the use of resources was definitive. For example; five millennia ago, Ur of Chaldees had grown to be the greatest city in the world (Pearce,F 1992). Resting between the Tigris and the Euphrates, in modern day Iraq, it used the resource of these great rivers to bring to life the parched desert and support the cradle of western civilisation. Around four millennia ago, the civilisation was failing, not through war or disease, but through salination of agricultural land - a result of unsustainable irrigation practices. Eventually their society expired.

In the recent history of our own society, rapid development has been achieved by industrialisation during the last few centuries. This development is questionable in terms of sustainability, as for example global warming is now proving. Its pace was only possible by borrowing from the past, in terms of resource, and from the future in terms of the legacy of environmental pollution.

Even before the era known as the Industrial Revolution, there were indications that our culture did not consider the use of our resources in the context of the future. A good example of this was the felling of a large part of the oak forests of England for naval shipbuilding during the Middle Ages. This was perhaps the first major denudation of the environment in Britain that was for 'industrial' purposes, rather than subsistence.

The majority of citizens that experienced the first round of industrialisation, which has now become the developed world, were happy with the material prosperity and security that it provided. There were some, however, who questioned the cost of this method of development. Those that did, tended to be labelled in pejorative terms by the majority; at best slightly cranky and at worst subversive.

One example of such a group which was set up in Britain in the 1940's to give focus to these doubts was the Soil Association. It was established by a disparate group, from agricultural to medical backgrounds, that were concerned about the disbenefits of intensifying food production. The editorial in the first issue of the Soil Association's journal in 1946 read "People have begun to see life on this planet as a whole, and Nature's plan as a complicated system of interdependence rather than one based on competition. As an outcome of this interpretation of Natural law, they share the belief that the only salvation for mankind lies in substituting co-operation for exploitation in all human activities from soil treatment to industrial and international relations..."(Soil Association, 1946). The key phrase is 'substituting co-operation for exploitation'.

Emanating from the free thinking 1960's, came pressure groups orientated towards environmental protection, such as Friends of the Earth. Some of these groups had policies of non-violent direct action which although it brought them publicity for their causes, also tended to get them labelled as extremists. The campaign by Greenpeace against dumping nuclear waste at sea is a case in point.

However, in the last two decades, public opinion has moved towards much of what these pioneering organisations were advocating. Indeed, now the dumping at sea of comparitively innocuous materials such as sewage sludge, let alone nuclear material, is being outlawed.

This movement in public opinion was driven by such factors as the effects of acid rain, the contamination of marine life, the disaster at Chernobyl, and human health problems due to deteriorating urban air quality. There was also a growing realisation amongst policymakers, based on information supplied by the scientific community, that industrial and economic development as they knew it, was incompatible with a sustainable environment on Earth. The evidence of global warming and of ozone depletion were probably the most powerful arguments for change.

In the 1980s politicians throughout the world realised their people were demanding that protection of the environment, as well as economic growth, be made a priority. This led in turn to business undergoing a paradigm shift in recent years. No longer is the environment considered a business constraint, it is now an opportunity for innovation and competitive advantage (Design Council, 1997).

2.2 Sustainable Development

Sustainable Development attempts to reconcile two objectives of human society:

- economic prosperity and security
- protection of the environment

In June 1992, the countries of the world came together to discuss these problems at the United Nations Conference on Environment and Development, held in Rio de Janeiro(UNCED, 1992). Out of much talking and many fine sentiments *did* come an agreement that has proved to be the basis and the focus from which real moves to sustainable development are being made.

2.2.1 The Rio Declaration on Environment and Development

The Rio Declaration on Environment and Development was a statement of 27 principles agreed by the participants. The principles cover a broad range and include poverty, warfare, the role of women, of youth and of indigenous peoples.

Some of the key principles of interest are:

> "**Principle 3.** The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations".

Principle 3 is perhaps the most definitive and fundamental statement of the declaration. From this principle, comes the more detailed expansion of actual criteria to assess sustainability. This is discussed later.

> "**Principle 8.** To achieve sustainable development and a higher quality of life for all people, States should reduce and eliminate unsustainable patterns of production and consumption and promote appropriate demographic policies"

There is less public awareness of this Principle than of Principle 3. It does however state the crux of sustainable development - that unsustainable practices should be discontinued. It does not acknowledge a time frame for either the pace of elimination of unsustainable practices or over what period the sustainability of a process should be considered. Principle 3 implicitly states the period of one generation for both.

> "**Principle 14.** States should effectively co-operate to discourage or prevent the relocation and transfer to other States of any activities and substance that cause severe environmental degradation or are found to be harmful to human health". The principle of Proximity.

> "**Principle 15.** In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full

scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". The Precautionary principle.

"**Principle 16.** National authorities should endeavour to promote the internalization of environmental costs and the use of economic instruments, taking into account the approach that the polluter should, in principle, bear the cost of pollution, with due regard to the public interest and without distorting international trade and investment." The Polluter Pays principle.

Apart from recognising the necessity for protection of the environment, the declaration also recognises that the alleviation of poverty is an "indispensable requirement for sustainable development".

There has been some media comment on the difference of approach between the countries of the North and the South - the developed and developing worlds. Blowers (1992) states that the Northern rich countries stress the need for environmental conservation through population restraint, cuts in consumption and protection of resources, while the poor South, pointing to the disproportionate share of resource consumption and pollution produced by the North, advocate a transfer of aid and technology from the rich to enable them to achieve a more sustainable development.

There is some evidence of this even within the slightly dubious wording of some of the stated principles, for instance, Principle 6.

Principle 6. The special situation and needs of developing countries, particularly the least developed and those environmentally vulnerable, shall be given special priority. International actions in the field of environmental and development should also address the interests and needs of all countries.

The second sentence appears to mollify the first, to the extent that any priority for developing countries no longer exists.

2.2.2 Agenda 21: Programme of Action For Sustainable Development

The other major piece of work to emerge from the Rio Summit was Agenda 21. This was divided into four sections:

1. Social and Economic Dimensions
2. Conservation and Management of Resources for Development
3. Strengthening the Role of Major Groups
4. Means of Implementation

Agenda 21 was a paradigm for each and every country to create a Programme for Action for Sustainable Development on a national basis, a regional and local basis.

Particular elements of Agenda 21 that relate to waste are discussed in subsequent sections.

2.2.3 The Climate Change Convention

Immediately prior to the Rio Summit, in May 1992, the United Nations produced the Framework Convention on Climate Change (United Nations, 1993; Great Britain, 1994). Essentially this was a framework working towards controlling 'greenhouse gases' but it also built on the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. The Framework was signed by many countries while attending the Rio Summit.

2.3 The EU Strategy

The European Union strategy, post Rio, is centred around its Fifth Environmental Action Programme entitled "Towards Sustainability, the European Community Programme of policy and action in relation to the environment and sustainable development" (European Communities. Commission, 1993). It was agreed in February 1993.

The programme considers that the features of sustainability are:

- to maintain the overall quality of life
- to maintain continuing access to natural resources
- to avoid lasting environmental damage
- to consider as sustainable a development which meets the needs of the present without compromising the ability of future generations to meet their own needs

Seven 'themes and targets' are established within the strategy as follows:

Climate change
Acidification and air quality
Urban environment
Coastal zones
Waste management
Management of water resources
Protection of nature and bio-diversity

Waste management is specified as one of these seven themes, but also has a significant role in another theme, Climate Change. The relevance of climate change to waste management is discussed in Section 2.4.1.

The Fifth Environmental Action Programme contains a wide range of instruments:

- Legislation to set environmental standards
- Economic instruments to encourage the production and use of environmentally friendly products and processes
- Horizontal support measures (information, education, research)
- Financial support measures (funds)

Of the instruments, the financial mechanisms are potentially one of the most powerful. However, details of the associated programme show it is orientated towards grant-based *funding*, to promote various sectors and there seems little emphasis of revenue generating financial instruments.

In the 1996 Progress Report on the Fifth Environmental Action Plan (European Communities. Commission, 1996c), this specific problem is recognised. It states "market-based instruments are seen as the most important group of tools available for future action. Despite this there has been very little progress on the development of market-based instruments at EU level despite successful experience of some Member States."

The European Environment Agency, one of whose roles is to the provision of timely and targeted information was asked by the European Parliament in early 1996 to produce a report on "green taxes". The report 'Environmental Taxes Implementation and Environmental Effectiveness' (European Environment Agency, 1996) recommends the wider use of both non-energy and energy taxes. It says that most of the barriers to implementation, both perceived and real, can be overcome by careful design, gradual enforcement and extensive consultation with stakeholders.

Part of the report is a study of 16 environmental taxes. Particularly effective taxes include those on sulphur dioxide and nitrogen dioxide in Sweden, and toxic waste in Germany. The latter tax reduced toxic waste production by at least 15% in 2-3 years. This had the further effect that planned capacities for incineration were reduced as well. The report concludes that the taxes are environmentally effective and are achieved at resonable administrative cost.

There is an increased scope for use of environmental taxes and if they are well designed, they could deliver improvements in four key areas of public policy:

- the environment
- innovation and competitiveness
- employment
- the tax system

The OECD has also produced a number of reports on the subject (OECD, 1991; 1995). They have conducted detailed studies on the effects of energy taxation.

'Green' taxes are part of a wider shift in taxation, away from employment and commerce (which are to be encouraged), towards materials, energy and consumption (which are to be discouraged). According to the British Government Panel on Sustainable Development (Great Britain, 1995) "Currently we tend to tax people on the value they add rather than the value they subtract". This change in the philosophy of taxation is in harmony with the Rio Principles of alleviating poverty, and encouraging economic prosperity while making patterns of production sustainable and forcing the polluter to pay.

2.4 The UK Strategy

Sustainable Development: The UK Strategy (Great Britain, 1994b) , published in January 1994, was the British Government's response to the Earth Summit at Rio. In it, is set out the issues that affect Britain and how the government will achieve the targets set at the Earth Summit. In addition to Agenda 21 and the Convention on Climate Change, it also addresses the Biodiversity Convention and the Statement of Forest Principles, the other two main outcomes from Rio.

In the UK document, the notion that Sustainable Development means having *less* economic development is rejected. In other words, the government position is that economic growth is sustainable, and in fact that a healthy growing economy is essential for Sustainable Development. That growth and sustainable development are necessarily linked is a contentious issue. Many in the Green Movement think not; but mainstream economists condone the growing economy. However, the UK government's own statistics show that inspite of a growth in Gross National Product of 97% between 1961 and 1991, the number of those living in poverty rose from 5.3 million to 11.4 million[1].

The UK Strategy also states that Sustainable Development does not mean that "every aspect of the environment should be preserved". So it appears that the UK government's response to the Rio Summit was that of promoting evolution rather than revolution, in our interaction with the Earth.

A number of areas are covered in the strategy; those that have specific relevance to waste management are:

> **Minerals.** The promotion of more efficient use of the resource and encouraging recycling.

The main promotion technique is likely to be taxation. The Institute of Public Policy Research (Tindale and Holtham, 1996), a leading left-of-centre think tank, has put forward a quarrying tax levied on virgin quarry materials. It also suggests increasing the rate of landfill tax on 'inert' material, which has been shown to be highly effective at increasing recycling of construction waste in Denmark.

These measures should lead to a reduction in the amount of construction and demolition waste being landfilled. In addition if the rate of recycling exceeds the growth of aggregate production, the availability of quarry void for landfill will be reduced.

The landfill tax was introduced on 1st October 1996. However, the time lag in production of Government statistics on waste is typically two years (e.g. Great Britain. Scottish Office, 1996). This does not allow for evidence its effect to be proved as yet.

---

[1] Study by Institute of Fiscal Studies, London, using Central Statistics Office data. Cited by Goldsmith, J 1993

Energy. Recognition that "new and renewable energy technologies have the potential to make a significant contribution to the UK energy supply in the next century."

Power generation from waste, which is classified as renewable by the Government, already plays an significant and growing role in the UK Renewable Energy sector. This is discussed in detail in the subsequent Section 2.4.1.

One of the key aims of the experimental part in this research, is to show that the yield of methane rich gas from landfill can be enhanced and controlled. This is stated in A priori Assumption 2 in the Introduction to this thesis. Achieving this will have two implications in terms of sustainability. Firstly, the length of time that the landfill represents an environmental threat is reduced. Secondly, it improves the quality and usability of this 'renewable' energy resource.

Waste. "Large quantities of waste arise as an undesirable by-product of modern production, packaging and consumption, with threats to soil, air and water quality if the waste is not properly managed." is how the problem of waste is defined. It goes on to say that the "aim must be to minimise the amount of waste produced and to make best use of the waste which is produced. In this way, the loss of valuable raw materials and the land which is required for disposal can both be minimised" which introduces the idea of a hierarchy in the management of wastes. While acknowledging that waste management practice is currently excessively orientated towards waste disposal, it asserts that "truly sustainable choices are complex....in some cases the environmental costs of recycling waste, in terms of energy consumption and emissions, are higher than disposal".

So while the disposal option is over-utilised, it is accepted that it will continue, and in some cases will be the waste management option with the least environmental cost. Therefore, enhancing the process of landfill is an important step towards sustainable waste management.

2.4.1 Climate Change

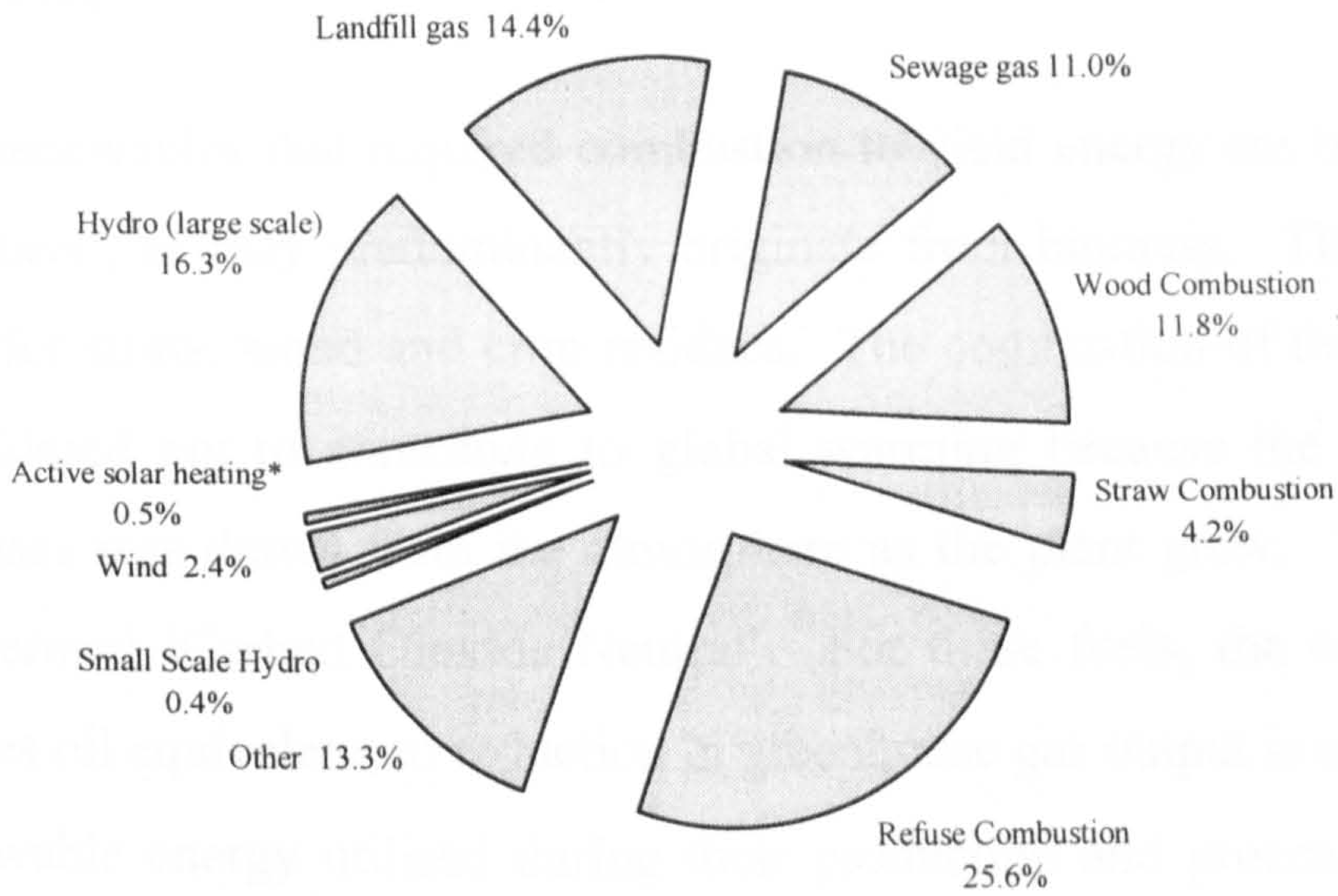
At the same time as the 'UK Strategy' was issued, *Climate Change The UK Programme* (Great Britain, 1994a) was also published. This was the UK's specific response to the Framework Convention on Climate Change.

It considers sources and levels of the major greenhouse gases; carbon dioxide, methane, nitrous oxide, and a number of significant volatile organic compounds and halocarbons. The rates of emission of these gases, on a global basis, is increasing. The general approach is to stabilise and reduce output to 1990 levels by the year 2000.

Carbon Dioxide Emissions

Of the greenhouse gases, carbon dioxide is the most significant, at 87% of the UK 1990 anthropogenic sources. The UK Programme envisaged a cut of 10 million tonnes of carbon (MtC) against projected emissions by 2000. This would be achieved by a combination of measures mainly relying on increased taxation of fuels, and improved energy efficiency. Of the savings, around 0.5 MtC are expected to come from supply side measures in electricity generation by further encouragement of renewables. As a total, renewables will still be making a relatively small contribution to electricity generation - projected at around 3% by 2000. In Scotland alone the situation is more favourable with around 15% of electricity coming from renewables - predominantly hydro.

Figure 2-1 UK Renewable Energy Utilisation, 1996



Notes: 1.'Other' includes farm waste digestion and chicken litter, waste tyres, industrial and hospital waste combustion.
2. * Excludes all passive use of solar energy

Source: DTI; Digest of UK Energy Statistics 1997

The renewables used to generate electricity and heat are shown in the chart above. The total amount of electricity produced from renewables in 1995 was 7.6 TWh

Within the renewables sector, it is recognised that there is little scope for further large scale hydro-power developments. It can be seen that landfill gas makes a significant contribution, though a little less than large scale hydro-power. However, new landfill gas generation capacity is planned, as discussed in the following Section 2.4.2. In the near future it is likely to exceed large scale hydro-power. The combined contribution of landfill gas and refuse combustion is stated as 40% in 1996. With both of these sectors growing, the combined contribution from these solid waste streams is likely to be in excess of 50% in the near future.

Renewables contributed 1.72 million tonnes oil equivalent (Mtoe) in heat and electricity to the UK in 1996 (Great Britain. DTI, 1997b). This means that renewables replaced fossil fuels equivalent to 1.72 Mt of oil, which did not have to be burnt, thus reducing carbon dioxide output.

However, it is essential to be clear that some of this apparent reduction in carbon dioxide is not real:

The renewables that required combustion to yield energy are broadly termed 'biofuels', as they predominantly originate from biomass. This is truly the case for straw, wood and crop residues. The combustion of these biofuels is considered not to contribute to global warming because the carbon in the biomass was drawn from the atmosphere as the plant grew. These biofuels are termed 'Carbon Dioxide Neutral'. For these fuels, the contribution, in tonnes oil equivalent, to reduction in greenhouse gas output is real. (The non-renewable energy utilised during their production and processing not being considered)

The energy yield from the combustion of refuse comes from fossil fuel derived materials, e.g. plastic, *and* from biomass derived materials, e.g. paper. The former element, which accounts for around half of the energy yield, cannot truly be considered a biofuel, and is not carbon dioxide neutral. The contribution of this element to the reduction of carbon dioxide output is therefore not real. The real benefit to Sustainable Development of using this fossil fuel derived element of refuse for energy production, is not reduction of greenhouse gas output, but conservation of the finite mineral resources.

The latter element - biomass derived material - could be considered carbon dioxide neutral. In reality it is likely to be less carbon dioxide neutral than true biofuels, due to the larger amount of processing it has undergone. However, its contribution in terms of reduction of carbon dioxide output must be considered as real.

The source of the materials that produce landfill gas also come from both fossil fuel and biomass derivation. In this case, however, the energy yield predominantly comes from methane which is produced from biomass. The element of the landfill gas that is produced from fossil fuel derived materials may be estimated to be 0 - 5%, and depending on the waste. Therefore landfill gas can be said to be relatively carbon dioxide neutral, and on a par with the biomass derived element of refuse combustion. The contribution that utilisation of landfill gas makes in mitigation of carbon dioxide output is real. This is its major contribution to Sustainable Development. In contrast to refuse combustion, the fossil fuel derived element of waste does not make a contribution to conservation of finite mineral resources, as it remains relatively inert, entombed in the landfill.

Thus to summarise, energy from landfill gas can be considered as truly carbon dioxide neutral, where as energy from refuse combustion can only be considered to be partially carbon dioxide neutral.

Carbon Reservoirs and Sinks

Fixing of carbon dioxide by trees followed by the storage of carbon in wood constitutes an effective reservoir for carbon. The quantity of carbon contained in the four billion hectares of global forest is comparable with that currently in the atmosphere (Great Britain, 1994a).

In the UK the main carbon sinks are the soil and vegetation. The table below shows the importance of peat to the UK.

Table 2.1 UK Carbon Sinks In Soil and Vegetation

Reservoir	Total Carbon (MtC)	Main Components
Soil (including plant litter)	9,500 (range 7,500- 11,500)	4,500 MtC in peat covering about 10% of land area; 5,000 MtC in other soils
Vegetation	110 (range 90-130)	Mostly in woodlands covering 10% of the land

Source: UK Institute of Terrestrial Ecology

Landfilling of waste is not considered as a carbon sink, although de facto it is - for materials that are relatively non-biodegradable in an anaerobic environment. These materials include most plastics and also lignin, the major constituent of wood.

The table below shows the contribution landfill makes as a carbon sink in the UK. It considers the part of the waste stream that may be classified as Municipal Solid Waste (MSW) and similar material.

Table 2.2 Mass of MSW Landfilled Annually

	arisings[1], Mt/yr	% landfilled[2]	mass landfilled, Mt/yr
household	20	90	18
commercial	15	85	13
household & commercial			**31 Mt/yr**

Notes: The figure for household waste arisings includes up to 5 Mt from Civic Amenity sites. The figure for commercial arisings includes around 5 Mt of waste collected from retail shops and small commercial premises by local authorities.

The literature shows (Porteous,J 1997; Beaven and Walker, 1997) that around 35% of the dry mass of waste is Carbon. Experimental measurements (Beaven and Walker, 1997) have recorded that a maximum of around 50% of this Carbon will be evolved from the landfill as gas and in the leachate. The balance will remain in the landfill in the long term and is in effect sequestrated. Therefore around 18% of dry mass of waste, which equates to around 12 % of the wet mass of landfilled waste, is immobilised carbon.

From these calculations, it is shown that landfill adds **3.7 Mt Carbon** every year to the UK carbon sink (at current landfill rates). Thirty years of sequestration in landfill at this rate, provides a carbon sink of the same size as the entire UK vegetation reservoir, as shown in Table 2.1.

---

[1]Table 7.1, page 125 (Great Britain. DoE, 1996b)
[2]Table 7.1, page 105 (Great Britain, 1996a)

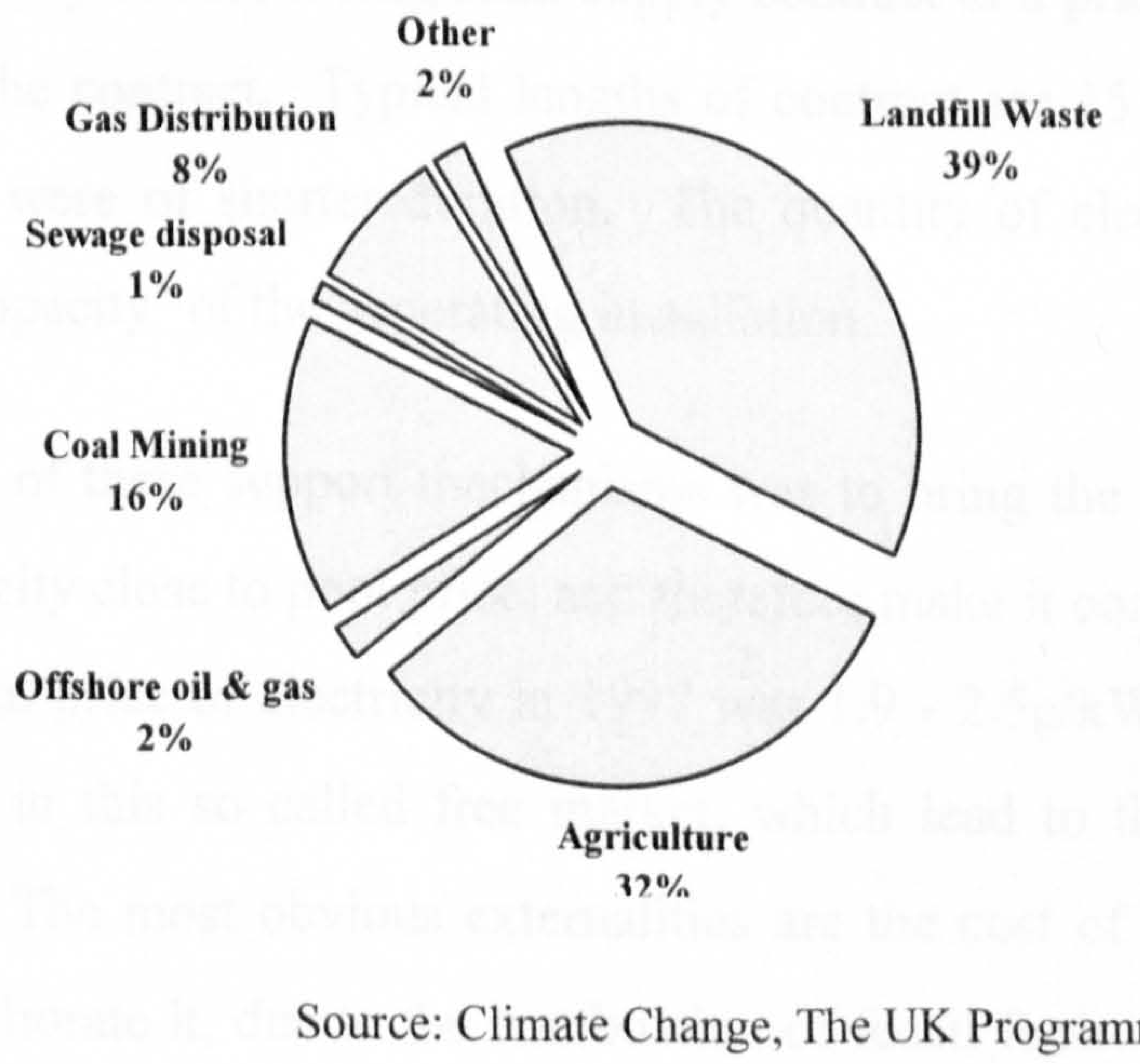
Had incineration been the disposal method for this waste, this quantity of carbon would have been liberated as carbon dioxide.

Methane

Methane is the second most important greenhouse gas, contributing around 8.1 % of the 1990 UK anthropogenic emissions of greenhouse gases (Great Britain, 1994a). Methane is considered to have a Global Warming Potential of 20 -25 times that of carbon dioxide, due to a larger specific radiative force. The situation of UK anthropogenic methane emissions is given below.

It can be seen that methane from landfill is highly significant, and alone accounts for in excess of 3% of the UK's *entire* greenhouse gas output. There have been reductions in methane emissions, mainly from coal mining. This has led to the landfill element of UK methane emissions rising to 46% by 1994, despite total emissions falling from 4.4 Mt to 3.9 Mt (Great Britain, DoE, 1996b). However total methane emissions are continuing to fall, and the latest projections are that by 2000, emissions will be 18% lower than 1990 levels (Great Britain, 1997).

Table 2.3 UK Methane Emissions by Sector in 1990



Source: Climate Change, The UK Programme (Great Britian, 1994a)

The promotion of landfill gas quality and usability, in term of controlling the timeframe over which it is produced, can make an highly positive impact on the feasibility of gas utilisation. Therefore control and enhancement of landfill gas output will directly affect the amount of methane that is allowed to vent to the atmosphere. The techniques that are being developed in the experimental element of this research will help reduce Britain's greenhouse gas output.

2.4.2 The Development of Renewable Energy in Britain

In order to fulfil its commitments, principally on climate change, the UK government created a programme to promote renewable energy generation. It announced in the Coal Review White Paper (Great Britain, 1993b), that it was Government's intention to create 1500 MW of new renewable electricity generating capacity by 2000.

The programme was essentially a system of subsidies, and was entitled the Non-Fossil Fuel Obligation (NFFO) in England and Wales, and the Scottish Renewables Obligation (SRO) in Scotland. Northern Ireland had a programme also (NI-NFFO).

The essence of the programme was that the regional electricity supply companies (RECs) were obliged to buy a certain amount of electricity from renewable sources, which would be at a premium to the pool price. The cost of this obligation is passed on to the customer as the Fossil Fuel Levy. Prospective suppliers of electricity to RECs, competitively bid for a long term supply contract at a price per unit fixed for the duration of the contract. Typical lengths of contract are 15 years, although the first two orders were of shorter duration. The quantity of electricity is based on 'Declared Net Capacity' of the generating installation.

An ultimate aim of these support mechanisms was to bring the price of renewables generated electricity close to pool price, and therefore make it competitive in an open market. The pool price of electricity in 1997 was 1.9 - 2.5p/kWh. However, there are externalities in this so called free market, which lead to the pool price being artificially low. The most obvious externalities are the cost of climate change and measures to ameliorate it, due to the combustion of fossil fuels. Energy and carbon taxes are in part designed to account for these externalities, but they tend to be unpopular with electorates and thus politicians.

The New York based NGO Earth Council estimates that industrialised countries spent US$70-80bn/year on energy subsidies that encourage the use of fossil fuels, while subsidies for all renewable 'clean' sources of energy (such as solar and wind) only amount to US$2bn/year (Financial Times, 1997b). In future years, when some of the externalities fossil-fuels are internalised, the economics will converge.

The first NFFO order was made in 1990, and by 1997 four tranches under NFFO, and two under SRO had been awarded. Prices under NFFO 4 were averaging 3.46p/KWh (ETSU, 1997). This is significantly lower than the previous renewable contracts, for example the NFFO 3 average price was 4.35p/kWh (ETSU, 1995).

By the end of 1996, 192 projects had been commissioned under the UK's renewables obligations (NFFO 1-3, SRO 1, NI-NFFO), with a total Declared Net Capacity (DNC) of 431MW. The details of NFFO 4, are given in the table below.

Table 2.4 NFFO 4 Summary of Technology Split and Price

Technology	Contracted Capacity for NFFO4 MW (DNC)	Number of Projects	Lowest Contracted Price p/kWh	Capacity Weighted Average Price p/kWh	Highest Contracted Price p/kWh
landfill gas	173.7	70	2.8	3.01	3.2
waste-fired combined heat & power ⊗	115.3	10	2.79	3.23	3.4
waste-fired fluidised bed combustion ⊗	126.0	6	2.66	2.75	2.8
small-scale hydro	13.3	31	3.8	4.25	4.4
wind energy >0.768MW	330.4	48	3.11	3.53	3.8
wind energy <0.768MW	10.4	17	4.09	4.57	4.95
anaerobic digestion of agric wastes	6.6	6	5.1	5.17	5.2
biomass, gasification or pyrolysis	67.4	7	5.49	5.51	5.79
Total	843.1	195			

Note: ⊗ includes non-gaseous sewage-matter up to 10% by mass. Source: ETSU, 1997

It is important to stress that the DNC is that contracted, and is not actually commissioned. However NFFO 4 is significantly larger than any of the previous awards, despite the reduced bid prices. This indicates that these technologies are becoming mature. Noticeable by their absence are solar and wave power, whose immature technologies cannot compete in the renewables market, on grounds of cost alone. This is rather unfortunate, and it is to be hoped that future tranches will support these fledgling technologies, which are 'clean'.

In this document, and with reference to energy production, 'clean' may be defined as producing negligible emissions to air, water and land during operational life. This obviously precludes combustion, even with a renewable fuel source.

Large scale wind power is the technology sector with the largest DNC, and the average bid price is rapidly moving towards the pool price. Landfill gas, followed by Waste Combustion take the bulk of the rest of the DNC. These too have prices approaching pool, although in the author's experience waste combustion plants operate in North America at lower prices, equivalent to 2.5p/kWh[1]

Thus it is clear that the technology of *utilisation* of landfill gas has been brought to maturity and operates at close to market costs. This has been achieved under the support of the Renewables Obligation. The next step in the development this energy resource will be in controlling and enhancing *production* of the gas. **The research presented in this thesis focuses on techniques to achieve control and enhancement of production.**

[1] e.g. 25MW incinerator in Ontario, Canada, visited in 1997. Project profile: Peel Resource Recovery Inc., Brampton, Ontario.

2.4.3 Sustainable Use of Soil

The 19th Report of the Royal Commission on Environmental Pollution, titled 'Sustainable Use of Soil' (Great Britain, 1996a) was published in February 1996. It appraises the UK's soil resource, its uses, the actual and potential for degradation of the resource , and sets out a strategy to ensure sustainable use.

The report states that soil is a vital resource, and that policies to protect it should be based on the five principles:

1. Soils must be conserved as an essential part of life-support systems
2. Soils should be accorded the same priority in environmental protection as air or water.
3. An integrated approach to environmental management must include management of land. That will involve not only giving greater protection to high quality soils and rare ecosystems but recycling previously developed land and severely restricting development on green-field sites.
4. Contaminated sites should, wherever practicable, be recovered for beneficial use
5. Further contamination of soils from any source should be avoided, whether localised or diffuse.

The report makes the point that the soil making process is slow and the dynamics are not well understood. Thus with reference to Principle 3 and 15 of the Rio Declaration, if we do not know how fast the resource is generated, we should be precautious about the rate at which we are degrading or loosing it.

Successful techniques for recycling derelict land are becoming well established (Fleming,G 1991), and in general the industrial contamination of yesteryear is no longer permitted. However, even modern landfill techniques can represent a serious hazard to the soil resource. Rowe, Quigley and Booker (1995) maintain that in the long term the soil barriers that form the containment to a landfill *will* fail. It is therefore essential that if pollution of the soil resource is to be avoided, the waste must have reached a non-polluting state before the containment fails.

The Royal Commission recognises this issue and concurs with this opinion. It goes on to endorse a policy of accelerated waste degradation and recommends that the *flushing bioreactor* approach to landfill be promoted.

2.5 The Current Situation

The prospects for global warming do not look good. In a recent study (Financial Times, 1997b), world emissions of carbon dioxide were modelled to increase by 14.5% during the decade 1990-2000, and 19.9% in the subsequent decade.

Five years on from Rio, a follow up to the Earth Summit has just been held in Kyoto, Japan. In the run up to this there have been bitter recriminations about broken promises of the Rio Summit. In particular the United States has been widely criticised for blocking specific pollution targets for greenhouse gases. Officially it claims that the reason it is blocking the proposals is that it wants targets that are legally binding and a climate change treaty that includes developing countries (Financial Times, 1997a). The problem as America sees it, is that developing countries in Latin America and Asia, and in particular China, are projected to have rapidly rising greenhouse gas outputs, which need to be controlled. However, many developing countries feel that legally binding targets would hinder their development (which will no doubt emulate the "west's" unsustainable path to industrialisation), and want aid promised at the Rio Summit in order to offset the adverse economic effects.

Though differences looked insurmountable, an agreement was reached at the Kyoto summit, after long and difficult negotiations. In the final agreement the USA agreed to a 7% cut from 1990 levels by 2012, the EU an 8% cut, and Japan a 6% cut. These cuts are lower than those already agreed at Rio, and are over a longer time frame. Many commentators and environmental bodies have said that the agreement will amount to no cut, due to the loopholes created by the USA insisting on the ability to trade pollution quotas. Further, the agreement is unlikely to be ratified by the US Senate, because emission cuts have not been imposed on developing countries like China. The USA generates around 25% of the world's greenhouse gases, and without it on board, the agreement will effectively be meaningless.

2.6 Summary

From the perspective of sustainability, the management of waste has four key implications:

1. efficient use of finite material resources by reuse and recycling
2. reduction of carbon dioxide production by use as a 'renewable' energy source, therefore displacing fossil fuel use
3. utilisation of biogas from landfilled waste (and anaerobic digestion) to reduce the anthropogenic methane output
4. all disposal options leave an environmental legacy for subsequent generations (with current practice)

For these reasons the way in which we create and deal with waste is at the core of a sustainable society.

3 Resources and Products in Society

3.1 Introduction

Resources are used to create products that society utilises. The resources that we are considering are material resources rather than pure energy resources, although there may be an intrinsic energy content of the materials and the materials will have had energy input during acquisition and processing.

3.2 The Cycle of Resources in Society

In the broader picture, Waste Management is about *The Cycle of Resources Within Society.* Waste Management covers the section of the Cycle in which the resource is no longer of use to resource holder. Figure 3-1 shows a conceptual diagram of the Cycle.

The diagram shows that the **status** of a material resource falls in to one of three categories:

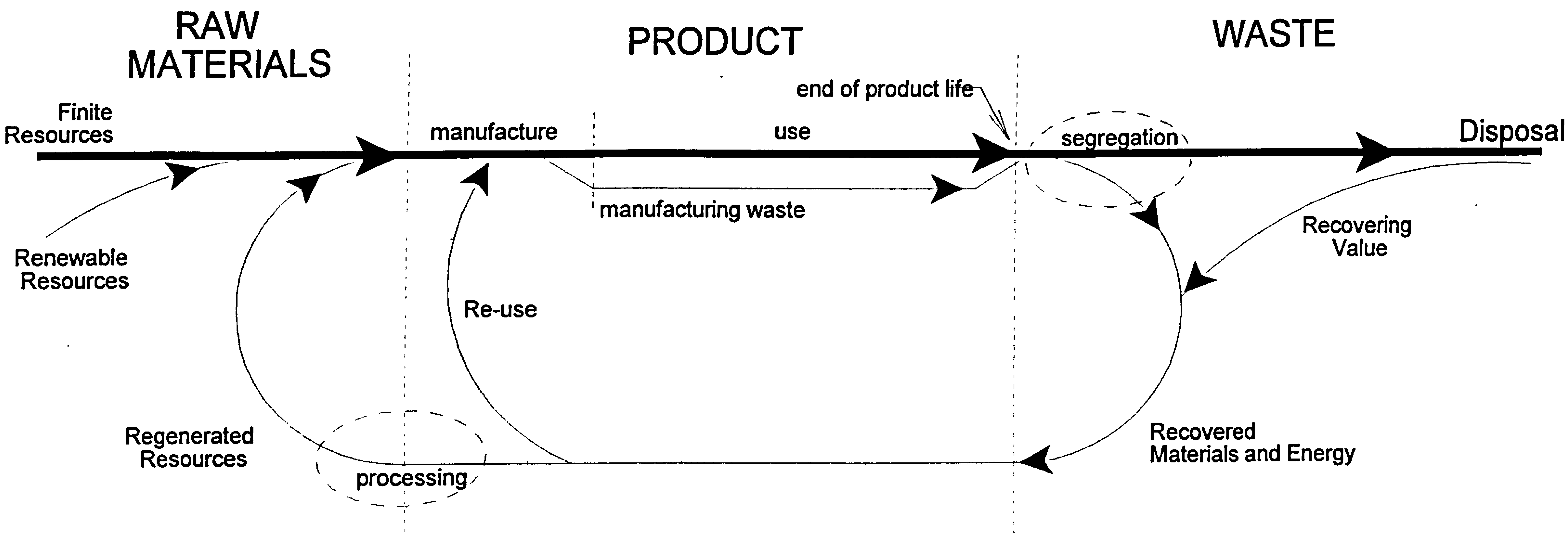
- **raw material**
- **product**
- **waste**

The way the diagram is drawn shows a straight line from finite resource through to disposal - the open loop of *unsustainable flow* in one direction. On to this is added a return mechanism that closes the loop. This allows material and value recovery to return as regenerated resources. This is the crux of sustainable waste management.

Raw Materials

The Cycle shows raw materials being acquired from various sources: finite sources; renewable sources, such as biomass; and what is termed here as regenerated, which comprises all types of recovered raw material. Raw materials are processed into a product.

Figure 3-1 The Cycle of Resources Within Society



Product

In the manufacturing process considerably more resource is used than is contained in the end product. For the UK as a whole, it has been calculated that (Jones,P 1996), on average 11 tonnes of raw materials[1] are required to manufacture 1 tonne of product. Much of the difference between these figures is manufacturing waste. For instance, the production of family car produces around 15 tonnes of waste, around 25 times the weight of the car (Forstner,U 1996). The product is utilised for its life, at the end of which the status of the material shifts from product to waste.

Waste

Product design and the technology of recovery dictate the amount of material that it is possible to recover, and the amount that will have to be disposed of. Contemporary product design and the current state of the art of recovery technology mean that it is not possible to recover 100% of the material. Moves towards 'Clean Technology', in which the manufacturing process does not produce waste or pollution, and a change in the philosophy of product design, so as to include the end of life product, will create a situation in which disposal can be greatly reduced. The reduction in disposal will be possible for three key reasons:

- improved product design and material selection will allow greater reuse and recycling
- improved product design will reduce the amount material contained in a product
- increased resource efficiency[2] will reduce the total amount of material used to manufacture a product

---

[1] Input includes mass of fuel for energy
[2] Discussed in Section 3.3.3

At the moment, far more material is disposed of than is actually necessary, due to a combination of free market economics and entrenched attitudes coupled with a lack of public interest or political will.

Of the material that is disposed of it should be possible to recover some value. Commonly this will take the form of energy recovery.

Of the recovered material, some product will be re-used directly, and some will require processing for re-use or recycling of the constituent raw materials to become a regenerated resource.

Sustainable Flow of Resources

Analysis of the cycle of resources reveals that there are two extreme cases. Seemingly, they both achieve sustainability in the cycle. They are:

1. if 100% renewable resources are utilised in a product, then it may be disposed of in its entirety

2. if 100% recovery occurs then a product may be made entirely from finite resources, and they will not continue to be depleted.

Both these cases appear to be competent. However, there are major flaws in both contentions. Case 1 fails because the act of disposal itself is not sustainable in the long term on environmental grounds. Case 2 fails because it ignores the overheads of the cycle; primarily energy used in production and post life processing. Case 2 would also fail due to growth in the amount of product in circulation.

Thus, to achieve sustainability, both maximum use of renewable resources *and* optimum recovery must be practised.

3.3 Materials and Product Design

3.3.1 Life Cycle Analysis

Life cycle analysis (LCA) evaluates a product from raw materials, through manufacture, during life and after end of life. The purpose is to develop the product so that it does not just perform well for the purpose that it was intended, but is also resource efficient to manufacture and is not a burden to society after the end of its life.

Previously product design tended to be evaluated on two basic requirements:

- serviceability - function adequately as intended
- cost - could be manufactured at a cost that the market would bear

In terms of the Cycle of Resources, these two requirements are located in the central zone - Product. LCA takes the consideration of product design upstream into the Raw Materials zone, to consider the suitability of materials on other than economic grounds, and downstream into the Waste zone to consider how the product may be recycled or disposed of.

Regeneration of resources and re-use of product are crucially affected by the appropriate choice of materials and product design.

This holistic approach is also being recognised in the 'design world'. Shayler (1998) states in a design journal that "product designers need to build environmental sustainability into the design process" and that they should "integrate environmental decisions into the design of the product as early as possible".

Thus **product design and material selection are key waste management issues.**

Taking a product example; the hot take-away food container. Providers of take-away food normally use 'single-use' containers, due to the inherent difficulty of return for re-use in their business. The polystyrene container has long been popular. From the cost and functionality point of view, it was excellent: cheap, light and thermally insulating.

Life cycle analysis reveals the product to be less than excellent. Looking upstream, polystyrene is made from a non-renewable hydrocarbon resource. During manufacture, CFC's were used to 'blow' the material into a foam, resulting in releases of CFC into the atmosphere, and subsequent damage to the ozone layer. At the end of their very short product life - probably lasting a few minutes with the final consumer - the polystyrene becomes waste. Segregation and recycling have not been shown to be particularly feasible. Disposal to landfill or incineration is the usual fate of this product. Energy value may be recovered by incineration. In landfill the material is unfavourable. It has low density, and is difficult to compact. It also creates problems of wind blown litter. It will not degrade quickly, thus value recovery through landfill gas is negligible. However, slow depolymerisation may occur, resulting in styrene, which is toxic, being released from the degrading waste.

Of course, there are alternatives for almost every product. Although most polystyrene is not now blown with CFCs, many companies have discontinued its use for the other reasons revealed by life cycle analysis. The popular alternative is paper. It is a renewable resource, and is sustainable if managed appropriately. The manufacturing process is relatively benign with modern techniques. At the end of product life, the material may be composted effectively, or provide value recovery in both incineration and landfill.

The example above shows how LCA can lead to the obvious conclusion about the suitability of a product. For many products, particularly as they become more complex, the optimum choice is not so obvious. Tools to assist in these comparisons have been developed. One of these tools is the 'eco-balance' designed to assess the rating of a product on the basis of environmental impact.

3.3.2 Ecobalances

An eco-balance is a systematic analysis for the purpose of evaluating the environmental burden associated with all phases of manufacture, consumption and disposal. It should cover:

- raw material
- energy consumption
- emissions to air
- emission to water
- solid waste
- feasibility of recycling and reuse

In this respect it is an absolute measure, yet is mainly used for comparison, to assess the optimum product for an application. The actual product should be the subject of the eco-balance, e.g. a bottle and not just a unit mass of the material from which it may be made, e.g. glass or plastic. The reason is that, for example a 1.5 litre bottle made of plastic may weigh only 43g whereas a glass version is around 450g.

It is possible for weightings to be given to each of the constituent parameters, and thereby a single figure 'eco-balance score' can be calculated. The decision on an appropriate weighting is to a certain extent subjective, and therefore subject to contention. The use of a single figure 'score' is however useful for 'in-house' comparisons, where weightings are agreed.

Just as with a financial balance sheet, an ecobalance has debits, e.g. environmental burden, and credits, e.g. energy recovery, regeneration of raw materials.

The ecobalance parameters may be constructed as follows (EVC, 1992)

Energy Consumption. Total thermal energy consumption (including oil usage and minus energy credits for recycling)

Emissions to air. Air pollution such as dust particles, CO, NOx, SO_2 and other pollutants is divided by regulatory air emission limits (mg/m^3) to obtain "critical air volume" (m^3/ unit reference quantity). It indicates how many cubic metres of air are necessary to adhere to the maximum permitted concentrations laid down in legislation.

Emissions to water. Calculation similar to that for the critical air volume, but divided by the regulatory effluent limits for water pollution. The "critical water volume" (litres/ unit reference quantity) corresponds to the level of water consumption required to reduce the quantity of pollutants in water to the legally permitted concentration.

Solid Waste. Total solid residues for landfill, resulting from raw material and energy production via processing to waste treatment processes (incineration, recycling, etc.)

The categories listed here are only one type of ecobalance, and are orientated towards comparing the relative merits of a material and its manufacturing process. As a tool to use in Life Cycle Analysis it must be applied carefully in order to be entirely objective.

3.3.3 Resource Efficiency

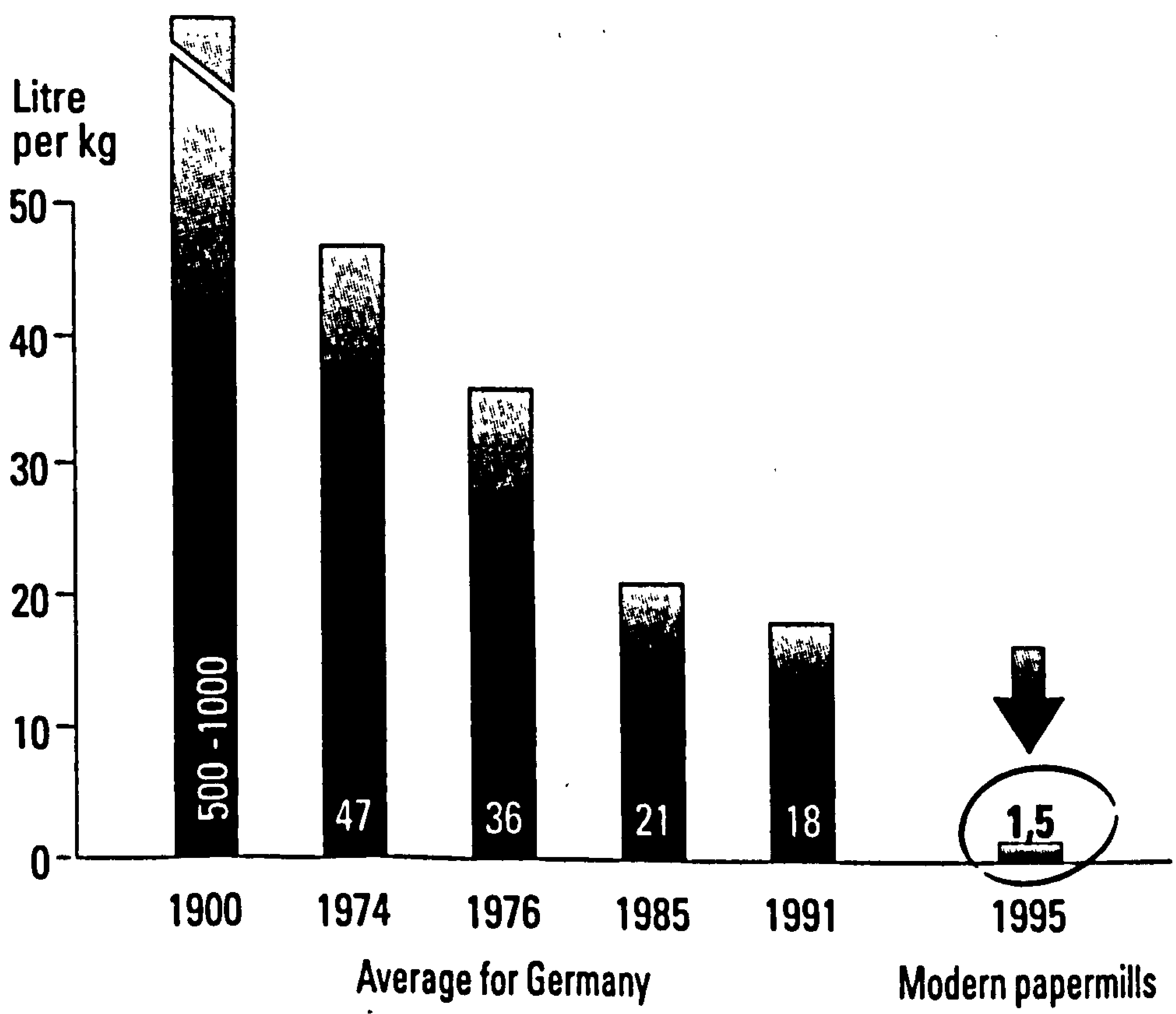
Resource efficiency is a likely to receive much attention as industry attempts to balance dwindling finite raw material resources against the greater output that is required by economic growth. Great strides towards making development more sustainable can be made by improving resource efficiency.

Resource efficiency is a measure of the amount of a resource required to produce a product or be part of a process. Efficient use of resources have a direct economic imperative, as well as for example, the indirect economic imperative of the dis-benefits of global warming. In many industrial sectors resource efficiency is the key to a competitive product.

An example of improvement in resource efficiency is given by the graph in Figure 3-2. It deals with one particular resource - freshwater. It demonstrates the improvement in resource efficiency in paper and board manufacture since the beginning of the century. A 40-fold increase in efficiency has been achieved by the recycling of water in paper plant. At one German plant, the stage has now been reached that there is no wastewater emitted. The small amount of freshwater that is used is accounted for by evaporation and inclusion in the product.

The efficiency use of freshwater is one of the elements that would make up a cradle-to-grave, or life cycle analysis, of a product such as paper.

Figure 3-2 Reduction in Freshwater Consumption for Paper and Board Manufacture



Source: von Weizsacker, Lovins and Lovins, 1997

Von Weizsacker, Lovins and Lovins (1997) quote a refinement of the basic concept of resource efficiency which was developed by Schmidt-Bleek(1994). This refined concept is the *materials input per unit service* (MIPS). It is a measure of the materials usage for a given service. If the service is provided by a physical object, then the MIPS is a measure of the materials required to manufacture that object, including acquisition of raw materials, maintaining the object during its life, and the materials required to deal with it at the end of its life.

However, it is more than just a measure of the materials input from cradle to grave, because it introduces the notion of an input: output ratio - the material input is per *unit* of service provided. This then introduces value to a product's durability. The longer the service life of a product, then the lower the fixed materials input (from manufacture and end of life treatment) per unit service received.

MIPS is analogous to the *average product* in the Production Function of regular economics. The concept of MIPS could therefore be extended and the equivalent of *marginal product* calculated, in order to determine the point of diminishing returns. The Marginal MIPS would be the additional material input required for an additional unit of service life. Thus, the optimum time to end the life of the product could be determined. This would be an effective way of optimising use of resources.

3.3.4 Example of the Selection of Material - The Case of PVC

PolyVinyl Chloride, one of the world's oldest thermoplastics, and is today second only to polythene in world wide production. Around 18 million tonnes are produced annually (Norsk Hydro, 1992), of which 5 million tonnes are made in Western Europe. A clear explanation of the production process is given in (Norsk Hydro, 1992; Greenpeace, 1996b)

Use of the Material

Rigid and flexible PVC is widely used in consumer and industrial products. The range of properties is well developed, partly due to the length of time that the material has been manufactured. By using different additives, the characteristics of

PVC can be tailored for a particular application, from rigid plastic housing for computers to flexible transparent blood transfusion bags.

The PVC industry states the following advantages of the material:

1. Properties(EVC, 1995)
   - excellent resistance to water and moisture
   - good mechanical strength and toughness
   - excellent resistance to abrasion
   - good chemical resistance
   - good barrier to gases
   - inherently non-burning (due to chlorine content)
   - excellent electrical properties
   - glass-clear transparency
2. Production Cycle (Norsk Hydro, 1992)
   - uses around 50% of the amount of oil to produce, compared to other plastics
   - is more tolerant of contamination with other materials in the recycling process than some polymers
   - the chlorine in PVC makes it easy to identify in the automatic materials sorting stage of recycling

The major uses by sector and product are (Norsk Hydro, 1992):

Building & Construction ; pipes and fittings, flooring, window frame

Packaging; film & sheet, containers, bottles,

Electrical; cable insulation

Consumer products; wall covering, hosepipe, household goods

Transport; mouldings, ducts

Should It Be Selected as a Material?

There are moves to have PVC banned in various countries of the world. But why ban a material that is so useful to humankind and that has many excellent and unique properties, for example it is the only flexible material approved for blood bags by the European Pharmacopoeia (EVC, 1995).

On the surface of it PVC also looks to be an environmentally friendly material. In contrast to other plastics, which are 100% oil derived, around 50% of PVC comes from salt. Therefore production of a unit mass PVC uses about half the oil of other plastics. Salt is a resource that is abundant in the world.

However, even the PVC industry concedes some of the disadvantages of the material (Norsk Hydro, 1992):

1. the basic building block of PVC is vinyl chloride monomer which can cause cancer
2. the burning of PVC in incinerators or accidental fires produces hydrogen chloride gas
3. the burning of PVC can lead to the formation of dioxins
4. the chlorine used in PVC manufacture has sometimes been produced in a way that pollutes the environment
5. under some conditions the formulation components used in PVC may migrate into other materials

The PVC industry claims that the advantages of the material far exceed these disadvantages. Environmental groups and some governments disagree and propose that the material be banned. The Swedish Minister for the Environment, Anna Lindh stated in November 1995 "Its no longer a question of if PVC should be phased out, but how it shall be phased out".

Industry and commerce are also considering the issues (Greenpeace, 1996a). The new Bilboa metro has used PVC-free cabling for environmental and safety reasons.

London Underground's policy is also to use PVC-free power cables in its underground stations - the new Jubilee line Extension is being built according to this policy. Architects in Germany and other European countries are specifying alternative materials for floors, windows, cables and pipes, so as to minimise the use to PVC. The Olympic stadium in Sydney, being built for the 2002 games, is to be entirely PVC-free.

Some key waste management issues are:

Recycling. As a thermoplastic recycling is possible. However only 0.6% of post-consumer PVC is recycled in Europe. This partly due to the fact that there are severe problems with recycling the diverse PVC waste stream. The quality of the recyclate depends heavily on the level of impurities of other polymers and the various additives. It is difficult to ascertain, visually and mechanically, which additives are contained within a sample PVC.

To recycle PVC it must be melted. This releases hydrogen chloride which causes other splitting processes in the PVC to speed up. This is known as 'autocatalytic corrosion' and the net result is a drop in quality of the end product. This is why most 'recycling' is actually 'downcycling'. This limits the number of times that PVC can be recycled.

Disposal by Incineration. Incineration of PVC contributes to the environmental burden of dioxins. In 1995 HMIP[1] stated that the dominant source of dioxin emissions to air in the UK was from MSW incineration (HMIP, 1995), contributing 53-82%. PVC in the MSW waste is the main source of chlorine, which creates dioxins in the combustion process.

Dioxins are also found in the incinerator ash, of which the fly ash has high concentrations. In a recent UK study (Great Britain. DoE, 1996a) on trace organic compounds in household waste, levels of dioxin in fly ash were found to be in the

---

[1] Her Majesty's Inspectorate of Pollution, now part of the Environment Agency

range 0.54 - 1.8 μg/kg i-TEQ[1] (equating to around 1500 Tolerable Daily Intakes per kg).

PVC is also estimated to account for 20-30% of cadmium entering incinerators. Other heavy metals such as lead introduced to PVC add to the contamination of ash. Figures from the German Office of the Environment estimate that in the medium term in Germany 10,000 tonnes of lead and 250 tonnes of cadmium per annum will be disposed of as end of life PVC.

Contaminated ash is then landfilled as the *long term storage technique* for incinerator residues. **Long term storage, without treatment to ameliorate environmental risk, is inherently unsustainable.**

Apart from the contaminants in the ash described above, PVC also contributes to the high chloride content of incinerator ash, which complicates landfill leachate treatment and discharge.

Disposal to Landfill. PVC is relatively non-biodegradable in the landfill environment, although vinyl chloride monomer may be detected in landfill gas (Mirza,A 1997). Leaching probably represents the largest problem. Phthalates and other additives can be lost from the plastic through leaching. Phthalates will not be ameliorated during leachate treatment or any subsequent waste water treatment, prior to being released into the aquatic environment. Heavy metals from PVC may also be released into the environment, either directly in dilute form as treated leachate or concentrated as waste water sludge.

Fleming (1994) summarises the key unknown factors in landfilling PVC, and goes on to state that "the amount of PVC reaching the landfill site is as yet a fraction of that being produced, the peak of PVC production reaching landfill is some way ahead". Therefore, the most serious consequences resulting from landfilling PVC have yet to be experienced.

---

[1] i-TEQ = toxic equivalence according to NATO/CCMS International weightings of congeners

The issues as stated above appear damming, and suggest that PVC should not be selected as a material. There are alternatives for nearly every product, whether it is a different plastic, or a different material. However The PVC industry has fought a vigorous rearguard action of the environmental front.

Environmental Justification by the PVC Industry

The PVC Industry has conducted various studies and projects to justify and add credence to their assertions that PVC is a perfectly acceptable modern material.

The REPRISE project (EVC, 1996) was set up to demonstrate the recyclability of plastics and in particular PVC. The plastic bottle and supermarket shelf tray waste stream was chosen and an automated sorting and chipping plant established. The project has been successfully producing PVC, PET, and HDPE flake of 99.995% flake purity. The applications of the recycled PVC have been foam cladding board, telecom and pipe fittings, packaging and knitwear. Typical market prices for PVC were reported to be £100/tonne but the costs were reported to be in excess of £140/tonne around half of which transport. Therefore the recycling of PVC bottle was not justified on economic grounds alone. The market price of the other polymers, HDPE and PET were £65-120/t and £100-200/tonne respectively, which appear to endorse the latter as more advantageous to recycle as far as the market is concerned.

Beverage bottle is probably one of the better waste streams to attempt to recycle. The product is of regular shape and size, which enables automated sorting, and it is relatively un-contaminated. Additives to the basic polymer will not be diverse. Most of the PVC used in beverage bottle is rigid - it has little or no phthalate softener in it. Other PVC products are far less likely to recycled easily.

An interesting recommendation of the REPRISE project was that bottle manufacturers/specifiers must make sure that bottles are designed for recycling, and conversely that reprocessors must make sure that designers are aware of suitable design criteria.

Eco-balances of PVC.

A major manufacturer has published a study (EVC, 1992) on eco-balances for various applications of PVC against the alternatives. The study shows that using the eco-balance criteria, as detailed in Section 3.3.2 above, PVC compares adequately and at times favourably to the alternatives.

One example is that of beverage containers. On an energy basis 'one-way'[1] glass is shown to have the worst ecobalance at around 3500MJ/1000l capacity, one-way PVC is much better, against the best that is returnable PET[2] at around 700 MJ/1000l. Similarly one-way glass is shown to have the worst ecobalance for solid waste, and emissions to air, although PVC showed the worst ecobalance for emission to water.

Another example is that of window frames. PVC/Steel, Wood/Aluminium, Aluminium. The ecobalance indicates that, over a 40 year lifespan there is little difference between the PVC with a steel insert and the Wood alone. Wood/Aluminium is shown to have the worst ecobalance.

Yet, there are flaws in the study, not least because disposal is to landfill and not incineration, and recycling is not considered.

Furthermore, the eco-balance parameter of 'Solid Waste[3]' takes no account of the toxicity of the material being landfill. For instance in the case of a wooden window frame, much of the waste may be saw dust emanating from the wood shaping processes. The sawdust is innocuous in comparison to the dioxin-contaminated organochlorine sludges from PVC manufacture. Nevertheless, they are given the same weighting on a mass for mass basis.

A further weakness of the study, and therefore to a certain extent these particular ecobalance criteria, is **whether it is environmentally (or morally) sound to make**

---

[1] no recycling or return
[2] 95% return rate
[3] defined in Section 3.3.2

comparison on the basis of legal emission limits. This is what the parameters of Critical Air and Water Volume do.

The level at which legal emission limits are set is not only a function of safety, but also a function of the ability of an industry to meet them. If a limit is set that is considered appropriate on grounds of safety but current technology cannot meet this limit, then the regulator is effectively closing down the operation. This seldom happens. Therefore legal emission limits, particularly those that have been set historically for older industries, are not necessarily set at a level that contemporary research indicates is safe.

Implications for Waste Management

The case of PVC shows that, apart from the wider environmental and sustainability issues, the Waste Management industry should be taking an interest in encouraging this material not to be selected.

The grounds for this are:

- other plastics are better suited to recycling
- incineration produces toxic gaseous emissions that need to be scrubbed out. Much of the toxic emissions come from PVC.
- incinerator ash has to be landfill as hazardous waste. Much of the dioxin and other organochlorine, and heavy metal contamination, comes from PVC.
- incinerator ash to be landfilled has high chloride levels which are difficult to deal with at inland sites.
- landfill (direct disposal) is affected by leaching of additives. Treated leachate discharge may be subject to controls on some of these additives in

the future, as water companies begin to incur the costs of removal of substances like phthalates from their supply.

This example has been used to show how why the Waste Management Industry needs to provide feedback, and impetus for change, to the parties upstream in the Cycle of Resources.

3.4 Summary

Historically the Waste Management Industry has been reactive, it has dealt with what society rejected - its waste. The Industry needs to be proactive, be cognisant of the Cycle of Resources in Society and play a guiding role in *what* society rejects. This requires feedback from the acceptors of end of life products to those who design, manufacture and use those products. This is the way forward to achieving sustainable waste management.

There will be a role for disposal, either to landfill or incineration, for the forseable future. However, it is clear from the early part of this chapter that

disposal can never be a truly sustainable waste management option

although in an optimised form it may move close to sustainability. Thus, other options must be considered for long term solutions to the waste issue.

The options available for the management of waste are now discussed in the following chapter.

4 WASTE MANAGEMENT OPTIONS

In the developed world, waste has not traditionally been considered a useful resource. Society has considered it a burden, and has dealt with it by the cheapest and easiest way - this has typically been disposal. The adage 'out of sight, out of mind' was fairly accurate.

The first disposal option has been landfill. In parts of the world where landfill space is limited, for example by a lack of quarry void or special situation such as in the case of Berlin during the Cold War, then incineration has been used.

As consumption of goods has increased, so has the amount of waste. This coupled with the increase in packaging of products and the growth in disposable products has led to an vast rise in the amount of municipal solid waste in the last few decades. For example, in Scotland, the mass of controlled wastes has risen from 9.2 Mt in 1989 to 16Mt in 1994 (Great Britain. Scottish Office, 1996)

The scarcity of cheap space to landfill, coupled with the concerns over pollution led to regulation. The west coast of the US, and some European states began to consider the issues of waste management in the early 1970's. In Britain, the statutory regulation of non-toxic wastes began in 1974 with the Control of Pollution Act.

Now there is a wide realisation amongst all nations that Sustainable Development requires that the issue of 'Waste' and disposal of resources should be examined.

4.1 The Hierarchy of Options

In 1990, the UK government put forward Britain's Environmental Strategy in a document titled 'This Common Inheritance' (Great Britain, 1990). Among a wide variety of environmental protection measures, the Act also provided a formalised approach to the management of wastes in the UK, and in particular what the preferred options are. The hierarchy of waste management options is shown below.

The concept of the hierarchy was previously enshrined in 1975 by the European Community Directive 75/442/EEC. Broadly the same hierarchy has recently been reinforced by the European Commission in a review of waste management strategy (European Communities. Commission, 1996b).

The Hierarchy of Waste Management Options

Waste Minimisation

Re-Use

Materials Recycling

Energy Recovery
(incineration/landfill gas/other)

Disposal
(without energy recovery)

The hierarchy has been subject to modification since publication, depending on the political climate. Composting has been inserted below Materials Recycling, and there is sometimes a differentiation between Energy Recovery from Incineration and that from Landfill, the former being elevated in the hierarchy.

The various elements of the hierarchy are discussed in the following sections.

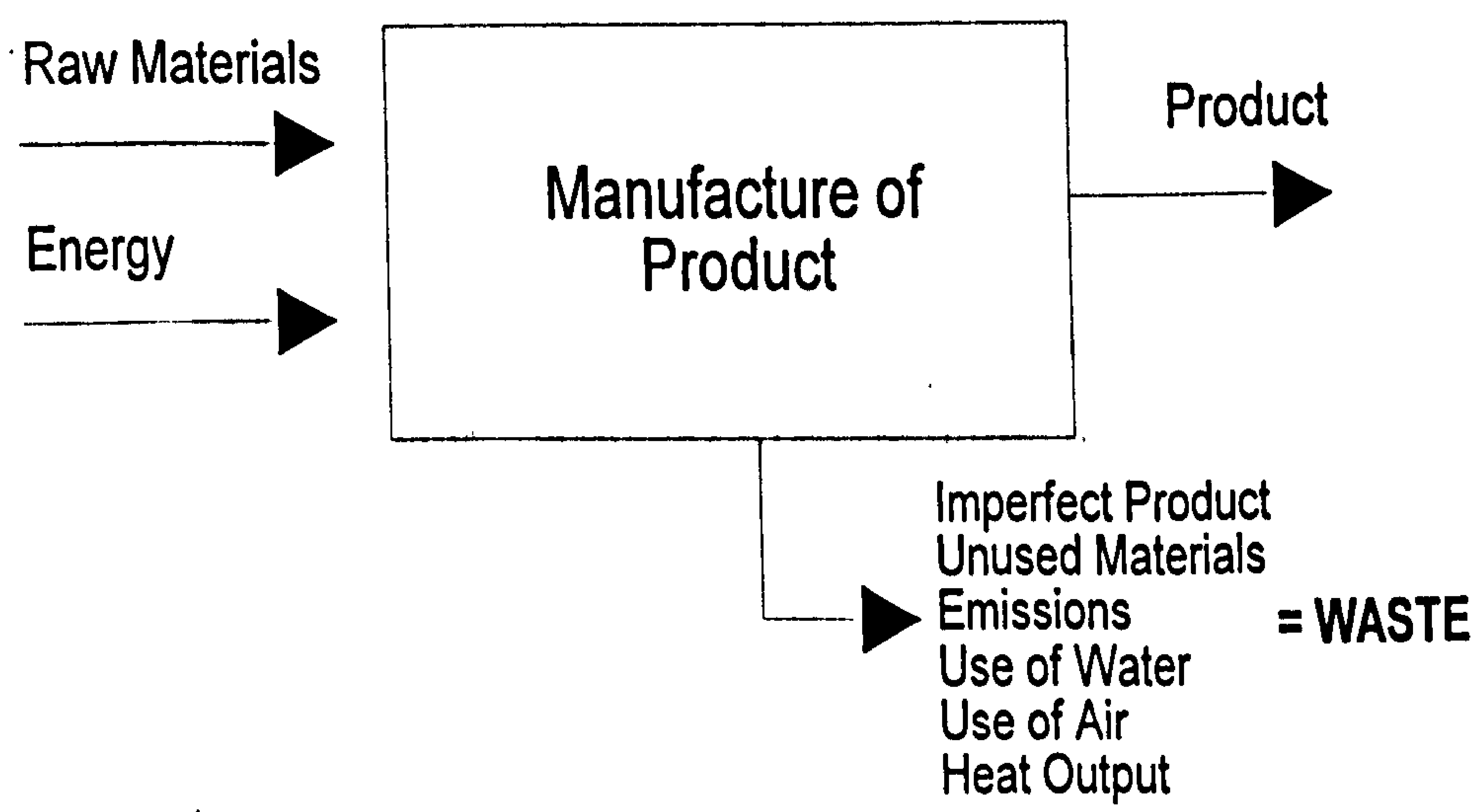
4.2 Minimisation of Waste

The minimisation of waste is not truly a waste management option. The reduction in the amount of waste is a 'production and consumption' issue. However, it is right to be at the top of the top of the waste management hierarchy, as it is the paramount solution to waste management problems - don't create the waste.

Definitions of waste minimisation vary from country to country (IWM Waste Minimisation Working Group, 1996). In the UK the definition is 'reduction of waste at source', in Sweden it is 'reduce volume as well as hazardous material content'. In the Japan and Germany it is taken to include recycling and other techniques to reduce disposal. In this document the definition is taken to mean reduction at source, that is reduction in the creation of waste. This implicitly includes gross mass as well as hazard to the environment.

In terms of manufacturing, the concept of minimisation may be stated by: 'Waste is any material and energy input to the manufacturing system that is not output as product'. Therefore any output that is not product should be minimised. The figure below shows this diagrammatically. Not just material emissions are considered, but also imperfect product, transient use of resources, and heat emissions.

Figure 4-1 Conceptualisation of Manufacture



The Institute of Wastes Management has summarised examples of waste minimisation and corresponding policy measures (IWM Waste Minimisation

Working Group, 1996: page 17). This provides details of changes to input, manufacture and product, and the relevant policy drivers.

In the UK, the DTI funded two large demonstration projects for industry;

Project Catalyst	14 companies involved, total savings of £8.9million for each and every year
Aire and Calder Project	10 companies involved, total savings of £2million for each and every year

It should be stressed that the savings involved are not one off, this amount of money was saved - through minimising waste - year on year.

These two demonstration projects involved large companies. Small and medium sized enterprises (SME) were not encouraged by the demonstrations; there was a belief that only large companies had resources and expertise to accomplish these savings. Thus, Scottish Enterprise (a government-funded development body) established the Clyde Waste Minimisation Project (Willey,R 1997). This project had 9 companies participating from all sectors of industry, with 14 - 200 employees. The maximum capital investment per company was £2500. Targets were set at total savings of £180k. However, total savings turned out to be much greater; £0.7M - 1.6M for each and every year were realised. The maximum payback period for any of the measures was 6 months. Many measures required no capital investment.

One of the facts that came out of the programmes was that often the Production Managers were unaware of the scale of waste, in spite of the fact it was in front of them. This a classic "factory blindness" scenario.

Programmes such those described above, are being carried out in many parts of the world (OECD, 1997).

Clean Technology

'Clean Technology' is the pre-eminent method of minimisation (and elimination) of waste from production. Clean Technology is an evolution in the design of industrial processes and methods of production, such that there are no waste products or polluting emissions. Industry is taking steps towards this goal, but has a long way to go before it is achieved (OECD, 1997).

Producer Responsibility

The EC Directive on Packaging and Packaging Waste (European Communities. Commission, 1994) came into force on 31 December 1994, with national legislation for the UK included in the Environment Act 1995. An important part of this legislation was that it created obligations for recovery and recycling. This meant producers of packaging had to consider design of packages for reuse and recycling. Recovery and recycling obviously have cost implications. As the obligations were set as a percentage of that handled or used, the logical conclusion that could be drawn was that the less packaging used, the less that would have to be recovered. In this way the Producer Responsibility has provided an impulse to minimise packaging, and therefore packaging waste.

Producer Responsibility is being implemented in other fields, to focus producers on their products throughout the life cycle, and this is intended to have similar beneficial effects on the minimisation of waste.

4.3 Reuse

Reuse should be clearly differentiated from Recycling. Reuse is the subsequent use of an intact product, after the initial end of life. Minimal processing, if any, is required. This is in contrast to recycling which indicates reuse of materials and usually includes significant processing.

Examples of reuse are (IWM Waste Minimisation Working Group, 1996: p17):

- commercial reuse, especially transit packaging

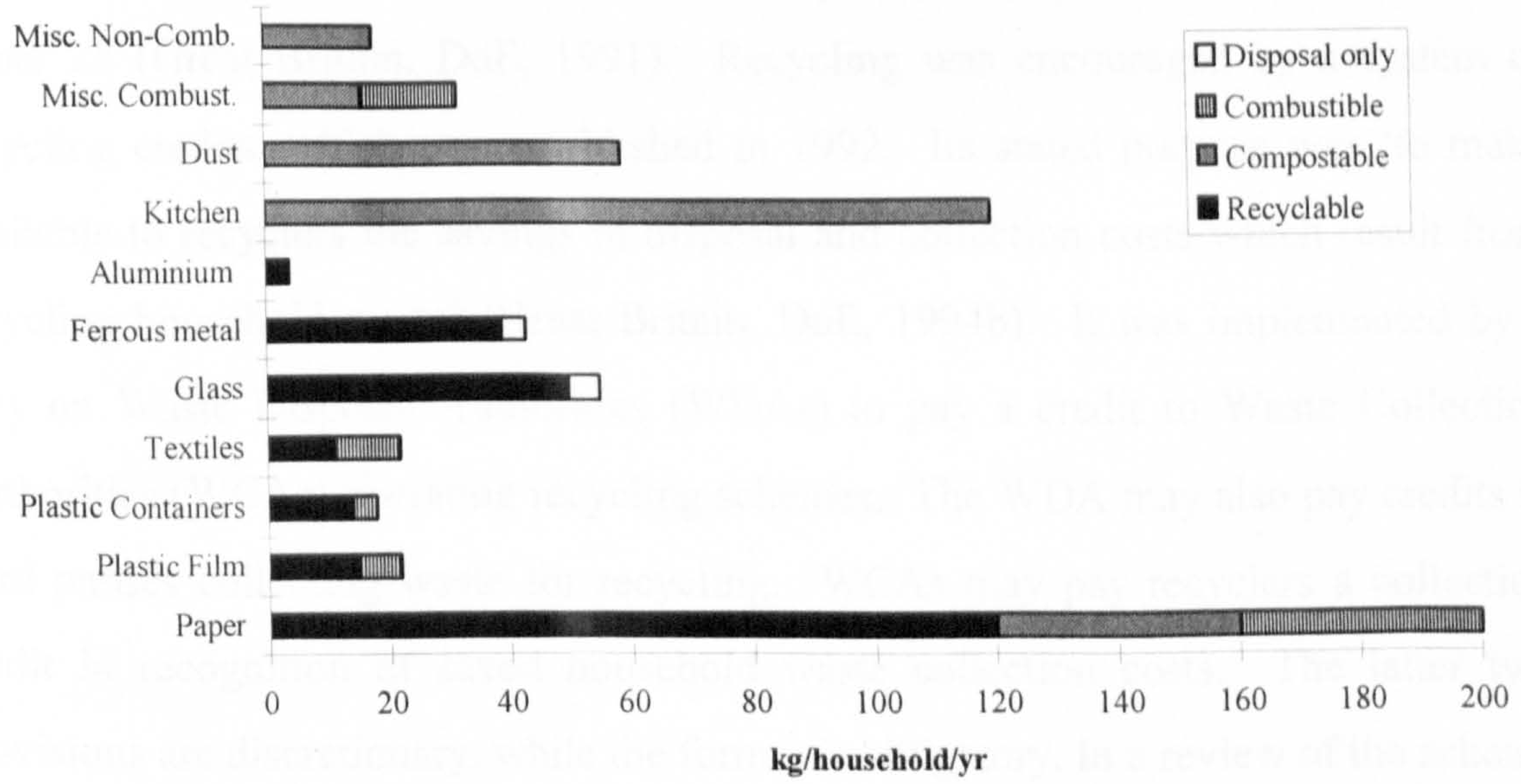
- informal household reuse (e.g. jam jars)
- post-consumer reuse (e.g. returnable bottles, Oxfam)
- refurbish/repair schemes
- recovery of components
- upgradability and product life extension
- reuse for the same or alternative purposes

Reuse is preferred to recycling because the overheads, and therefore the environmental costs, to bring the product back to use are much lower.

4.4 Recycling

Recycling of materials in the MSW waste stream is highly feasible particularly if segregation of recyclables is conducted at source. Figure 4-2 shows the proportions of household solid waste in the UK that it is possible to divert from landfill. It is clear that a significant amount of household waste is recyclable. It is also clear that little *has* to be disposed of.

Figure 4-2 UK Household Waste: Composition and Recyclability



Note: Assumes hierarchy of: recyclable, then compostable, then combustible.

Source: The UK Environment (Great Britain. DoE, 1992)

In the 1995 document 'Making Waste Work' (Great Britain. DoE/WO, 1995) the government set out their targets for the nation's household waste. By the year 2000, 25% of the household waste should be recycled or composted. Local authorities were tasked with implementing this and other commitments. Although no additional funding from central government was provided, £26 million in borrowing approvals were allocated in the period 1995-1997 (Great Britain, 1996b).

Other commitments to recycling were:

- recycle 90 % of lead acid batteries
- increase use of waste/recycled aggregates from 30 to 55 million tonnes per annum
- recycle 58% of waste glass by 2000
- recycle 25 - 45% of packaging waste by 2001, with a minimum of 15% for each material
- ensure 40% of UK newspaper feedstock to be wastepaper by 2000
- achieve easily accessible recycling facilities for 80% of households by 2000

Government advice to local authorities on recycling is given in Waste Management Paper 28 (Great Britain. DoE, 1991). Recycling was encouraged by a system of recycling credits, which was established in 1992. Its stated purpose was 'to make available to recyclers the savings in disposal and collection costs which result from recycling household waste' (Great Britain. DoE, 1994b). It was implemented by a duty on Waste Disposal Authorities (WDAs) to pay a credit to Waste Collection Authorities (WCAs) operating recycling schemes. The WDA may also pay credits to third parties collecting waste for recycling. WCAs may pay recyclers a collection credit in recognition of saved household waste collection costs. The latter two provisions are discretionary, while the former is obligatory. In a review of the scheme (Great Britain. DoE, 1994b) it was found that there was no reliable link between the level of recycling credits offered and the amount of recycling. However, the review did find that the scheme helped stabilise the market price for secondary materials.

The table below shows the position of the best and the worst local authorities in the UK.

Table 4.1 Percentage of Household Waste Recycled '95 - '96

	Local Authority	%
The Best		
	Weymouth & Portland	21.9
	Adur, West Sussex	21.4
	North Devon	20.2
The Worst		
	Ribble Valley, Lancashire	0.0
	Alnwick, Northumberland	0.6
	Wear Valley, Durham	0.0

Source: The Audit Commission in Cosslett, G. 1997

As can be seen, the better of the local authorities should achieve the 25% recycling target by 2000, whereas the worst have an extremely large task to overcome. The authorities that have made little effort, have had the effect of reducing the UK average recycling rate to only 5% in 1993 (Coopers and Lybrand, 1996). This compares with over 20% in Denmark, Germany and Luxembourg. In 1996 the USA achieved 25% recycling of MSW (anon, 1996c).

4.4.1 Recovering Recyclables

Broadly speaking, there are three ways in which recyclables are recovered from the MSW waste stream:

Segregation at Source

Households separate their recyclables from other waste. Typically these materials are glass and plastic bottles, steel and aluminium cans, and paper. These recyclables are put into a separate container, often a blue box, for collection by the Waste Collection Authority's contractor. Schemes like this were pioneered in the UK by certain local authorities such as Adur District Council. In their scheme, the personnel on the recyclables collection, segregate the different materials into a compartmentalised vehicle. In other schemes the recyclables are collected together in an ordinary collection vehicle, on a different day to the unrecycled waste. The mixed recyclables are then taken to a sorting facility. Although sorting facilities can be automated to a great extent, some manual picking in generally employed.

Schemes like this operate successfully in many parts of the world, including New York and Toronto. In Montreal, there is a four bin system for paper, bottles/cans and compostables.

These schemes usually cost more to operate, in short term economic costs, than the value of the recyclable materials recovered. Sometimes the separate collection and transport may have greater economic cost than direct disposal.

Bring Schemes

Bottle, can and paper banks in car parks and at local authority 'Civic Amenity' sites. These have the advantage of being cheap to operate for the local authority, and this is a contributory factor to their prevalence in the UK. However, if a special journey is made to the facility by car, the environmental cost of the journey may well be greater than that saved by recycling. Therefore, siting of these facilities is crucial to their environmental benefit. Supermarket car parks are seen as a logical location, so a special journey does not have to be made.

Materials Recovery Facilities

An unsegregated MSW waste stream is processed through a plant designed to separate and remove particular materials. Although these plants are highly automated, they still require manual picking to ensure purity of separate materials.

These facilities are capital *and* revenue intensive. In the UK they are generally not economically viable, and often close after the first few years of operation[1].

The extensive Coopers and Lybrand (1996) study found that the economic and environmental costs of semi-automated sorting/processing were two and a half times those of manual sorting.

In other European member states, Segregation at Source is practised extensively and is successful at diverting material from disposal. It should be the preferred method of recovery as the recyclables remain uncontaminated, and it does not require transport by the householder. Bring schemes operate well, but the take-up is insufficient to recycle a large percentage of the MSW waste stream. If Segregation at Source is to be successful in the UK political will is required for implementation, and education is required for public acceptance.

A comprehensive recent EU wide study (Coopers & Lybrand, 1996) found that recycling had lower total economic and environmental costs than landfill or incineration. Currently however, the widely held perception is that disposal is still cheaper in the short term, on purely economic criteria.

4.4.2 Examples of the Recycling of Particular Products

There are a number of particular product types that have been identified either as requiring special treatment or as suitable for single product recycling. They represent either a particular hazard in the waste stream or a particular opportunity, often both.

Fluorescent Tubes

Fluorescent tubes are a major source of mercury contamination, each one containing about 42mg. Mercury is now a "red list" substance that is toxic, persistent and bio-accumulative. An average fluorescent tube contains enough mercury to pollute 30,000 litres of water to beyond the established standards for drinking water.

---

[1] Shanks & McEwan's MRF, Edinburgh

However, even when very dilute, the bioaccumulative effect can be extreme. For instance, in a lake in Minnesota, USA, in which the concentration of mercury in the water was 2ng/l, pike were found to have 450ng/g bodymass, a bioaccumulation factor of 225,000 (Moore,ER et al, 1996).

In the UK around 100 million fluorescent tubes and lamps are disposed of each year. Modern plant can recover not only the mercury but also fluorescent material, metals and glass[1].

Some waste management companies are now taking steps to segregate and exclude fluorescent tubes from disposal to their landfills, due to the balance sheet implications of mercury contaminated leachate[2].

Electronics

End of life electronics have been identified by the EU as a priority waste stream. Many electronic goods are difficult to recycle and most are not designed, at the moment, for extensive disassembly. A computer contains around half the elements known to humankind. The common method of recovering much of this is fragmentation, followed by chemical or physical extraction. Due to the cost of this sort of plant, often, the most cost effective component to recycle is the plastic housing.

In some cases reuse of components, e.g. memory chips, is possible. In other cases, products that have reached their end of useful life in one part of the world, may be exported to other less advanced places. This of course is a temporary solution, but does provide extended life to a product that is obsolete, but still serviceable.

In Sweden, there is a proposed ban on the disposal of electronic and electrical goods in landfill, incinerators or shredders, without prior treatment by an authorised recycler (Rose,J 1997). In Germany, the draft Closed Cycle Industry Act does not go

---

[1] company literature; Electrical Components Recycling Ltd, Belfast.
[2] personal communications with Peter Jones, Biffa Waste Services Ltd, High Wycombe, UK

quite as far but will oblige manufactures and importers of computers to pay for the recycling or safe disposal of their product.

Take Back

Take Back is a form of recycling in which the product manufacturer gets back the product at the end of its useful life.

In 1995, a group of the five main mobile phone manufacturers initiated an EU wide scheme in an effort to show that voluntary action can make legal requirements unnecessary (anon, 1997b). There are around 15 million mobile phones sold in the EU each year. Their useful life is 5-15 years, but due to technological advances, the average life is 1-5 years. In the six month pilot project in the UK, Motorola, Ericson and Panasonic collectively recycle their phones, while Alcatel and Nokia deal solely with their own. BT is responsible for recycling the batteries.

Remanufacturing

Remanufacturing is the ultimate form of recycling and reuse. Rank Xerox has been one of leaders in this field. They take back photocopiers, disassemble them, clean components and test them to the original specification. Most components are reused, and those that are not are recycled. The remanufactured products are a second, complementary line to the new machines. In 1995, the company saved £50 million on purchases of raw materials. Remanufacturing not only made environmental sense, it also made business sense.

'Design for Environment' is being applied within Rank Xerox, so as to ease disassembly and maximise reusability and recyclability in new products. Soon the company will launch "zero landfill" machines with *all* components fully reusable or recyclable (anon, 1996b).

4.4.3 Environmental Benefits of Recycling

Recycling is widely assumed to be environmentally beneficial, although the collection, sorting and processing of materials into new products has significant environmental impact.

A commonly quoted example is that it requires only 5% of the energy to manufacture an aluminium can from a used can than it does from raw materials. The figure for a plastic bottle is around 10%. In addition to process energy, the table below takes into account atmospheric emissions that arise from transport, sorting and disposal.

Table 4.2 Various Material's Contribution to Global Warming and the Savings Due to Recycling

Material	Waste Disposal, CO_2 equivalent (kg/t)	Recycling, CO_2 equivalent (kg/t)	Recycling Saving CO_2 equivalent (kg/t)
Aluminium	52 999	2653	50346
Glass	2514	1395	1119
Paper	548	50	498
Steel	122	116	6
HDPE	159	31	128
PET	162	98	64
PVC	156	54	102

Source: Modified from Craighall and Powell, 1996

The recycling overhead can become highly significant, particularly if the material has a high weight/value ratio. In this case the desirability of recycling will be very sensitive to transport costs.

The right hand column of the table shows that the energy saving that can be achieved by recycling, rather than disposal. The energy is expressed in terms of mass of carbon dioxide emitted per tonne of material. Aluminium is the extreme example, as its manufacture from ore is highly energy intensive. However, there are significant energy savings from recycling most materials.

In assessing the most environmentally benign method of recovering value from an end of life product, Life Cycle Assessment is a key tool. There is currently much discussion, for instance, on the optimum method of recovering value from dense plastics, e.g. plastic bottles (Lea,WR 1996; Craighill et al, 1996; Molgaard,C 1995). Plastics have a high energy content compared to other materials in the MSW waste stream, as they are predominantly hydrocarbon. The question posed is whether use as a fuel is more beneficial than recycling the material. One study by Lea (1996) concludes that energy use is minimised if plastic is used in Waste To Energy.

The aims of recovering value, and their environmental implications in terms of climate change and resource depletion, need to be clear in order to address this question properly.

4.4.4 Markets

A key element of recycling is putting the recovered materials to use. It has been stated that "the recycling market is demand deficient, causing prices to be low and unstable' (Singer,J 1995).

While the supply side of the market has been concentrated on, the demand side has suffered from lack of development. This is the widely held comment on the German Packaging Ordinance, and the French Eco-Emballage scheme (Singer,J 1995).

In the USA, a more balanced market approach is being encouraged. The EPA and environmental groups along with the Chicago Board of Trade has set up a Recyclables Exchange to trade in glass, paper, plastics and other recycled materials (Feder,BJ 1995). It is expected that a trade in 'futures' will be established once the market has matured sufficiently.

Promoting Buy Recycled

In the UK the National Recycling Forum is promoting a 'Buy Recycled' Programme (McHarry,J 1997). One of the programme's key aims is to increase understanding of the value, reliability and performance of recycled content products. There is tremendous scope for incorporating recycled materials into product specifications and for the development of private/public sector preferential purchases.

In the latest report by its own Panel on Sustainable Development (Great Britain. DoE, 1997), the British Government has been criticised for lack of progress on green procurement. It notes that around £40 billion a year is spent on procurement, which could have a significant influence on the raising standards if enlightened environmental criteria were applied.

In the USA, from whence the 'Buy Recycled' idea came, companies such as American Airlines have embraced it wholeheartedly. All napkins, towels and tissues on aircraft are 100% recycled, as is the paper at their corporate headquarters. Another company Anheuser-Busch is the worlds largest recycler of aluminium can, annually recycling more than 17 billion cans. Each new can contains more than 50% post-consumer material (McHarry,J 1996).

4.5 Biotechnology in the Treatment of Wastes

Biotechnology is an efficient tool for processing materials. This is as true of waste and of other manufacturing processes. Since the industrial revolution, industry has tended to concentrate on physical and chemical processes to achieve results, with a few notable exceptions such as brewing or sewage treatment. It is now being realised that biotechnology has a huge role to play (Great Britain. DTI, 1997a). Biotechnology utilises micro-organisms to do the work for us - we just need to provide the right conditions. The UK Government is promoting biotechnology in all fields through the DTI's 'Biotechnology Means Business' Programme.

In waste management, biotechnology has a significant role to play. In the short term it will be mainly used to recover value from waste and to ameliorate pollution potential. In the long term, with biotechnological advance, it will be used to produce new raw materials from waste - thus truly closing the loop for the cycle of resources.

4.5.1 Landfill

Landfill and Anaerobic Digestion are essentially the same micro-biological process of anaerobic degradation. The principal gaseous products are methane, CH_4 and carbon dioxide, CO_2.

Landfill and anaerobic degradation are dealt with in detail in the subsequent chapter.

4.5.2 Composting

Composting is the aerobic degradation of biodegradable waste. . Within the MSW stream, green waste, putrescible materials such as kitchen waste, wood and paper are the substrates that compost. Significantly, lignin, a principal constituent of wood, degrades rapidly by composting. In an anaerobic environment, such as a landfill, lignin is resilient to degradation.

The principal gaseous products are carbon dioxide, CO_2 and water, H_2O. The process is highly exothermic. Basically, the energy yielding process of oxidising hydrogen and carbon, is occurring within the composting mass.

The exothermic reaction results in the characteristic temperature rise, which will maintain the compost at a temperature in excess of 70°C for many days. This has the fortunate effect of pasteurising the material to a great extent, killing pathogens and also rendering many plant seeds unviable. The former effect is important if the product is going to be handled by the public, and the latter if the product is going to be used horti- or agriculturally.

Approaches to Composting

There are three approaches to composting in terms of MSW. The different approaches reflect different aims.

1. Composting A Segregated Fraction of MSW. If the aim of composting is to divert part of the MSW stream from disposal, this part of the stream is usually segregated at source. Segregation at source is essential to obtain an uncontaminated substrate, which will produce an uncontaminated product.

The substrate is usually garden waste plus green waste from the parks department and in some cases putrescible materials including paper food containers e.g.. the waxed paper carton. The composting process is conducted on a large scale, with quality control of the material produced. The product is used as a soil conditioner and mulch for amenity horticulture, land restoration and may be sold to the public.

This system is popular in North America[1] and continental Europe (Coopers & Lybrand, 1996). In the UK, some Local Authorities practice composting. Dundee City Council operates an interesting scheme in which a second specialised bin is used to collect garden/kitchen waste from around 10,000 households in the city[2].

2. Composting prior to Disposal. Composting may be carried out as a pretreatment of waste prior to the disposal of waste to landfill. There are three reasons that this:

1. Volume reduction in order to save landfill space. Composting may be conducted outside the landfill, or as with a novel practice conducted by Landfill Services Corporation (Hansen,D 1995), expedited on the landfill itself.

2. Reduction in pollution potential. If the readily biodegradable materials are stabilised by composting, then the potential to produce leachate is reduced. This is one justification used by the European Union to implement mandatory pretreatment in its forthcoming landfill legislation.

3. Sustainability. Although this is not usually a stated aim of composting prior to disposal, it has the effect of taking the process of landfill closer to sustainability, because a significant part of the stabilisation process is conducted initially.

---

[1] company literature; LH Resource Management Inc. Walton, Ontario.
[2] site visit 21st May 97, contact; Peter Olsen, Assistant Recycling Officer, Dundee City Council

Quality control of the product can be kept to the minimum, as all that is required is rapid conversion of biodegradable constituents.. Therefore, it is not usual to separate the biodegradable fraction of MSW prior to composting in this case.

Home Composting. Kitchen and garden waste is composted at home, and is therefore removed from the MSW stream. There are obvious cost advantages to the Local Authority in the reduction in collection and processing of waste. In addition, it removes an element of the waste stream that generates leachate in a landfill, and which provides little energy yield in an incinerator. There are also advantages to the householder in that a ready supply of free compost is available, which will displace peat based soil conditioners. When considering economic and environment costs, home composting is less costly, mainly due to the elimination of transport (Coopers & Lybrand, 1996). Some Local Authorities in the UK are providing subsidised or even free composting containers to households in order to encourage home composting.

Methods of Composting

To optimise composting the correct conditions need to be established. The principle factors are (Fermor,TR 1993): oxygen supply, particle size and structure, moisture, temperature, balance of nutrients, pH and the carbon : nitrogen ratio. The optimum C:N ratio is considered to be around 35:1. Elements of the incoming green waste stream are typically contain:

grass cuttings	12:1
food	3:1
wood	500:1

Therefore, to obtain the best conditions, it may be necessary to blend various substrates.

Particle size reduction and mixing are desirable, particularly if there are larger particles to wood. This is typically achieved using a hammer mill or flail type of device. Particle size reduction increases the surface area to volume ratio, which assists degradation, as many bacteria and fungi colonise surfaces. It also controls the particle size in the product. It is, however, expensive in terms of plant and energy. Mixing assists in obtaining a homogeneous substrate.

Where compost is produced on a large scale, typically a windrow method is adopted. With this method a row 2-3m wide and 1.5 - 2m high is built. The row is turned at regularly, initially often, and subsequently when the compost is maturing, less often. Maturity is indicated by a low level of ammonia and a high level of nitrate, the culmination of oxidation for ammonia. Depending on the system, climate and substrate, mature compost takes 2 - 4 months to produce.

Some intensive, indoor systems are operated in various parts of the world which have cold winters. Material is composted in channels with forced air introduced from below. Although this is a more capital intensive approach, the main advantages are speed, automation and ability to control odour. Some operations in Canada[1] claim to make compost in 15-30 days in this manner.

The novel method used by Landfill Service Corporation (Hansen,D 1995), mentioned above, is to compost whole fraction MSW on the landfill surface. 150mm high A-section perforated ducting is placed on the open waste surface. A mobile shredder places a 2m high lift of MSW over the duct network. The waste is not compacted and traffic is kept off it. Forced air is introduced to the shredded MSW via the ducts. After typically 4-6 weeks, a significant amount of degradation has occurred. The waste is then compacted, ready for the next lift, the ducting being sacrificed.

The fact that the composting is conducted in situ, has the massive advantage of not having to handle the material twice. Another advantage is that a separate space is not required for composting, although it must be said that a large working face is required. Also any leachate generated from the composting waste will infiltrate into

---

[1] company literature, LH Resource Management Inc. Walton, Ontario.

the wastemass below, thus removing the problem of contaminated surface runoff that can occur on composting areas.

LSC maintain that this system is economic on the amount of landfill void immediately saved. This is true in the short term, and probably during the active life of the landfill. However in the long-term (50-200 years), theoretically the only additional space that will have been created is from the aerobic degradation of ligno-cellulosic material, such as wood, that is refractory in the anaerobic environment.

In a source segregation system, such as that operated in Dundee, also described above, special bins are used to collect the substrate material from households. The bins are called Compostainers, and outwardly appear as normal wheel bins. In fact they have a perforated floor and lid, with a perforated plenum at the base of the bin to ensure aerobic conditions. In this way, the aerobic degradation begins prior to the material being collected, and odours from anaerobic degradation are minimised.

Government Policy

The UK Government's targets for composting are (Great Britain, 1996b):

- 25% of household waste to be recycled or composted by 2000
- 1 million tonnes of organic household waste per annum to be composted by 2000, and 40% of domestic properties with a garden to carry out composting by the year 2000
- 40% of total market requirements for soil improvers and growing media in UK to be supplied from non-peat materials in next 10 years.

Most local authorities in the UK are unlikely to meet these targets by 2000.

Energy Recovery - Comparison With Anaerobic Degradation

In terms of benefit to the environment and sustainable development, the drawback of composting is that there is no energy yield that is easily recoverable on a large scale.

The energy yielding oxidation reaction is part of the degradation process and as such occurs in the composting mass. On a small scale, successful trials have been conducted that recover low grade heat in the form of hot water by a plastic pipe network in the degrading material.

In contrast, anaerobic degradation does not include significant oxidation. Therefore, the main gaseous emission is unoxidised, that is methane. Energy recovery can be achieved through the oxidation of the collected methane.

Aerobic Degradation of Non-Organic Material

Composting of whole fraction MSW has become a political reality within the EU, even if not yet an operational reality, with the likelihood of mandatory pretreatment required by the new Directive on landfill (European Communities. Commission, 1996a). Therefore the biodegradability of materials from non-organic sources has become of interest, as has the degradation products.

The aerobic degradation of synthetic polymers has being researched. Experiments to assess aerobic degradation of an aliphatic polyester (Pettigrew,CA et al, 1995) concluded that although the material was shown to be biodegradable, the rate of biodegradation of these complex high molecular weight polymers can be very slow.

4.5.3 Anaerobic Digestion

Anaerobic Digestion (AD) is the managed process of anaerobic degradation in a controlled reactor environment. Details of the anaerobic degradation process are discussed in the subsequent chapter 'Landfill Technology', as the similarities between the degradation dynamics of Landfill and Anaerobic Digestion are great.

AD is widely used in the waste water treatment industry. It is also used routinely for the treatment of wastes from the food processing industry. In these systems the substrate is a high moisture content slurry, containing organic matter.

There is some interest in using Anaerobic Digestion in the treatment of MSW or the putrescible element of the MSW stream, with a variety of pilot plant investigations in Europe in the last 10 years, and progress towards commercialisation in the last 5 years (Braber,K 1995).

According to Braber, the leading concepts are currently:

> **Dry Continuous** systems which involve a continuously fed treatment system with a dry matter content of 20 - 40%.
>
> **Dry Batch** systems in which a batch is sealed for 2-3 weeks prior to complete emptying. Percolate is recirculated to stimulate mixing and digestion.
>
> **Wet Continuous** systems, which can be divided into conventional slurry systems and anaerobic filters. The former operates with a dry matter content of around 10%. Anaerobic filters operate on a two or multi-phase basis, where hydrolysis and acidification occur in a first vessel and then methanogenesis occurs in a second vessel. High concentrations of methanogens are retained in trapping devices onto which the bacteria can adhere and not be flushed out.
>
> **Co-digestion,** using liquid manure or sewage sludge

It is not been established which is the superior system at this stage.

Segregation at Source for Digester Substrate

Segregation at source is desirable to provide an uncontaminated feedstock. Putrescible kitchen and garden waste is collected in separately from the rest of the MSW stream.

Quality control of the feedstock is more readily achieved and the digestate is potentially a higher value and more marketable material. It is therefore seen, from the process and product point of view, as the best method of procuring the substrate.

Southampton City Council's proposed AD facilities will process 70,000 tonnes of source segregated waste per year (anon, 1996a). Energy derived from the process would supply the city's existing geothermal district heating scheme.

The main problem with Segregation at Source is that it does however suffer from increased costs of collection, and at introduction requires an investment in educating the public. Therefore separation of putrescible material from the combined MSW stream is often attempted using a Materials Reclamation Facility (MRF). Separation at an MRF is costly as well, but is easier to implement and operate than Segregation At Source. However, separation at an MRF is an 'end of pipe' solution, and inevitably leads to a contaminated substrate.

Costs of large scale AD are close to the cost of incineration according to UK operators (anon, 1996a). Landfill is still £ 3 - 4 / tonne cheaper, even in premium areas, such as the south-east England.

AD of a Separated MSW Fraction: The Shewalton Experiment

The Shewalton Pulverisation Plant in Ayrshire, Scotland pretreats MSW prior to landfill, by a wet pulverisation process using a Dano Drum. As part of the DEMOS[1] programme, a pilot plant[2] was set up to anaerobically digest part of the 'fines' fraction produced by the pulverisation plant (Great Britain, DTI, undated). The input to the pulveriser is the whole fraction of MSW, and the output fines passing 15mm were used in the digester. This fraction contains the usual fines fraction of MSW (material passing 10mm), plus macerated organic matter, and fragments of glass,

[1] acronym: Department of trade and industry's Environment Management Options Scheme
[2] Participating parties: Motherwell Bridge Envirotec Ltd; Environmental Energy Ltd; Newcastle University

metals and plastic. The passing 15mm fraction represents around 30% by mass of the incoming MSW stream.

The 25m^3 digester had a loading rate of 750 kg/day and was operated on a continuous semi-dry basis, with a solids content of 20%. Gas production of 150 - 200m^3/tonne organic fines was achieved, with a methane content averaging in excess of 50%.

In a refinement of this process Thames Waste (undated) have incorporated a grit removal stage prior to digestion, which will remove the majority of inert material in the form of grit and fragments of glass and metal. This makes the reactor more efficient, but possibly more importantly, removes unsightly and dangerous contamination from the end product. Thames claim the solids residue from their process is suitable for 'beneficial use in agriculture as a fertiliser/soil conditioner'. However, caution should be applied, as there are likely to be some dis-benefits as well.

The real problem with these systems is that the digestate is contaminated, physically and chemically. The process can be improved to remove much of the physical contamination, but it will be difficult to guarantee that there will be no sharps in the form of fragments of glass or metal. Chemical contamination can be tested for by sampling the product, but because of the lack of control over an unsegregated MSW stream, variability and 'hot spots' are a fact. The chemical contamination in the form of heavy metals will probably always preclude its use as a garden soil improver, the high value market in which the government wants to promote peat-free alternatives. These are the reasons that a Segregation at Source approach is inherently sounder.

Energy Efficiency

The methane produced by anaerobic digestion is a useful energy source. The net energy **output is around 100-150 kWhe per tonne MSW putrescible fraction.** This takes into account pretreatment, digestion, and post treatment, and the figure assumes a typical engine/electrical conversion efficiency of 33%.

In comparison, **composting** has a **net consumption of 30 - 35kWhe per tonne.**

4.5.4 Fermentation

Fermentation of carbohydrate to produce alcohol is an ancient application of biotechnology. Its use outside the food industry to produce fuel is a more recent application, but nevertheless well established. In countries that grow sugarcane, for example Brazil and Zimbabwe, the production of ethanol from process by-products is routine[1]. The by-product molasses is used as a substrate in large scale fermentation and distillation, to produce ethanol of 99.9% purity. Ethanol is a versatile fuel, which can be used in spark ignition internal combustion engines. It can be blended with petrol, up to around 18% ethanol, without modification to or adverse effect on the engine. In Zimbabwe, 'petrol' purchased at a filling station is around 14% ethanol. In Brazil, vehicles and tractors are manufactured that operate on 100% ethanol.

The major advantage of ethanol, in terms of sustainable development, is that:

- it is carbon dioxide neutral
- it is a renewable resource

The second point must be qualified; the substrate material must be produced in a sustainable manner.

Paper contains a high percentage of the carbohydrate cellulose. This can be used as the substrate for ethanol production. In a multi-phase process using waste paper, researchers at the University of Toronto (Wayman,M et al, 1993) have been able to convert up to 85% of the cellulose to ethanol in a pilot plant.

The experiment used the light fraction from Material Recovery Facilities in Europe and the USA. This fraction is usually destined to be a Refused Derived Fuel. It contained about 55% paper, and was overall around 50% cellulose. In a process

[1] Triangle Ltd, Triangle, Zimbabwe.

employing fungi, enzymes and bacteria, the final stage of which is fermentation, ethanol yields of 460 litres/ ton of waste were achieved.

Costings for a large scale plant, producing 40 Ml/year show that it is economically feasible, provided there is a small tipping fee for the waste paper.

4.5.5 Other Novel Treatments

'Thermo Tech'[1] have developed a novel application of biotechnology in recycling of food and other putrescible waste. In North America, 28% of food produced ends up in the solid waste stream, amounting to over 100 million tons per year. Diverting some of this material from disposal, and then producing a valuable end product is the strength of the Thermo Tech process.

The principle is to use thermophilic aerobic bacteria, to process and pasteurise the material. In some respects the process may be likened to composting, but with the substrate in a slurry form.

The feedstock is food waste, consisting vegetable/kitchen waste and of out of date goods e.g. Coca-Cola, cat food, etc. This material is turned into an watery slurry by a "hydro-pulper". The material goes into an aerobic reaction vessel for just 24 hours, in which a temperature of 70°C is maintained. The resulting biomass of pasteurised food waste and dead bacteria is dewatered, the water being recycled. Further drying and pelletisation produces a commercially valuable animal feed supplement, having a protein content of around 18%.

The key to the financial viability of the system is that there is revenue at both ends of the process. A 'tipping' fee is levied on material input and the output is sold as an animal feed. The reason that out of date goods are included is that ThermoTech gives food and beverage manufacturers a guarantee of 'destruction' ie. their out of

---

[1] company literature, and visit to Toronto plant by author. Thermo Tech™ Technologies Inc., Langley, BC, Canada V3A 8H9

date stock or returns will not end up in a back street market, as is the case sometimes when sent for landfill. Of course, this material is dealt with at a premium.

The company also processes sewage sludge (on a separate line) claiming it to be a superior treatment option to anaerobic digestion, in terms of pasteurisation and a lower final mass of solids produced.

Comparison of System with Composting

The key advantages of the system are speed of conversion (1-2 days), ability to control of the system, and the high value feed product, given a high quality substrate.

The disadvantage is that it is more resource intensive. This is only justified if a high value product is obtained.

Comparison of System with Anaerobic Digestion

The key advantages of the system are speed of conversion, integral pasteurisation, less solid residue and the high value feed product, given a high quality substrate. The disadvantage is that there is no energy yield. In North America, the application of this technology is growing fast.

4.6 High Temperature Treatment of Waste

In contrast to the previous Section 4.5 Biotechnology in the Treatment of Wastes, this section considers the treatment of MSW by what can be described as a 'process chemistry' approach. The optimum environment in which the reactions occur is often different to conditions that are found in the natural environment, and typically include elevated temperature and/or pressure.

4.6.1 Incineration

The subject of incineration of MSW has evoked much study. It is not within the scope of this thesis to consider incineration in any depth. However, as the other major disposal option, the basic issues will be stated, so that incineration as a waste management option can be evaluated in comparison with the alternatives. In addition, incineration has direct relevance to landfill because of the disposal of incinerator ash.

Historical Background

Historically, in Britain incineration has been used extensively since the last century for the purpose of destruction. Latterly, in the last few decades, incineration has been used in the disposal of MSW. In the UK, energy recovery to any significant extent has not been practised, with a few exceptions. The standard of operation of these incinerators was poor, and emissions not controlled adequately. This is in sharp contrast to many European countries which had well operated plants. As a result of EU legislation of emissions (European Communities. Council, 1989a, 1989b), many of Britain's ageing and polluting incinerators were forced to close in 1996, on implementation of new emission limits.

Modern MSW incinerators are clean and non-polluting in comparison to the unpopular plants that did exist. The public, nevertheless, remember the older plants, and this has led to a great deal of public antagonism to proposed incinerators in the UK.

Purposes of Incineration

Incineration can have a number of objectives.

1. **Destruction.** The prime purpose of incineration is destruction - conversion of toxic or dangerous substances to more benign and stable substances. This is achieved by high temperature controlled combustion. Many types of hazardous and difficult wastes, which have limited disposal or reprocessing options, are dealt with in this way.

Landfill of untreated MSW is seen in some parts of the world, notably many north European countries, as an unacceptable pollution threat. Incineration is seen as a necessary pretreatment for MSW, prior to landfilling of the residues.

MSW is a high volume waste and is of low value in terms of the amount of disposal charge it can attract. This is predominately due to competition from landfill. Therefore, within the context of MSW management, other factors become important.

2. Volume Reduction. One of the properties of the incineration process is that the volume of solid waste is reduced. Incineration reduces the volume to around 15-30% of the original. Available landfill capacity that is close to sources of waste is becoming scarcer. Incineration is seen as a useful tool in utilising less landfill.

3. Recovery Of Value. With contemporary views on sustainable development, the recovery of value from waste has become a priority. One method of recovering value is to use the energy content of waste. Although a little misleading as there are other methods of recovering energy from waste, incineration with energy recovery has become known as 'Energy from Waste' (EfW) and 'Waste to Energy' (WtE).

In the table below the energy value of MSW, and MSW derived fuels is shown together with traditional fuels.

Table 4.3 Energy From Waste vs. Traditional Fuel

Fuel	Net Calorific Value MJ/kg
Oil	40
Mixed Plastic Waste	25 - 40
Coal	25
Packaging Derived Fuel	20
Refuse Derived Fuel	15 - 17
Municipal Solid Waste	10
Wood	8

Source: Association of Plastics Manufacturers in Europe (Mader, F. 1996)

What is clearly shown is that MSW has a significant, but low energy value when compared to conventional fuels. However, if fuel enhancement is conducted, or only a particular element of the MSW waste stream is utilised, the energy value is more comparable to traditional fuels. Mixed plastic waste has a energy content between that of coal and oil; its use as a fuel in industry is discussed in Section 4.6.3.

Waste to Energy

MSW is a heterogeneous material and the different elements of the MSW waste stream have different properties as a fuel. The following table shows typical calorific values and moisture contents.

Table 4.4 Typical Heating Value of Principal Constituents of Household Waste

Material	Calorific Value, MJ/kg As Received	Moisture Content (Wt %) As Received
Paper and paper products	12	30
Plastic film	27	25
Dense plastics	30	15
Textiles	15	25
Misc. Combustibles	13	25
Putrescibles	6	65
Fines (<10mm)	4	40

Source: Waste Management Paper 28; Great Britain. DoE, 1991

What can be clearly drawn from this is that plastics are the most energy rich components of the MSW waste stream. They compare closely with the energy value of conventional fuels (see Table 4.3 for conventional fuels). Paper, textiles and miscellaneous combustibles are moderately energy rich, at around one third that of oil, or half that of coal. The high moisture content of putrescibles and fines contributes to their low energy yield.

When these data are combined with a 'typical' MSW characterisation, an appreciation of which components are significant producers of energy can be ascertained. The results of this calculation are shown in Table 4.5 below.

The calculation shows that plastics contribute nearly half the energy, at 43%, paper being the other major contributor. Surprisingly, putrescibles are shown to make a significant contribution as well. However, during a process of 'fuel enhancement', some incinerator operators[1] remove as much putresible material as possible, as well as fines and metals. Ironically, the biologically active putrescible material then often goes to landfill, untreated and unstabilised.

Table 4.5 Energy Contribution of Elements of MSW Stream

Materials	Composition[2] %	Energy Value MJ/kg waste	Energy Value % for unit mass waste
Paper and paper products	25	3	30
Plastic film	7	1.89	19
Dense plastics	8	2.4	24
Textiles	3	0.45	4
Misc. Combustibles	2	0.26	3
Putrescibles	28	1.68	17
Fines (<10mm)	9	0.36	4
All other non-combust	18	0	0
	100	10.04	100[3]

[1] such as Peel Resource Recovery, Ontario.
[2] source of composition data; Great Britain. Scottish Office, 1994
[3] figures do not sum to 100 due to rounding

If the source of the elements in the MSW stream is considered, it is found that about **half the energy value comes from renewable sources,** although this does not include any non-renewable input during processing and transport of the material.

Effect of Recycling

Operators of WtE facilities are in the unfortunate position of having far less control of their fuel than a conventional power plant. The dynamics of the MSW stream combined with recycling mean that there is likely to be a reduction in the 'dense plastics' and 'paper' fractions, which are the most significant energetically.

Operators of major plants, like the South-East London Combined Heat and Power, believe that recycling and WtE are not incompatible, provided they are part of an integrated waste management programme(Atkins,G 1996). They point to experience in both Europe and the USA.

In France, incineration of segregated plastic waste for energy recovery is considered a valid 'recycling' process. This adds ambiguity to the Hierarchy of Waste Management. It is part of a wider discussion over the comparative benefits of recycling plastics or recovering value in the form of energy.

Carbon Dioxide Emissions

Carbon Dioxide emissions have been discussed previously in Section 2.4.1 Climate Change. With reference to that section and the section above it can be stated that, although non-renewables contribute around half the energy value, they contribute less than half the carbon dioxide emissions. Porteous (1997) maintains that MSW contains 24% carbon by mass, and of this 85% is of paper and vegetable origin. He therefore contends that, as a fuel, MSW is 85% carbon dioxide neutral.

This assertion must be qualified; the overheads of manufacture and operation of incineration plant, transport and disposal of ash are high, in terms of carbon dioxide production. The whole process of recovering value should be studied not just the carbon dioxide neutrality as a fuel.

Efficiency of Incineration

The thermal efficiency of a Waste to Energy facility is 22-25% when producing electricity only (Porteous,A 1997). This compares unfavourably with conventional fuels; a modern coal-fired power station has a thermal efficiency of around 40%, and new combined cycle gas turbines are even higher. Removal of inert materials and high moisture putrescibles would probably improve the efficiency, but would of course have implications for the carbon dioxide neutrality.

The lower efficiency MSW as a fuel is partly due to its heterogeneity, but a further reason is the presence of chlorine in the fuel (substantially from PVCs). This can cause high temperature corrosion on superheater tubes. For this reason, WtE boilers are operated at a lower temperature and pressure than conventional plant.

As a result the steam produced in less energetic, and less energy can be extracted from it before its only use is as a heat source. Therefore, for serious exploitation of energy from waste, the low grade heat has to be used. This is usually achieved by a district heating scheme. This can raise the efficiency of a WtE facility to 60 - 80%. The Bollmora district of Stockholm has a system that provides heat for 11,000 people from 13,000 tonnes of RDF per year (Porteous,A 1997).

MSW Incineration Ash

Ash from MSW incineration has a number of sources. Bottom ash and slag is the heavier material that remains at the grate or base of the incinerator. Fly ash is separated from the flue gases, usually by filter membranes. Both ashes are contaminated and have high levels of chloride, but the fly ash contains high levels of dioxins and other heavy metals. This means it needs to be disposed of very carefully, at high cost to specialised landfill.

One of the major aims of incineration is stabilisation, and it is widely taken for granted that MSW incinerator ash is inert. The Royal Commission on Environmental Pollution (Great Britain, 1993a) stated in its 17th Report, that incineration was the preferable method for 'conversion of heterogeneous and unstable wastes to a stable state'. However, some respected researchers (Forstner,U 1996) disagree and contend that in the long term calcium, chloride, sulphate and heavy metals will be released from bottom ash and slag. Recent experiences in the USA (Musselman,C et al, 97) relate explosive levels of hydrogen (>5%) emanating from ash monofills, and temperatures up to 68°C being generated. This reaction is thought to be caused by the 3 - 6% of elemental aluminium in the ash.

In the long term there are concerns about the implications for "chemical time bomb" which is a time delayed and non-linear response (Fleming,G 1992). For example, a toxic metal can break out once a specific buffering capacity of the surrounding material has been exceeded, or there is a change in the conditions that cause it to be immobilised.

Re-use of bottom ash is possible as a construction fill material, and this is practised in some European countries. Research has also been conducted in the USA on encapsulating bottom ash in bitumen, and using it as road base (Porteous,A 1997).

UK Policy

A seminal review of the incineration of waste was conducted by the Royal Commission on Environmental Pollution. Their seventeenth report titled 'Incineration of Waste' was published in 1993 (Great Britain, 1993a).

In the wide ranging report, comparisons with landfill are made, and in particular the fate of carbon in the waste stream. Calculations put forward show that disposal to landfill is significantly more costly than incineration with energy recovery, in terms of greenhouse gas emissions. This key finding is the basis for their recommendation that "the government should give targets to waste disposal authorities for the recovery of energy from municipal waste."

This finding does not appear to take any account of the greenhouse gas implications of manufacture of a large incineration plant. These will be considerable. Although the landfill site that will accommodate the ash will only occupy around a quarter of the volume, it will have to be more thoroughly engineered to contain the highly contaminated ash mixture.

Of the emissions to the atmosphere the report states that the emissions are 'most unlikely to cause any health effects'. The report consider that an acceptable incremental risk of death is greater than 1 in 1,000,000. It reports that the consensus among UK and USA regulatory authorities, is that above this, the measures to achieve a further improvement would not be justified in terms of the benefit gained.

Overall the report concludes that "Incineration, followed by landfilling of the solid residues, will in our view prove to be the best practicable environmental option for municipal waste."

Subsequent policy has generally tended to follow this lead. In particular the target (Great Britain. DoE/WO, 1995) to reduce the amount of controlled waste going to landfill to 60% by 2005, signals not just increased minimisation, reuse and recycling, but also an increase in incineration.

EU Policy

Directorate-General XI of the Commission of the European Communities is responsible for the Environment, Nuclear Safety and Civil Protection. It states (European Communities. Commission, 1997b) that "experts believe that landfills ought to be progressively replaced by incinerators and that they should only be used in the future to bury the most 'stubborn' waste products (those that can't be processed any further). Ironically, these products include ashes from waste incineration plants."

Therefore, policy in both the UK and the EU is to promote incineration, despite some significant drawbacks, and its high cost.

4.6.2 Pyrolysis and Gasification

Pyrolysis and Gasification are thermal 'cracking' processes in which polymer chains are broken into shorter chains. All organic[1] materials in the MSW are capable of being cracked; paper, plastics, and putrescible materials. Definitions of the difference between gasification and pyrolysis are not clear in the literature. Gasification, it has been stated (Phillips and Carey, 1997) has the prime purpose of producing gas. Gasification takes place in the presence of air at a relatively high temperature (1000-1400°C) and produces low molecular weight gases. Pyrolysis takes place at a lower temperature (600-900°C) in the absence of oxygen. The heat source is external to the pyrolysis vessel. Gas, oils and a high carbon solid residue are produced (Clark,C 1994).

The potential advantages of this technology is that chemical feedstocks as well as a fuel can be created. In addition, gas and liquid products can be cleaned prior to use as a fuel, thus controlling emissions more effectively than costly ' end of pipe' solutions that are used in incineration.

There has been considerable research on the subject (Solantausta et al, 1995) in the past in the USA and currently within Europe utilising biomass as a fuel.

4.6.3 Elements of the Waste Stream as a Secondary Fuel

There has been growing interest in use of elements of the waste stream as secondary fuels in energy intensive facilities such as cement kilns. The use of contaminated solvents and scrap tyres has been investigated, but now there is interest in plastic packaging waste. In trials (anon, 1997a), it has been shown that in fact 100% substitution of primary fuels can be achieved, and in the UK there is sufficient plastic packaging waste to entirely satisfy the 1.1 GW requirement of British kilns.

---

[1] in the chemical sense, indicating carbon containing rather than of vegetable origin.

4.7 Comparison of Waste Management Options

Minimisation - reduction of waste at source - should always be the default waste management technique. If conducted properly, minimisation through moves towards Clean Technology, embracing both design and operation, should intrinsically be the most sustainable method of dealing with waste.

Only after the possibilities for minimisation have been fully explored should the subsequent levels of the waste management hierarchy be considered.

4.7.1 Externalities

Comparison requires some medium of measurement. Comparison is possible without a medium of measurement, but then it is difficult to show that the comparison is not subjective. Usually, money is the medium of measurement due to ease of numerical comparison and the market orientated society that we, in the developed world live.

Costs in a perfectly free market are in theory a true and absolute measure of a commodity's worth. The 'free' markets of capitalist societies are rarely perfectly free. Factors outside the free market are known as 'externalities', that is they are external to, and do not take a part in the activities of the market place.

Examples of externalities in the context of waste management, are landfill gas emissions to atmosphere or dioxin emission from incinerators. These emissions are uncosted, in terms of the operation of the facility, do not take any part in financial decision making. They are however disbenefits to the environment and ourselves in the long term, and even in the short term in ways that we have not realised. For the free market to take account of these disbenefits, the factors causing them need to be internalised, that is brought into the marketplace. This can be done by allocating a cost to the parameter. For instance, the regulator could internalise the externality of methane emission from landfill, by charging the operator a pro rata fee for emissions. [A 1993 study (CSERGE Warren Spring Laboratory, 1993) for the UK government concluded that the global cost of methane emissions were £72/tonne CH_4 .] This would have the effect of making methane emissions to the atmosphere economically unattractive.

Costing of factors such as methane emission is difficult, and in fact usually worked out by establishing scenarios in order to cost the effects. For example, if a certain sea level rise occurs, projected to be caused by a particular level of greenhouse gas emissions over a period, the loss of land associated with that rise, or the cost of its defence, can be said to be the cost of that level of emission.

It is much more difficult to cost human mortality or morbidity. This is the problem with externalities such as dioxin emission from incinerators. A further problem is the there is often some contention between interested parties, over the real effects of such emissions. Where there is not overwhelming scientific proof, judgement can be subjective. Nevertheless, the Precautionary Principle does not require overwhelming proof.

In practice, regulation controls the level of emissions so that they are not excessive. However, this provides no incentive to reduce the emission further than the regulatory standard. When conducting a comparison, the regulatory mechanism is not part of the measuring system. Therefore the externality stands.

4.7.2 System Boundaries

The outcome of a comparison largely depends on where the boundaries of the system that is being considered are set, and thus there will generally be some room for disagreement from parties with vested interests. So that externalities do not stand, it may be necessary to consider the entire Life Cycle Analysis of all the components of the System. This is inevitably a large task, which is the reason that the extent of a System is often limited by boundaries.

If comparisons of Systems are to be meaningful, and the whole Life Cycle of components in the System is not going to be assessed, then the setting of System boundaries is critical.

4.7.3 Making Comparisons

It can be seen from the foregoing that a comparison of waste management options is not entirely straightforward. It has been the established hierarchy of options that incineration was preferable to landfill, and composting to both of these. However, the recent Europe wide study by Coopers & Lybrand (1996) for the European Commission, shows that the hierarchy may need amending.

Coopers & Lybrand approached costing the different waste management options on the basis of 'total net economic cost'. This is the **combined economic and environmental** cost.

The study concludes that:

- Recycling offers the most significant environmental benefit, although it is not consistently preferable to other waste management options, it depends upon a variety of factors, notably the materials being recycled.

- Municipal composting of organic waste results in net environmental costs, most of which are associated with transport.

- Incineration with energy recovery leads to significant net environmental benefits if it replaces a marginal power source (ie. highly polluting old coal fired stations), but has significant nets costs if it replaces the EU average power source

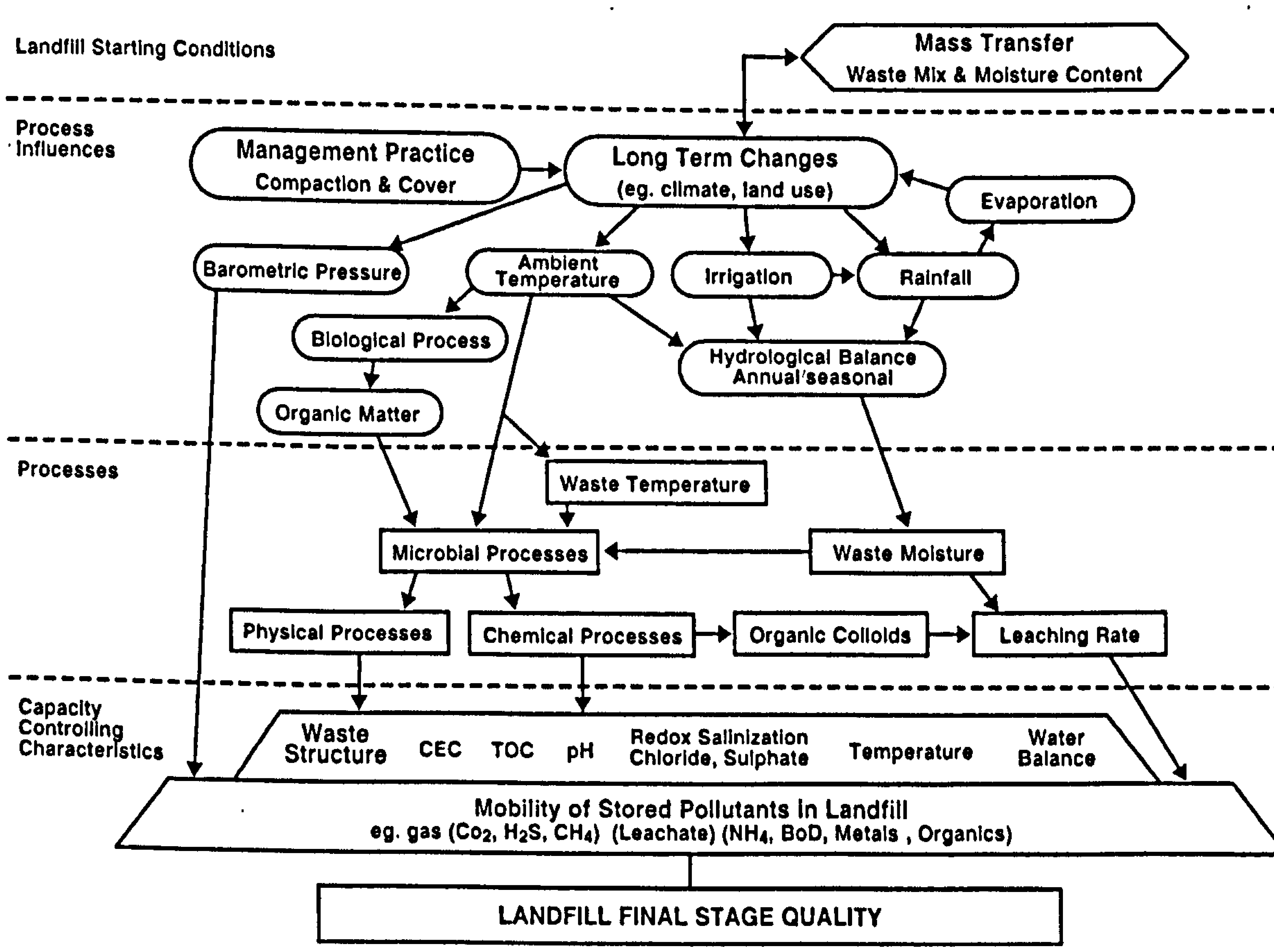
- Landfill has small net environmental costs with and without energy recovery

The boundary of the system used by Coopers & Lybrand excluded the environmental disbenefits associated with both groundwater pollution by landfill leachate, and air pollution by dioxins from incinerators. Both of these items are difficult and contentious to cost. However in omitting them, parties that disagree with the findings of the report, have been given a tool to discredit the rest of the generally comprehensive and thorough study.

5 LANDFILL TECHNOLOGY

The technology of landfill is a diverse and necessarily multi-disciplinary field. Landfill degradation is essentially a microbiological process, but it is occurring within a wastemass in which the hydraulic and geotechnical properties are important. To enhance and gain some control over the landfill process as a whole, requires an understanding of the sub-processes. This understanding is not entirely at the theoretical level given the current state of knowledge, and therefore empirical knowledge is important. The diagram below shows the relationship between various factors in the landfill process.

Figure 5-1 General Diagram of Landfill Processes



Source: Fleming,G 1992

From the diagram, an overall picture is defined, showing the complexity of the interactions that will lead to the wastemass reaching final stage quality.

This chapter discusses the process occurring in and affecting the degradation of the wastemass.

Editorial Note

Unless specifically stated, the term 'waste' used in this chapter should be taken to mean Municipal Solid Waste. The abbreviation MSW is also used.

5.1 Pretreatment of Waste

There are several reasons why waste may be processed in some way prior to landfilling. They are:

1. Space. Most pretreatment processes reduce the volume of waste to be landfilled, and therefore be justified on purely economic grounds.

2. Handling and Ease of Transport.

3. Pollution Abatement. Some processes render waste less potentially damaging to the environment.

4. Enhancement of Degradation. Pretreatment processes that start the degradation process or condition the waste to enhance degradation once landfilled.

The pretreatment processes that are practised may achieve just one of the above or all of them, and to varying extents.

5.1.1 Shredding

Shredding is the mechanical reduction of particle size, usually by a device with rotating blades that cuts, breaks or crushes the material in the waste stream. Typically the length of time to process the material is very short; the material passing through the shredder in a matter of seconds. Some machines shred by shearing and typically the cutting rotor operates at a low speed. Other reduce the particle size by impact, having a high rotor speed. Although built specially for the processing of waste, many shredders are based on machines developed originally for shredding materials like tyres, scrap metal and wood. Shredding consumes a significant amount of energy. This is usually in the form of a high grade energy source such as diesel oil or electricity.

5.1.2 Pulverisation

Pulverisation pertains to turning to dust or fine powder (Chambers Concise Dictionary, ed. by Schwarz,C 1991). Some particular types of waste may be pulverised, in for example a hammer mill, in which a high speed rotor smashes the substrate to pieces small enough to pass through a screen. This is costly in terms of energy use and wearing parts of the machinery .

In terms of treatment of MSW, violent particle size reduction in this manner is not normal practised. It is deemed unnecessary, inappropriate and expensive. The word pulverisation, in terms of treating MSW, is probably best known in relation to the Dano Drum Pulveriser[1]. This is however something of a misnomer. The pulverising action is a gentler breaking up of the material, in which shearing and impact do not play a significant role, and in which moisture may be added.

The Dano Drum is a rotating tube 25m long and 4m in diameter. It rotates at about 4 revolutions per minute, tumbling the waste. It is a continuous process in which waste is fed in at one end and progresses to exit at the other. Residence time for pretreatment of waste is around four hours. Throughput for this set-up is approximately 25 tonnes per hour.

---

[1] Head Office: Dano AG, PO Box 4, Logans Rd, Motherwell, ML1 3NP, Scotland

5.1.3 Sorting

Sorting of the MSW is practised usually to recover materials. In terms of the biodegradable substrate, removing elements from the waste stream may have an effect on the microbial activity in the landfilled wastemass.

Carbon: Nitrogen Ratio

The carbon: nitrogen ratio of MSW is below optimum for microbes operating in the landfill environment. Thus if carbon sources such as paper were removed, the ratio would move further away from the optimum. Conversely if, less nitrogen was introduced by for example reducing the amount of proteinaceous food waste, then the ratio may become more favourable.

The Role of Surfaces

Not only the biodegradable elements in the waste stream are significant in terms of the microbial activity. Many microbes in the landfill environment operate preferentially as a biofilm, rather than in a solid mass (Watson-Craik and Robin-Jones, 1994). This is mainly for reasons of substrate availability. The role of surfaces, including that of plastic sheet may be important in the degradation process.

Structural Components

Non-biodegradable components in the waste stream play a part in the structure of the wastemass. Their removal from the waste stream has implications for the physical properties of the wastemass, affecting parameters such as permeability and porosity. For example, the removal of plastic film might increase permeability, but the removal of tin cans might reduce porosity.

The discussion above is not an argument against recycling. It is merely stating that the composition of the waste stream affects the landfill process, and therefore the implications of altering the composition artificially should be considered carefully.

5.1.4 Other Pretreatments Prior To Landfilling

Some countries consider incineration, composting and anaerobic digestion as pretreatment processes, prior to landfill. However the author contends that they are processes with objectives of their own, which change the substrate into a different material, and produce waste as a by-product that needs to be disposed of. As such they are not considered as pretreatment here.

The popularity of pretreatment is primarily governed by economics in the UK. In other parts of the world, for example Germany or France, it is a legislative matter, it having been decided in the political arena that it is desirable. This may also become the case in the UK when the EU directive on landfill is established.

5.2 Biodegradation in the Management of Wastes

5.2.1 Introduction to Biodegradation Processes In Landfill

Landfill gas is a rich and renewable source of energy that has come to be exploited on an increasing scale in recent years. The microbiology and biochemistry processes of gas generation from solid waste are not well understood, despite being of fundamental importance to both the stabilisation of refuse, and energy recovery from landfill.

Generally, parallels are drawn between anaerobic digestion systems and the anaerobic environment of the degrading waste in a landfill. Specific anaerobic biodegradation systems, such as sludge digesters or ruminants have been thoroughly researched and are fairly well understood. This body of knowledge has been transposed on to the landfill environment. In landfill, the operating conditions are distinct from other anaerobic environments and, consequently, the microbial ecology is unpredictable. Landfill microbiology and biochemistry cannot be directly analogous to other anaerobic systems, although the general process of anaerobic digestion is undoubtedly involved in landfill waste degradation (AFRC, 1988).

In recent years there has been much research on landfill microbiology (Archer, Reynolds and Blakey, 1995), and a better understanding of the identity and role of specific micro-organisms in the degradation process has been established. The heterogeneity of landfill biodegradation, in terms of parameters such as substrate or environment, means that there is still much work to be done.

The substrate for biodegradation when considering landfill is obviously material in the waste stream. Of importance though is not the type of product that has become part of the waste stream, but what biodegradable components are contained within it.

The biodegradable components in the waste stream are of either organic and inorganic nature; that is containing carbon or not containing carbon. The organic element of waste degradation is of most importance because:

- organic compounds form the bulk of the waste stream
- to recover energy from landfill we harvest methane, a hydrocarbon

The degradation of inorganic materials, mainly inorganic salts, is significant as well. The processes involved are not entirely separate from the degradation of organic compounds, and of course the products of these reactions become part of the emissions of the landfill (Great Britain. DoE, 1995b). Sulphate reducing bacteria play a particular role in reducing the redox- potential to a level favourable to methanogens (Watson-Craik,I 1994).

5.2.2 The Stylised Biodegradation Process Of Landfill

The main organic substrates for biodegradation in solid waste are biological polymers, also known as biopolymers. Biopolymers in waste are large molecules, typically cellulose, proteins and lipids.

There are four stages in their breakdown into the final products of methane, carbon dioxide and water. The first is aerobic, the subsequent three stages are anaerobic.

Stage 1 Hydrolysis / Aerobic Degradation. Hydrolysis is the breakdown of polymers into monomers i.e. the constituent units that made up the polymer. The first stage is aerobic, that is in the presence of oxygen. It occurs in waste prior to, during and for a period after, placement of the waste in the landfill. Cellulose is converted to soluble sugars, proteins to amino acids and lipids to long chain carboxylic acids and glycerol. Carbon dioxide and water are by products.

The process is very similar to composting and is highly exothermic, raising the temperature of the wastemass to more than 35°C. Carbon dioxide is produced in significant quantities, and in a passively vented site, this will typically be evolved as a gas saturated with water vapour. The author has measured gas temperatures of 70°C at a commercial site during this stage of degradation. The heating in this stage is important to the whole degradation process. The subsequent stages are not significantly exothermic, but are driven by mesophilic bacteria, so it is desirable for the wastemass to be brought well into the mesophilic range, the optimum being around 35°C.

The pH of the wastemass drops during this stage. This is explained by the insufficient amount of oxygen present to oxidise the soluble sugars. These are readily degradable and as oxygen becomes more scarce are converted into fatty acids (Barlaz, Ham and Schaefer, 1989).

Stage 1 ceases when all the oxygen trapped in the wastemass is consumed. The wastemass then becomes anaerobic.

Stage 2a Acidogenisis: Anaerobic Hydrolysis. The brevity of Stage 1, caused by the limited oxygen supply, means that the substrate materials are not fully hydrolysed. As anaerobic conditions develop facultative anaerobes prevail, in this case fermentative bacteria. These bacteria excrete exo-enzymes to continue the hydrolysis of the biopolymers.

Stage 2b Acidogenisis: Fermentation. The same group of bacteria convert the products of hydrolysis to soluble intermediates such as volatile fatty acids (VFA), acetate, hydrogen and carbon dioxide. The type of VFA produced depends on the initial substrate and the environmental conditions. The most common VFAs are propionic, acetic, butyric, iso-butyric, valeric and iso-valeric. The pH falls further as VFAs accumulate.

Stage 3 Acetogenisis. The third group of bacteria are obligate anaerobes, more specifically obligate hydrogen-producing acetogens. They oxidise the fermentation products to acetate, carbon dioxide and hydrogen. The conversion of intermediates, such as butyrate and propionate, is only thermodynamically favourable in low concentrations of hydrogen. Hydrogenophilic methanogens (in Stage 4) maintain a low hydrogen concentration environment for these reactions to continue.

Should a build up of hydrogen occur, the intermediate products cannot be oxidised to form the main feedstock for methane production, and a build up of propionic acid occurs. Acetogenic bacteria alter their metabolisms to produce ethanol and lactic acid rather than acetate. This process is known as 'acid souring'.

Stage 4 Methanogenisis. The fourth group of bacteria is the methanogens, which are the most obligate anaerobic organisms known; they are inhibited or killed by trace amounts of oxygen (Luton et al, 1995). They may be divided into two types: Acetophilic and Hydrogenophilic. Methanogens can only utilise a number of substrates, which are respectively; acetate and, hydrogen + carbon dioxide. These bacteria work in harmony with the acetogenic bacteria, maintaining a suitable environment in which the acetogens may continue to produce substrate for them. The products of the methanogens are carbon dioxide and methane.

The two reactions may be shown as:

acetate dismutation by Acetophilic Methanogens

$$\underset{\text{acetate}}{CH_3\text{-}COO^-} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{methane}}{CH_4} + \underset{\text{bicarbonate ion}}{HCO_3^-}$$

and the reduction of carbon dioxide by hydrogen, by Hydrogenophilic Methanogens

$$\underset{\text{hydrogen}}{4\,H_2} + \underset{\text{carbondioxide}}{CO_2} \rightarrow \underset{\text{methane}}{CH_4} + \underset{\text{water}}{2\,H_2O}$$

In anaerobic digesters, the substrate acetate, utilised by acetophilic methanogens, is found to be the main source (70%) of methane production (Zehnder et al, 1978). Hydrogenophilic methanogens, utilising hydrogen and carbon dioxide produce the balance. However, it has been shown (Barlaz and Ham, 1993) that the hydrogenophilic reaction is far more energetically favourable.

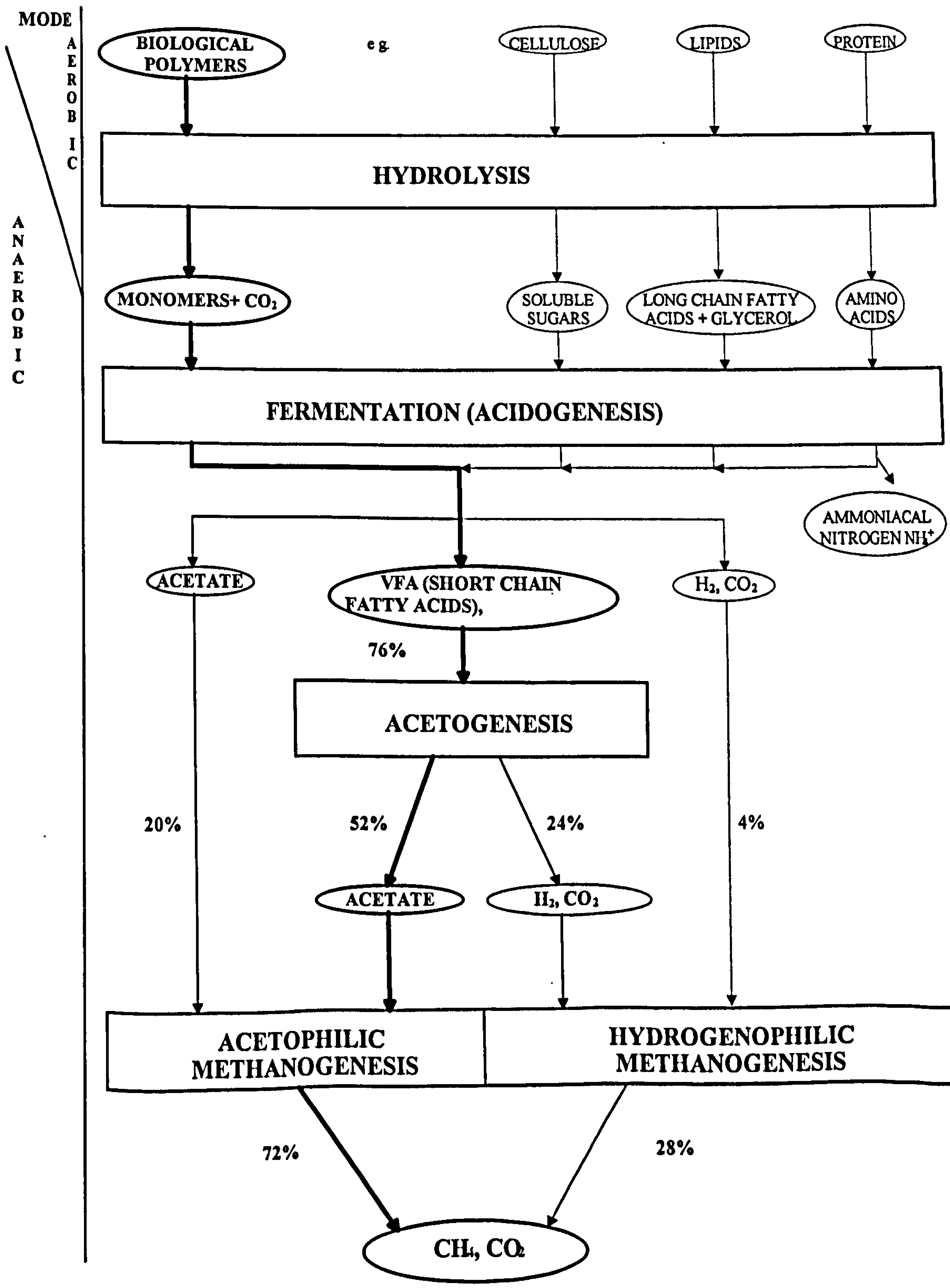
Figure 5-2, overleaf, summarises the whole degradation process, showing the pathways from substrate to methane. In the diagram, the four process stages are indicated by rectangular blocks, while substrate/products are shown in ellipses. For the first process stage, Hydrolysis, examples of substrates and products are shown on the right of the diagram, while the generic substrate and product is shown on the left.

The Fermentation process stage produces similar product from different substrates. The exception to this is ammonia which is produced by the fermentation of amino acids.

The mode of the process stages is given at the extreme left of the diagram. It shows that Hydrolysis is carried out in both the aerobic and anaerobic environment. All subsequent process stages are entirely anaerobic.

The diagram indicates each pathway's significance. However the figures indicating importance of routes are based on anaerobic systems such as marine sediments, bogs, marshes, trees, and digesting sludge, and not from research on waste.

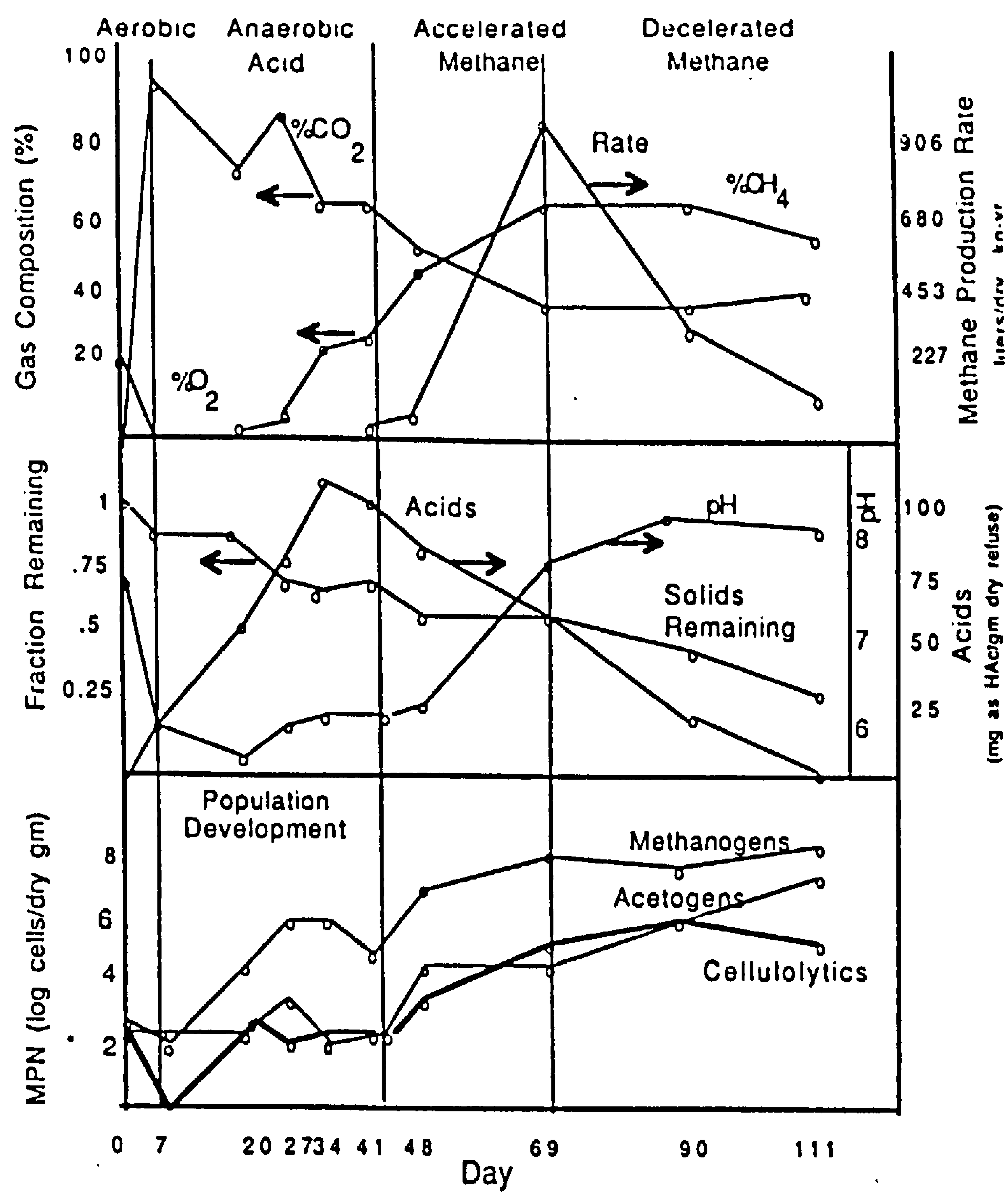
Figure 5-2 The Stages of Organic Waste Degradation



Adapted from: Barlaz,MA 1993; AFRC, 1998; Gendebien et al., 1992; Great Britain. DoE, 1995b; Zehnder et al, 1982.

In the figure below Barlaz, Ham and Schaefer (1989) have measured various parameters during the decomposition of waste in a laboratory lysimeter experiment. Samples of shredded waste were incubated in two litre containers at 41°C, and leachate recirculation was practised. The classification of the stages is slightly different to that given in the text above.

Figure 5-3 Observed Trends in Refuse Decomposition with Leachate Recirculation



Source: Barlaz, Ham and Schaefer, 1989.

Notes. Arrows indicate which scale should be read. Gas volume data corrected to dry gas at standard temperature and pressure. Acids expressed as acetic acid equivalents. "Solid Remaining" is the ratio of cellulose plus hemi-cellulose removed from a container divided by the weight of cellulose plus hemi-cellulose added to the container initially. Methanogen Most Probable Number (MPN) data are the log of the average of the acetate- and H_2/CO_2-utilising populations.

"Aerobic" is the same as Stage 1. Barlaz then amalgamates Stages 2 and 3 into "Anaerobic Acid". Stage 4 is split into "Accelerated Methane" and "Decelerated Methane".

The graphs show that all three groups of bacteria were present in the waste stream. The population of methanogens continues to grow until the rate of methane production peaks, after which the population remains steady. However, the population of Acetogens continued to grow. As the remaining substrate fell below 50%, the population of cellulolytic bacteria began to fall.

The pH level continues to rise above neutral, after the peak of gas production, to a level that may be considered above the optimal zone.

Limiting Factors in Methanogenisis

In lysimeter research on MSW, it has been shown that in the longer term, after the utilisation of the initial flush of VFA, the limiting factor is polymer hydrolysis (Barlaz and Ham, 1993).

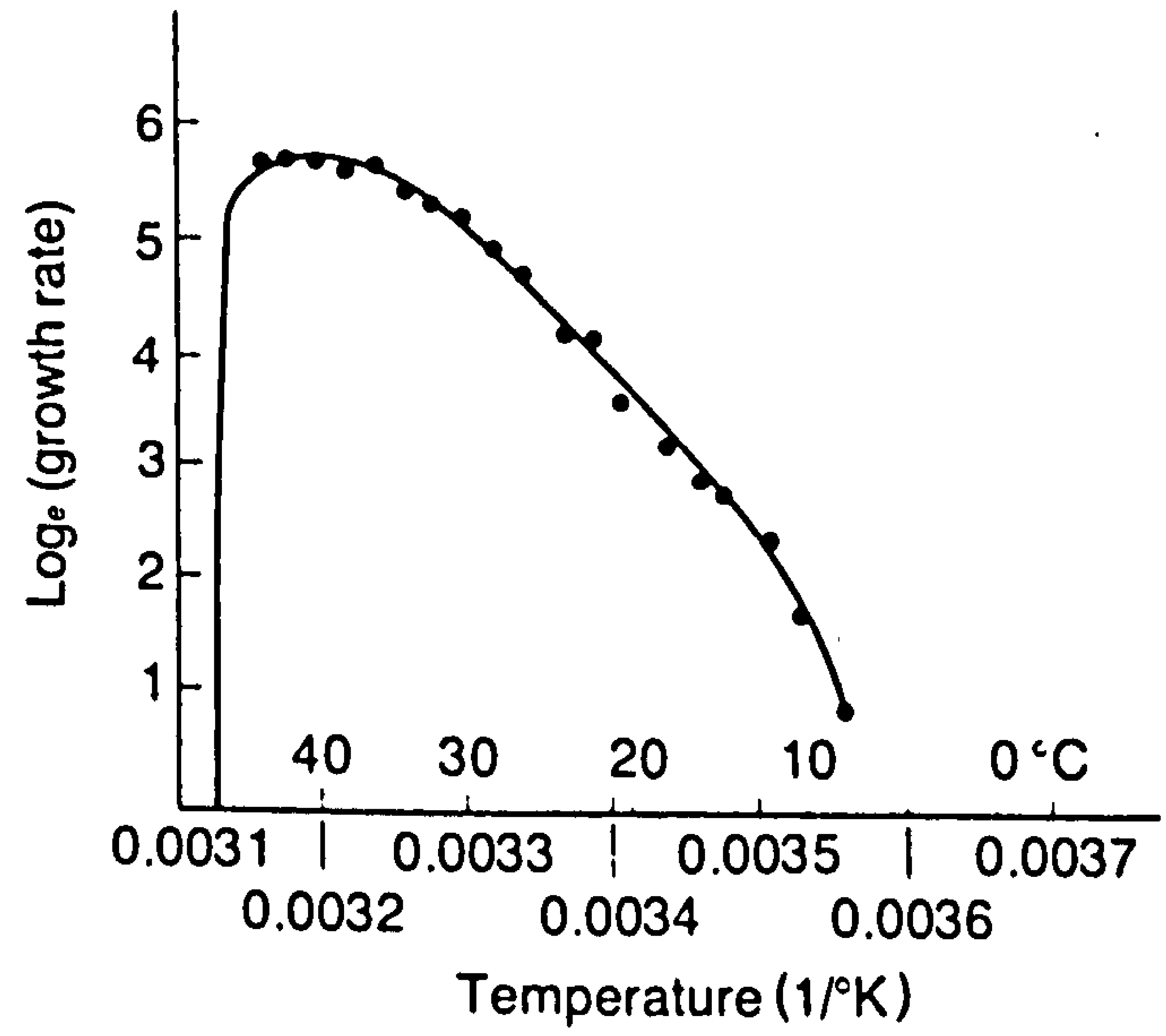
The Significance of Temperature to Microbial Growth

The rate of chemical reactions is a direct function of temperature. Thus temperature has a direct effect on the rate of microbial growth (Stanier, Adelberg and Ingraham, 1977). A typical relationship is shown in Figure 5-4 below. This example is for *E. Coli*, which is a mesophile, having an optimum temperature between 30 - 40°C.

The curve is linear only over a portion of the temperature range for growth, since the growth rate falls abruptly at both the upper and lower limits of the temperature range. The abrupt fall in growth at high temperature is caused by the thermal denaturation of proteins. The maximum temperature for growth is the temperature at which these destructive reactions become overwhelming. This temperature is only a few degrees higher than the optimum growth rate.

Conversely, as temperature is reduced the rate of growth continues to fall, and ceases *entirely* at the minimum temperature for growth. This may be well above freezing.

Figure 5-4 Plot Showing Relationship Between Microbial Growth Rate and Temperature



Source: Stanier, Adelberg and Ingraham, 1977

On the basis of temperature over which growth occurs, bacteria are divided into three broad groups:

thermophiles >50°C

mesophiles 10 - 45°C

pychrophiles ≈ 0°C

Methanogens are considered to be mesophiles.

5.2.3 Landfill Microbiology

The key reason for studying landfill microbiology is that landfill yields of gas are much lower than would theoretically be possible. Current average gas yields indicate that 150m^3 per tonne of placed waste is typical, this represents approximately one third of what may be theoretically attainable (Archer, Reynolds and Blakey, 1995).

The previous section described a stylised chain of events in the biodegradation of solid waste to methane and carbon dioxide. This is based on knowledge of anaerobic digestion being applied to landfill. In this section the current state of knowledge on landfill microbiology will be described. Detailed analysis of the reactions occurring at an electro-chemical level will not be attempted. In a somewhat empirical project such as this, three objectives should stand in this section:

- an understanding of the differences between the real landfill and the well understood anaerobic digestion
- a knowledge of the environmental parameters that effect the various species, that we may know how to optimise them
- a look forward at microbiological developments

Comparison with Anaerobic Digestion

There are significant differences between the degrading solid wastemass and anaerobic digestion systems. A comparison is made below:

Scale. A landfill wastemass is several orders of magnitude greater than an anaerobic digestion systems (AD).

Oxygen. Prior to placement MSW is predominantly aerobic. After placement a preliminary aerobic phase has to occur in the wastemass before anaerobic conditions establish. The growth of colonies of obligate anaerobes cannot commence until the oxygen is depleted. AD is anaerobic all the time.

Methods of operation. Landfill degradation is essentially a batch treatment process, in which a batch of waste, the wastemass, goes through a number of stages of processing. ADs often operate on a continuous process; substrate material is added continuously, at a rate such that the microbes are not overloaded and a steady state is achieved. Usually the influx rate is equal to the efflux of treated material.

Moisture Content. Landfilled waste has a typical moisture content of 40 - 60% (dry weight basis). ADs tend to operate at very high moisture contents, the substrate particles being suspended in liquid.

Particle Size. AD operate on substrate particles at maximum a few millimetres in diameter. Untreated waste in landfill can have a large effective particle size e.g. a bundle of newspaper.

Temperature. AD maintain an optimum temperature for the bacteria. The rumen, for example, is sustained at 37-40°C. Commercial landfill has to date made little attempt to control temperature of the degrading wastemass. Few landfills even measure wastemass temperatures.

Mixing. The nature of the solid waste in landfill means that mixing of the substrate material after placement is not possible. The substrate and microbiological elements of AD are in a well mixed liquid, mechanical agitation is often used.

From these differences between anaerobic digestion systems and landfilled waste, we may conclude that landfill is spatially heterogeneous in terms of substrate, microbiology and environmental conditions. In addition there is little or no attempt to optimise conditions for microbiological activity. One of the results is that the development of proper growth conditions is much slower and can take from a few weeks to years.

Characteristics and Requirements of Landfill Microbiological Species

Due to the heterogeneity of the landfill environment, several types of microbial ecosystem exist. Microbial communities that develop in the solid material in landfill may not be identical to, or even in equilibrium with, communities developing in leachate. Furthermore, those developing within the saturated zones of the wastemass may be different to those developing in the unsaturated zones.

The source of micro-organisms and the size of inoculating colonies is not known with any certainty (Archer, Reynolds and Blakey, 1995), but the micro-organisms are present on fresh refuse. The microbiological degradation of waste is not achieved solely by bacteria. Anaerobic fungi and anaerobic protozoa are present. The former are known to be important members of the microbial community and assist in the breakdown of cellulose polymers. Anaerobic protozoa have been found to house methanogens. Species that have been found in landfill are phagotrophs (i.e. bacterial predators) and it is thought that a mutualistic existence may have developed to remove competitors to the methanogens (Archer, Reynolds and Blakey, 1995).

Some bacteria compete with those in the methanogenic process. This is as a result of the presence of sulphate and ferric ions, which allows sulphate reducing and iron reducing bacteria to compete with methanogens for volatile fatty acids. In a sulphate-rich environment, sulphate reducing bacteria have a thermodynamic and kinetic advantage over methanogens. The metabolism of organic matter with ferric ions has also been demonstrated to be more thermodynamically favourable (Archer, Reynolds and Blakey, 1995).

The presence of high levels of sulphate, from for example gypsum construction materials, has been found to indirectly inhibit cellulose degradation (Gurijala and Suflita, 1993).

The Carbon : Nitrogen ratio of the wastemass is important as nitrogen is required for growth of the relevant micro-organisms. The biodegradation of organic nitrogen-containing compounds mineralises the nitrogen and liberates ammonia, which contributes to the neutral pH. Opinions on an optimum C:N ratio vary from 16-19 (Gendebein et al, 1992) to 25-30 (AFRC, 1988).

Cellulolytic Bacteria

The importance of biopolymer hydrolysis, and the evidence that it may be the limiting factor in long term biodegradation of wastes has been established. Much of the research into landfill microbiology has been conducted on methanogenic micro-organisms, for obvious reasons. Cellulolytic bacteria, that is cellulose degrading, play a key role in biopolymer hydrolysis because cellulose is the main component of biodegradable organic waste. Until Westlake et al (1995) conducted their recent research only one cellulolytic organism had been fully characterised (Bagnara et al, 1985).

Westlake and his team sampled waste at various depths from the Stewartby and Brogborough landfills in the UK, using conventional drilling techniques. Leachate was sampled from a site in Portland, Oregon, USA.

They isolated 37 cellulolytic bacteria, and characterised four in detail. Of the four, one was an aerotolerant anaerobic cellulolytic *Clostridium*, and three were obligate anaerobic *Eubacterium*.

The optimum pH for these isolates was found to be neutral apart from the *Clostridium* which was pH 7.7

The waste temperatures from which they were sampled was around 30°C. However, three of the bacteria were found to be thermophilic, with their optimum temperature around 50°C, suggesting that they were operating below their optimum in the wastemass. The same three were also found to be motile, while the fourth was non-motile. Westlake suggests that the heterogeneous and solid nature of the landfill environment selects bacteria that have motility and are able to move to areas with more favourable conditions.

Methanogenic Bacteria

Methanogens are one of the key species in the chain of degradation culminating in the production of methane. *Methanobacterium spp.* are the predominant species found in the landfilled wastemass. There can be great spatial variability of strains, even with the same landfill (Gendebien et al., 1992). Their mobility is limited, to the extent of a few centimetres.

Again, much of the research on methanogens has been conducted in the anaerobic digestion field. This has shown that methanogens:

are most active in the pH range 6.8 - 7.4 (Zehnder et al, 1978)

control the pH of their ecosystem by the consumption of acetate (Zeikus, 1980)

regulate the flow of electrons by the consumption of hydrogen, creating thermodynamically favourable conditions for the catabolism of alcohols and acids

excrete organic growth factors including vitamins and amino acids which are used by other heterotrophic bacteria in the ecosystem.

achieve methanogenisis using a series of enzymes. The last enzyme in the pathway is called Methyl Coenzyme M Reductase. It essentially confers methanogenisis on an organism, and is unique to methanogens (Luton et al, 1995)

Future Developments - DNA Probes

It is accepted that the microbiology of landfill is extremely complex. Without a knowledge of numbers and population dynamics of the species of micro-organisms in landfill, the ability to enhance degradation may be limited.

The progress in genetic engineering in recent years have enabled techniques to be developed that assist in understanding these complexities. DNA Probes are an example of emerging molecular biological techniques that offer the potential to study microbial populations without the requirement for growth. Since each species of organism has its own unique genetic code, the differences in the code can be used to detect and identify the species. These techniques have been applied to landfill methanogens (Luton et al, 1995).

5.2.4 Post Methanogenic Landfill

When all the substrate material is utilised, or conditions become unfavourable for anaerobic degradation, the wastemass will once again become aerobic. In conducting research to enhance gas generation and waste stabilisation, it is easy to loose sight of the fact that the degraded wastemass still exists after the methanogenic stage has been completed.

The length of time between placing of waste in a landfill and the end of the methanogenic stage of degradation is subject to some conjecture. Literature tends to suggest 50 to 500 years. Certainly if waste is 'entombed' dry and maintained so, degradation is extremely slow if not halted entirely (Rathje,W 1991). It is one of the objectives of this project to expedite degradation to the extent that the methanogenic stage will be significantly complete within a 30 year time span.

Once this stage has been reached, aerobic conditions will begin to prevail within the wastemass. Aerobic micro-organisms will then recolonise the degraded wastemass (Great Britain. DoE, 1995a). At this stage we may have considered the landfill not to pose a pollution risk, and to have come to a relatively inert state. This is valid assessment while conditions remain anaerobic. As conditions cease to be anaerobic, metals, and in particular insoluble metal sulphides produced indirectly by sulphate reducing bacteria, may become mobilised. These will cause pollution if these are released into the surrounding environment at a rate greater than which they can be naturally ameliorated. Depending on the nature of the landfilled waste, this mobilisation is likely to include heavy metals which are phytotoxic.

5.2.5 Settlement of the Wastemass

Settlement of the landfilled wastemass is a gradual process that can result in reduction in waste thickness of between 25 and 40% (Stearns, 1987). This change in thickness takes place over large periods of time, measured in decades rather than years, after the landfill has been closed As a result redevelopment of the landfilled area is highly restricted for many years. Often landfills were located on the peripheries of metropolises, which have subsequently become valuable development zones.

The mechanisms of settlement in landfill are complex. As with many aspects of landfill technology, knowledge is drawn from other fields which have been studied for a greater length of time. Research into the settlement of waste has been based on transposing soil mechanics to the wastemass.

Forms of Settlement

There are considered to be three forms of settlement of the wastemass (Wall and Zeiss, 1995). These are; Initial, Primary, and Secondary.

Initial Compression. This is the immediate compaction of waste once load is applied. It is analogous to the elastic compression of soils. It is generally not measured by researchers as it occurs almost instantaneously upon placement of the waste in the landfill.

Primary Settlement. Primary Settlement occurs soon after the waste is placed, during the first 30 days. It can be explained by the dissipation of pore water and gas from voids. Empirically, the classic Terzaghi theory of primary settlement of soils is found to provide a reasonable estimation of the primary settlement of a wastemass. Theoretically, it is unproven whether the application of the Terzaghi theory to a material that is physically different in particle size and shape, moisture regime and permeability is appropriate (Wall and Zeiss, 1995).

Secondary Settlement. Creep in the structure of the wastemass and biological decay are the causes of Secondary Settlement. The process occurs over many years, starting when the waste is placed in the landfill. It is not usually measurable during the stage of Primary Settlement because the magnitude of the latter is much greater over that period. Over time the magnitude of the Secondary Settlement will equal and probably surpass that of the Primary Settlement.

Settlement and Biodegradation

It is estimated that between 25 and 40% of MSW is available for biodegradation (Barlaz, Ham and Schaefer, 1989). The key stage of biodegradation as far as settlement is concerned is the change from solid waste to a liquid. This stage represents the most significant potential for volume reduction. The hydrolysis of mainly insoluble biopolymers to soluble intermediates is therefore the key area for volume reduction. Therefore hydrolysis is the limiting factor in the biodegradative enhancement of settlement.

Research into the effects of enhanced degradation on settlement are not conclusive. Leckie and Pacey (1979) found that settlement rates were enhanced during work with a leachate recirculated test cell. However other researchers (Yen and Scalon, 1975; Landva et al, 1984; Wall and Zeiss, 1995) found that enhanced degradation did not significantly expedite settlement.

In the experiment conducted by Wall and Zeiss (1995), six laboratory lysimeters were used three of which were enhance with the addition of water and leachate and three of which had the waste left at natural moisture content. The pressure applied to the cells was equivalent to 2-3m of waste overburden. They report that the most significant settlement occurred in the enhanced cells during the addition of water to bring the waste to field capacity, amounting to a settlement of 30%. During the first 10 months of the experiment reported, there was minor, but not significant increase in settlement rate in the enhanced cells. Decomposition was found to be adequately represented by a first order kinetic model, whereas settlement was found to be well represented as linear with the logarithm of time. They concluded that in the short term enhanced degradation does not appear to enhance settlement, but in the longer term enhanced degradation is likely to be significant.

5.3 Hydraulic Characteristics and Hydrology of Landfill

5.3.1 Introduction

Hydrology is the study of the occurrence, circulation and distribution of the waters of the Earth, in the atmosphere, oceans, on land and below the ground surface. It includes solid and gaseous states as well as the liquid state. It is explained thoroughly in most texts on the subject (Shaw, 1988 ; Ward and Robinson, 1990). Landfill hydrology considers the occurrence, circulation and distribution of water in the landfill environment.

Hydraulics is the science of the motions and equilibrium of a material system, partly or wholly fluid. Landfill hydraulics primarily considers the motions of liquid within the landfill system, and in particular on and in the wastemass.

Landfill hydrology has been studied and practised for many years (Fleming,G 1988a). It is quite common, for example, to conduct water balance analysis, but current methods are fairly straight forward (Great Britain. DoE, 1995b) as the landfill is analysed on the macroscale. The wastemass has also been considered as a number of discrete units. Computer models have been created on this basis to predict leachate production (Dickson,A 1987; Khan,TA 1996).

However, it is generally accepted that at present the hydraulics of landfilled waste is not well understood[1]. Hydraulics of landfill are closely linked to the heterogeneous and anisotropic nature of the wastemass. This inevitably means that it is not satisfactory to consider just the macroscale.

---

[1] Leachate Recirculation Workshop, Session W15 on 17/10/97, Sardinia '97 Symposium. Chaired by Howard Robinson, Aspinwall & Co. Ltd., Walford Manor, Shrewsbury, SY4 2HH.

Traditionally, the prime objective of landfill hydrology has been to determine leachate generation, in order that measures be taken to minimise the quantity of free leachate. Leachate is generated by the biodegradation of the wastemass and through drainage from high moisture content wastes; however the majority of leachate is created by water entering the wastemass from outwith the landfill. Surface water infiltration and groundwater influx are the sources of this water.

5.3.2 Background to Hydrological Strategies

Historically there have been two main approaches to sanitary landfill; that of dilute and disperse, and that of total containment[1]. With dilute and disperse, precipitation was allowed to infiltrate, through the permeable capping medium, into the waste. The subsequently generated leachate was then allowed to continue its downward movement into the underlying geology.

It was recognised that the leachate emanating from these types of landfill did, in many cases, pollute groundwater and surface water resources. Due to this, there was a move in much of the developed world, and particularly in the USA and Europe, to contain landfills so that they did not cause this pollution. Thus the 'containment landfill' became the norm for new landfill sites in the 1990's.

The total containment system took the approach of excluding water from entering the landfill, and containing any leachate that was produced. This was achieved by lining the base and capping the top of the landfill with 'impermeable' layers. Techniques of filling the landfill evolved to minimise the surface area for effective precipitation to infiltrate by placing the waste in cells and capping them as soon as they were full (Great Britain. DoE, 1995b) . In locations where precipitation is minimal, the result of this methodology was that the waste remained dry and did not degrade readily, hence the North American term 'dry tomb' landfill.

---

[1] see Waste Management Paper 26 for details of these two operating concepts (Great Britain. DoE, 1986)

5.3.3 Hydrological Strategy of a Sustainable Landfill

Neither of these systems comply with the principles of sustainable development, discussed elsewhere. This project, amongst others, is developing methodologies of sustainable landfill. The *wet bioreactor landfill* seeks to optimise the degradation of waste, by a number of means, a key element being elevated moisture content. Then in the subsequent *flushing bioreactor* phase, pollutants are flushed out using clean or treated leachate which is introduced to the wastemass. This new approach has significant implications to the hydrology and hydraulics of the wastemass.

It has been seen as a goal of landfill operation to minimise the amount of free leachate, as techniques of landfill engineering have improved and the anti-pollution regulatory framework has strengthened. In the UK, many landfills have licence conditions imposed that limit the head of free leachate to a maximum of 1.5m above the lining system.

The concept of the wet bioreactor landfill includes a partially, or even fully saturated wastemass, and the flushing bioreactor stage encourages input of 'clean' water to remove pollutants. Thus the exclusion of water from the landfill and the minimisation of free leachate are not the prime objectives of sustainable landfill hydrology. Control and prediction of leachate quantity and quality are still required, however under the sustainable landfill regime, these are planned for with different objectives.

5.3.4 Hydrological Processes

Landfill hydrology has two distinct parts:

- Exposed Wastemass. Hydrological processes occurring on an open landfill cell.
- Capped Landfill. Hydrological processes occurring on a capped (and probably vegetated) landfill.

The processes involved in the latter part are of an ordinary hydrogeological nature, but those in the former are specialised, and the literature indicates, not as well researched.

Both wastemass hydraulics and hydrology have developed on parallels with soil systems, which have been studied thoroughly for sometime[1]. In the analogy that has developed, particles of waste are considers like particles of soil, and the wastemass is considered as an aquifer.

The elements of the hydrological cycle that are relevant to landfill are shown in Figure 5-5. It depicts the two stages of landfill that are important when considering hydrology; that is during filling and after capping.

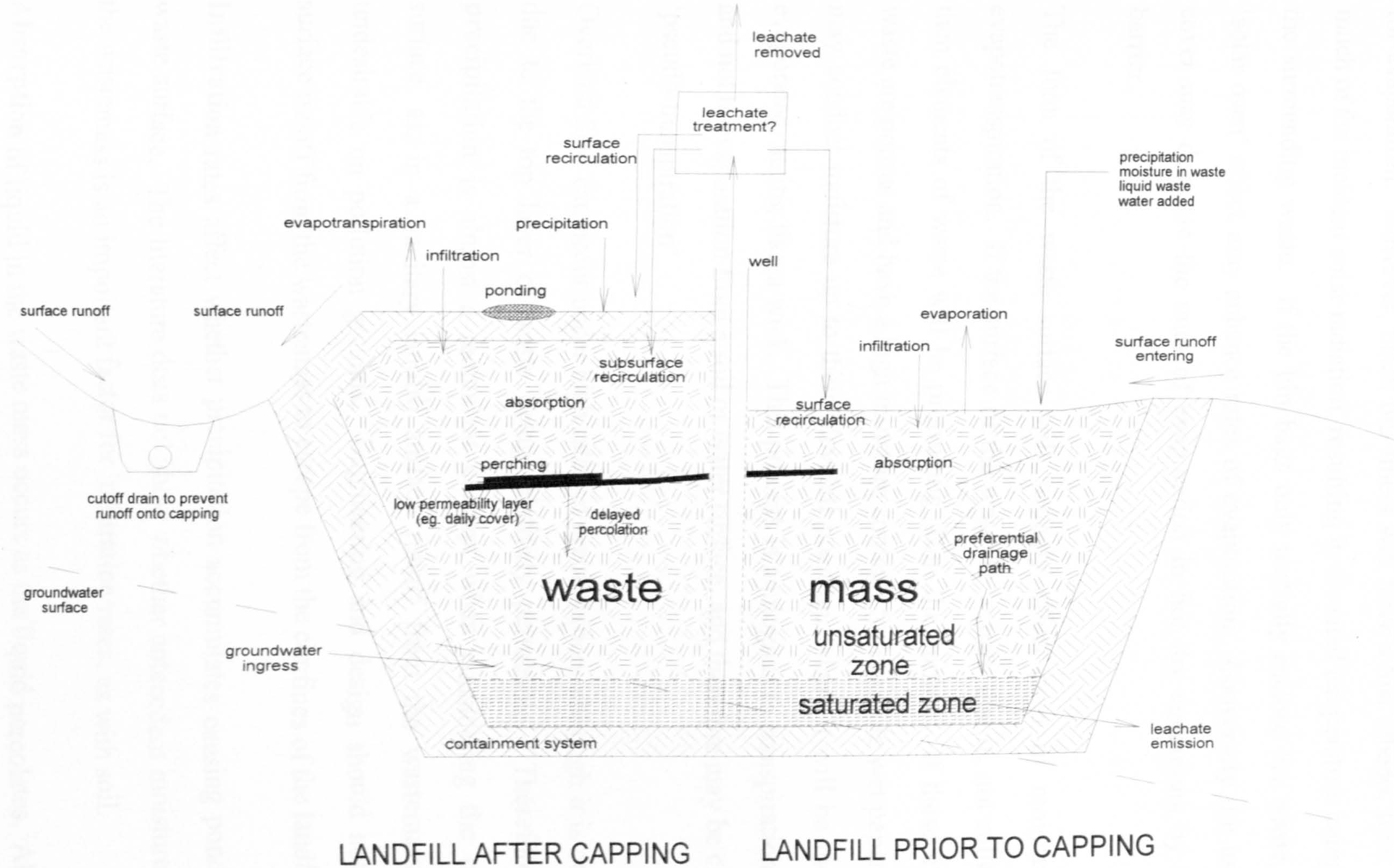
The diagram shows the potential inputs and output for the system. Observations show that many of the hydrological processes on the exposed waste surface are analogous to the ground surface.

Moisture can be lost through **evaporation** from the waste surface of an <u>open</u> landfill cell. The factors affecting evaporation are the same as those affecting normal hydrological situations. The literature shows little research into the rates of evaporation from waste, waste specific factors, and correlations with measured potential evaporation.

---

[1] for example Darcy in the 1850's

Figure 5-5 Conceptual Diagram of Hydrological and Hydraulic Processes in Landfill



Evaporation will occur from **ponding**, as it will from a damp waste surface. The common practice of containing MSW in plastic bags - bin liners - will effect evaporation. Obviously, if totally enclosed, the moisture in the bag is not available for evaporation. However, black bin liners will have a low albedo, thus absorbing much of the incident solar radiation, resulting in elevated temperature compared with the surrounding waste. If the bin bags only partially enclose the waste, then this 'solar oven' effect may enhance rates of evaporation. Conversely the use of daily cover may decrease the rates of evaporation in hot dry conditions by creating a barrier.

The form of the waste surface will strongly effect rates of moisture loss to evapotranspiration. If the surface of the waste is 'rough' that is, not rolled smooth, then elements of waste will be protruding from the surface. If these elements of waste are porous and have a high moisture content, for example wet paper, then they may conduct moisture up to their elevated position, where it will be more readily evaporated, acting like a wick. This process is analogous to transpiration by plants, and not to evaporation from a soil or water surface, and therefore may be classified as 'pseudo-transpiration'

Overland flow can occur under high rates of precipitation, although it is not common due to the top layer of waste being relatively permeable. Therefore **effective precipitation** is almost a redundant concept when considering the open waste surface, as, in a sanitary landfill surface runoff from the wastemass is highly undesirable on pollution grounds. Engineering and design should not allow for surface runoff from the wastemass to escape from the confines of the landfill cell.

Infiltration rates affect whether precipitation accumulates causing ponding on the waste surface. The literature does not show whether antecedent moisture content of the wastemass is an important factor for infiltration rates, as with soil.

Absorption of liquid in the waste mass occurs as the liquid percolates. Absorption is the detention of liquid against gravity. The maximum absorption is at the moisture state called field capacity. Knox (1985) collated previous research and found values for absorptive capacity of MSW quoted as being 120 - 1300 litres/ tonne waste.

If the input of liquid/leachate in excess of the absorptive capacity of the wastemass, free leachate will be generated. This will accumulate at the base of the wastemass (unless it is removed). This accumulation will create a saturated zone.

Daily cover can create low permeability layers, depending on the characteristics of the material that is used. On the open wastemass this can have the effect of creating surface runoff, by limiting the infiltration rate. Once the daily cover has been overfilled, the low permeability layer has the effect of delaying percolation, and can create perched masses of water/leachate. These will inhibit the even distribution of fluids within the wastemass.

Preferential drainage paths are routes of easy passage for liquid flowing through the wastemass. They may be created by connected voids between waste 'particles'. They allow the flow of liquid to concentrate and bypass the majority of the waste.

5.3.5 Water Balances for Landfill

Many forms of water balance calculation have been put forward in the literature. In the UK, government guidelines, in Waste Management Paper 26B (Great Britain. DoE, 1995b), give the calculation shown below:

$$Lo = [ER + LIW + IRA] - [LTP + aW + DL]$$

where:
Lo = free leachate remaining
ER = effective rainfall (or actual on active surface area); this may need to be modified to account for runoff, especially after capping*
LIW = liquid industrial waste (including any surplus water from sludges with a high moisture content)
IRA = infiltration through restored capped area
LTP = discharge of leachate off-site
a = unit absorptive capacity of wastes
W = weight of absorptive waste
DL = designed seepage (if appropriate)

* The WMP 26B definition of effective rainfall is different to that normally used in hydrology, as it subtracts only evapotranspiration losses and not infiltration losses. Perhaps a more appropriate term for the precipitation that increases the bed volume would be *additive precipitation.*

Values for absorptive capacity have not been given in the 1995 WMP26B, however the 1986 edition WMP26 (Great Britain. DoE, 1986) suggested that 0.1 - 0.2 m^3 added liquid per cubic metre of waste at densities of around 0.75 t/m^3 . If densities were appreciably greater, absorptive capacity would be reduced and in excess of 1.0 t/m^3 absorptive capacity would fall to around 0.025 m^3.

The calculation can be used to predict leachate generation throughout the life of a site, therefore allowing leachate management to be planned, so that capacity is available when required. It may be conducted on an incremental basis, e.g.. annually so that a basic model of leachate generation is created.

The calculation above in not overtly a water balance of the landfill, but a method of calculating the leachate generated. A balance approach is taken by Buchanan (1994), in which the change in storage is calculated. It is given below:

$$\Delta L = P + R + W_l + W_s\Theta_i - E_t - D - L_r \pm S$$

where :
ΔL = net moisture gained by waste
P = precipitation
R = runoff entering site
W_l = liquid waste inputs
$W_s\Theta_i$ = inherent moisture in solid waste
E_t = evapotranspiration
D = runoff/drainage from site
L_r = leachate removed
S = seepage to/from groundwater

These simple approaches to water balance have limitations, and in practice tend to underestimate the quantity of free leachate produced. Numerical modelling of moisture movement and leachate production has received researchers attention during the last decade. Many models for both water balance and flow through porous media have been created (Khan,TA 1996). One of the more recent of the models, NUMMOL created by Khan (1996), has been applied to the experimental landfill described later in the thesis.

5.3.6 Hydraulic Characteristics of the Wastemass

Introduction

There have been a number of objectives in the research of hydraulic characteristics of waste. One of the main objectives has been to determine liquid percolation rates through the wastemass. Initially the interest in percolation rate has been to predict the delay of liquid input, e.g.. a precipitation event or liquid waste, on reaching the leachate discharge or collection system. More recently, interest has centred on percolation being a limiting factor for the high rate recirculation of leachate, as required by the flushing bioreactor concept.

Successful operation of the flushing bioreactor landfill requires that a significant quantity of liquid be passed through the wastemass in order to remove soluble pollutants. Walker, Beaven and Powrie (1997) have shown that to achieve the flushing rates required, the permeability of the wastemass needs to be in excess of 10^{-7}m/s. Previously, Beaven and Powrie (1995) had established, in large scale compression cells, that the permeability of waste would be reduced to this figure at the base of a 60m deep landfill. In the case of pulverised waste the permeability would be reduced to 10^{-9}m/s at a depth of 60m.

Another important physical characteristic of the wastemass is that of porosity. In field scale experiments, this has been shown to decrease as degradation progresses (Blakey, Reynolds, Bradshaw and Young, 1996). Decrease in porosity has been implicated in increasing levels of free leachate, although this has not been proven.

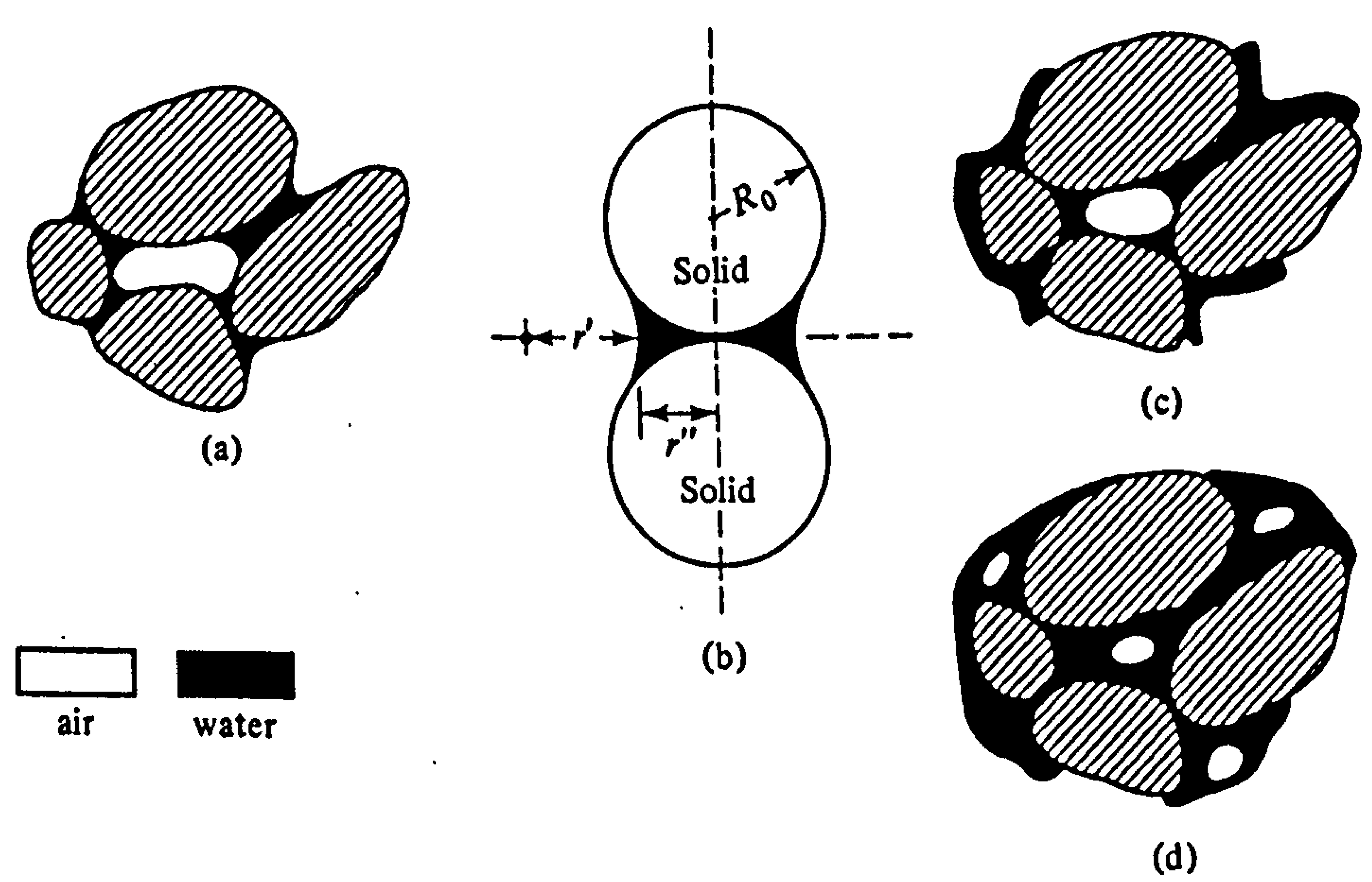
Thus, a deeper understanding of the hydraulic properties of the wastemass are crucial to landfill moving towards sustainability.

Analogy With Soil

Consideration of the hydraulic properties of waste has relied heavily on the way we consider soils. Theory and practice are well developed in the field of soil mechanics and soil hydraulics, having undergone development for many decades. So engineers and scientists have approached this field in waste management as if waste was a special soil.

Particles of waste have liquid adsorbed on their surface, and they may also have liquid absorbed within the particle. The space between the particles is called void or interstices . The void may contain liquid or gas. If the particles are in a saturated zone, the void will contain predominantly liquid and possibly some transient or adsorbed gas. If the particles are in the unsaturated zone then the void will contain predominantly gas and some transient or adsorbed liquid.

Figure 5-6 Conceptual Anatomy Of Soil At Different Saturation States



a) Pendular saturation, b) Pendular rings between two spheres, c) Funicular saturation, d) Insular air saturation

Source: Bear,J 1979

Bear states that, at a very low saturation (a), water forms rings, called pendular rings, around particle contact points. The air-water interface forms the shape of a "saddle". At this low saturation , the rings are isolated and do not form a continuous water phase, except for a very thin film of water of nearly molecular thickness. Practically no pressure can be transmitted from one ring to the next through the water phase. The idealised case of two spheres and a pendular ring is shown in (b). The radius of the air-water interface is related to the capillary pressure.

As water saturation increases, the pendular rings expand until a continuous water phase is formed, the *equilibrium water saturation.* Above this critical saturation, is called funicular saturation (c), and water flow is possible. Both water and air phases are continuous. As the water saturation increases, the air becomes a non-continuous phase, and it breaks into droplets lodged in the larger pores (d). The air is then in a *state of insular saturation.* The globule of air can only move if a pressure difference, sufficient to move it through a capillary size restriction, is applied across it in the water (Bear,J 1979).

If no air is present in the interstitial void, then the media is completely saturated.

The conceptual figure above presents soil as rounded particles. As with soil, the representation of waste (MSW) as a rounded particle is not accurate in reality. However whatever shape the particles of waste take the explanation above holds.

Above the 'saturated zone', ie above the phreatic surface of the groundwater, there is a zone that is saturated or nearly saturated. It is called the *capillary fringe*, and is a result of *capillarity* caused by the surface tension of the fluid, water. The interconnecting pores in the soil matrix act as capillary tubes. The diameter of these 'tubes' dictates the height of the capillary fringe, fluid properties aside. The equation below gives the height to the capillary rise.

$$h = \frac{2\sigma}{R\rho g}$$

where:
h = height of liquid column
σ = surface tension of the liquid
R = radius of curvature of the gas/liquid interface
ρ = density of the liquid
g = gravitational acceleration

The literature does not show values for capillarity in a waste/leachate/landfill gas situation.. Neither does it appear that measurements of the surface tension for leachate have been carried out, or that the radius of curvature of the landfill gas/leachate interface has been determined. In terms of leachate generation, it is not a important property, which may explain the apparent lack of attention. Since capillarity is a result of pressure balances between two fluids, it is probable that active extraction of landfill gas will effect the height of the capillary fringe.

There are various ways that a large capillary fringe might influence the flushing bioreactor landfill. High capillary storage would increase the volume of leachate being stored and increase the ratio of saturated/unsaturated wastemass, without increasing the head of leachate of the containment system. If it were possible to engineer a massive increase in capillarity, a high 'saturation ratio' of wastemass could be achieved, thus enhancing degradation while not having to over engineer the containment.

Parameters For Assessing the Liquid and Gas Content in Porous Media

Some basic definitions of key parameters are shown below (Buchanan,D 1994):

Voids ratio, $e = V_v / V_s$ max. value $\rightarrow \infty$

Porosity, $\alpha = V_v / V_t$ max. value $\rightarrow 1$

similarly when considering whether the void volume is occupied by liquid or gas:

Degree of saturation, $S = V_w / V_v$ max. value = 1.0

Volume moisture content, $\theta = V_w / V_t$ max. value $\rightarrow 1$

where
V_v is volume of void
V_s is volume of solid material particles (soil or solid waste)
V_t is total volume
V_w is the volume of liquid (water or leachate)

When measuring moisture content it is often convenient to measure mass and loss of mass when the water is removed, rather than volumes:

Dry mass moisture content, $\theta_d = M_w / M_s$ max. value $\rightarrow \infty$

Wet mass moisture content, $\theta_w = M_w / M_t$ max. value $\rightarrow 1$

Dry mass moisture content (mcd) tends to be used by engineers and those dealing with inert material, whereas wet mass moisture content (mcw) is preferred by biologists and those dealing with biotic matter.

Volumetric Moisture Content (mc_v). Volumetric moisture content is independent of density. This is a useful property when comparing moisture contents of different wastemasses. It is also independent of degree of saturation and porosity, although the latter may be a limiting factor.

Dry Mass Moisture Content (mc_d) and *Wet Mass Moisture Content* (mc_w), as the names imply are mass based and independent of volume. This means however that when considering the mass of matter in a unit volume of waste, the density of the matter affects the moisture content. As liquid and gas densities are assumed to be fairly constant, it is the density of the solid material that primarily affects mass moisture content in this way. It is noticeable that mc_d is more sensitive to density fluctuations than mc_w.

A further useful parameter is *Hydraulic Radius* . It is the total volume of effective pore space divided by the wetted area of solids (the area of liquid solid interface). In sedimentary rocks it is regarded as the characteristic dimension of the pores, taking both size and shape into account. This is a useful concept in the study of waste hydraulics, in which the particles of waste are likely to deviate from the roughly spherical approximation often used for soil particles. When considering a pipe or a channel it is an easy parameter to calculate. The author is not aware of any published attempts to measure of hydraulic radius of a wastemass.

In sedimentary rock, *Tortuosity* is the ratio of the true mean flowpath length through the rock to the macroscopic length of rock traversed. It is dimensionless, but is a vector quantity, having both magnitude and direction, and in sedimentary rocks accounts for anisotropy of permeability (Chapman,RE 1987). It is normally calculated using resistivity measurements, being estimated from the resistivity factor, which is the ratio of resistivity of the a rock saturated with an electrolyte to the resistivity of the electrolyte. Landfill is highly suited to resistivity surveys due to the high electrical conductivity of leachate.

Saturated Flow Through Porous Media

Henri Darcy is attributed with first devising the equation that described flow in saturated porous media. Darcy was working on the water supply of Lyon in the 1850's, and was experimenting with water flowing through sand beds. Darcy's equation, given below, shows that rate of flow is proportional to the hydraulic gradient.

$$v = -K\left(\frac{\delta h}{\delta l}\right)$$

where:
v = macroscopic velocity of the fluid
K = saturated hydraulic conductivity
δh/δl = hydraulic gradient

The negative sign indicates that flow is in the direction of decreasing head.

The hydraulic conductivity in Darcy's equation, is specific to both the porous media and the fluid occupying the pores. Commonly, the fluid is water and the porous media soil or rock. Alternatively, the fluid may be leachate and the porous media the wastemass. If the fluid is gas, a modification needs to be made because mass density is not constant, but a function of pressure.

To dissociate the type of fluid from the intrinsic properties of the porous media in terms of hydraulic conductivity, a further term has evolved, *intrinsic permeability.* The relationship between intrinsic permeability and hydraulic conductivity is:

$$k = \frac{K\nu}{g} = \frac{K\mu}{\rho g}$$

where :

k = intrinsic permeability
ν = fluid kinematic viscosity
μ = dynamic viscosity
ρ = density
g = gravitational acceleration

Dimensions of k are L^2 and so m^2 are appropriate SI units. The oil industry uses a unit called the Darcy. It is defined as 'the permeability that permits a flow of 1ml of fluid of 1 centipoise viscosity completely filling the pores of the medium to flow in 1s through a cross-sectional area of $1cm^2$ under a gradient of 1atm/cm flow path'. This term has become almost universal in the oil industry despite the combination of inconsistent units and the use of a pressure gradient term rather than a hydraulic gradient (Price,M 1985).

The reason for popularity of intrinsic permeability as a parameter in the oil industry, is that in contrast with groundwater reservoirs, the fluids in 'oil' reservoirs have variable viscosities and may be either in the gas or liquid phase. From this, it follows that petroleum hydrogeology may be more applicable to the landfilled wastemass than groundwater hydrogeology.

In terms of groundwater, the interstices of the soil or rock aquifer are usually small, and there is some resistance to the flow. This means that the flow regime of groundwater is considered to be *laminar*.. As velocity of the groundwater increases, and particularly if the interstitial voids become larger, the occurrence of turbulent eddies dissipates kinetic energy and means that the hydraulic gradient becomes less effective in inducing flow (Ward and Robinson, 1990).

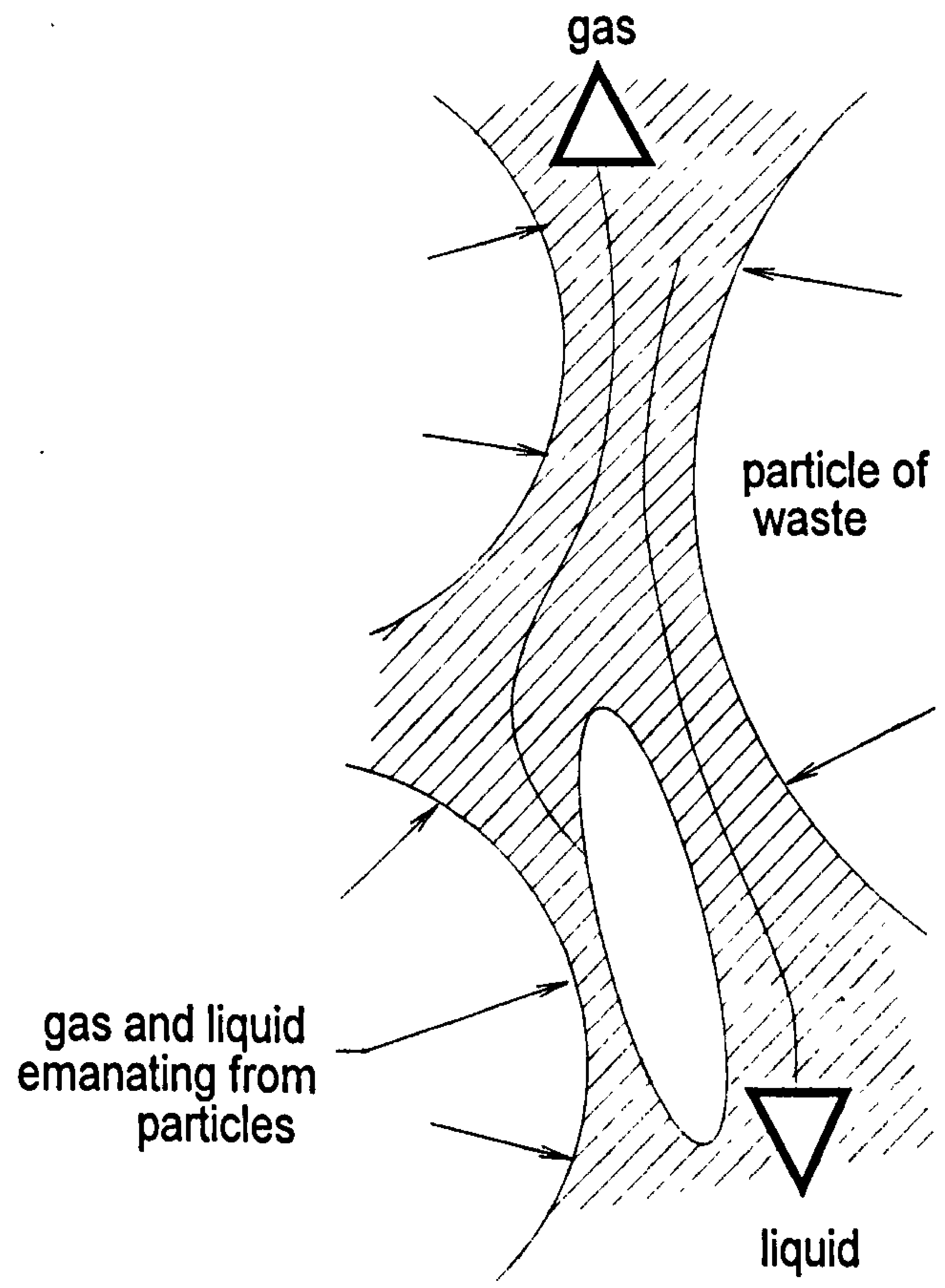
For a natural soil system, Buchanan (1994) quotes the transition between laminar and turbulent flow at the Reynold's number of between 1 and 10. The Reynold's number is the ratio of inertial and viscous forces on the fluid. Above the transition zone into turbulent flow, Darcy's law is no longer valid. From the literature, the author has been unable to find figures for the transition zone of leachate in the landfilled wastemass.

Unsaturated Flow Through Porous Media

Unsaturated flow means that one fluid does not fill and flow through the porous media interstices. In a groundwater situation, unsaturated flow occurs when the interstices are partially filled with water and partially air, for instance above the phreatic surface in an aquifer.

In the wastemass situation, conditions are not so well defined. Unsaturated flow occurs both above and below the leachate phreatic surface. The most significant difference between the geological situation and that of the wastemass is that the latter case has a *living* porous media. Until biodegradation ceases, the media itself produces large quantities of fluids, mainly in the form of gases, but to a lesser extent liquids. This, coupled with the relatively low hydraulic conductivity, means that the system is never in static equilibrium, and the region below the leachate phreatic surface is never truly saturated.

Figure 5-7 Schematic Representation of the Interstitial Contraflow of Fluids



A further complication is that contra-flow may be occurring; that is gas and liquids moving in opposite direction, as depicted in the figure above. Increased friction losses between the fluids in contra-flow will result in reduced flows.

Description of the processes in unsaturated flow are more complex, and less well understood. Equations describing the motion of two immiscible fluids in anisotropic porous media are available in some texts on groundwater (e.g. Bear,J 1979: p.208), but they are very complex.

For this reason, the current state of the art of landfill modelling does not address the problems of unsaturated flow.

5.4 Leachate Treatment

Landfill is an 'end of pipe' solution for society's waste management problems. Landfill produces problems; liquid and gaseous effluent. Leachate treatment, in turn, has tended to be an 'end of pipe' solution to one of the problems created by landfill.

5.4.1 Conventional Treatment Methods

In an unenhanced landfill, typically leachate is removed and treated by oxidation processes to reduce BOD and ammonia, prior to discharge. The processes are modified from waste water practice, and details of this well established technology can be found in many text books and journal papers.

With the exception of a few sites, with specific toxic constituents in the leachate or sensitive receiving waters, UK regulation and practice has not been concerned with many of the micro-constituents that are present in the leachate. Many other countries in Europe do take the micro-constituents more seriously, and this is beginning to be the case in the UK as well (Robinson,HD et al, 1997).

While it is not within the scope of this thesis to discuss leachate treatment in depth, some of the more interesting developments are worth including, particularly as they have implications for sustainability.

5.4.2 Leachate Treatment for Flushing Bioreactor Landfill

If a landfill is operated as a flushing bioreactor, much of the conventional treatment of leachate is avoided. The organic loading of the leachate is removed by microbial degradation, and leaves the landfill as methane and carbon dioxide.

The nitrogen load, in the form of ammonia, builds up with the recirculated leachate. However, pioneering work by Burton and Watson-Craik (1995) indicates that if the leachate is nitrified during the recirculation process (by aeration), when it is returned to the wastemass, reduction of nitrate to nitrogen gas occurs. Nitrogen then leaves the wastemass as a constituent of landfill gas. These ideas are soon to incorporated into an Environment Agency funded field trial at the Mid Auchencarroch research facility.

In the flushing bioreactor landfill metals, salts and refractory organic compounds will accumulate in the leachate after being mobilised from the wastemass during the flushing process. Depending on their concentration and the sensitivity of the receiving waters, treatment may well be required, prior to assimilation in the environment. There are a number of treatment technologies that can be used to ameliorate these non-biodegradable components in leachate. Some of the methods are inherently unsustainable.

5.4.3 Unsustainable Developments in Leachate Treatment

Reverse Osmosis

The process reverses the osmotic flow of water across a semi-permeable membrane by the use of differential pressure between the dilute and concentrated solutions. It is commonly used in industry as a method of concentrating solutions, and for making de-ionised water. The process is plant intensive, and has high maintenance and energy requirements.

It is currently used in parts of Europe, especially Germany, to 'treat' leachate (Peters,T 1997). Around a 75% reduction in volume can be achieved, with clean water being discharged, and the concentrate being disposed of - often back to landfill!! As such the process is intrinsically unsustainable, and has significant environmental costs in terms of operational overheads.

Vacuum Enhanced Evaporation

This is another method of concentration, used extensively in industry. It too is plant and energy intensive. A pilot plant has been trialed in Britain by UK Waste at their Risley facility. A 0.8 bar vacuum is applied to the evaporation vessel so that the leachate boils at around 52 °C. A 7:1 volume reduction is achieved. The vapour is condensed and collected, and can be discharged to surface water courses. However, the use of boiling point as method of separation could be problematic with leachate. Before water boils, many organic compounds in the leachate will boil, and so there is potential to contaminate the condensate.

If the concentrate is disposed of to landfill, this process will also be intrinsically unsustainable, and has significant environmental costs.

5.4.4 Sustainable Developments in Leachate Treatment

The problem with most treatment technologies that deal with micro-constituents in the leachate, is that they are not sustainable even as an end of pipe solution. The techniques separate or concentrate the hazardous elements in the leachate. The problem is then transported elsewhere - sometimes even back into a landfill.

The solution is to *separate* and *recover* these materials, some of which can safely be destroyed, and for others which are recalcitrant, e.g. heavy metals, the only non-polluting and sustainable option is reuse.

Activated Carbon

Activated carbon can be used to remove non-biodegradable Chemical Oxygen Demand and adsorbable halocarbons from leachate. Once the adsorbency of the activated carbon has been depleted, it is removed and reprocessed in a re-activation plant. During re-activation the carbon is heated to 800°C and all the adsorbed organic compounds are destroyed (Pinker,B 1997). There are no concentrated waste products to be disposed of. The carbon is then reused.

This process does appear to be sustainable, in that the removed contaminants are destroyed, (by high temperature oxidation during the re-activation process) and the removal vehicle, carbon, is recycled.

Polymer Supported Resins - A Potential New Opportunity to Sustainable Leachate Treatment.

A developing technology that has the potential to separate and recover is Polymer Supported Ion Exchange. This application of the technology to the treatment of landfill leachate was identified by the author and Dr Stuart Finnie[1]. Subsequently, contact was made with Professor David Sherrington[2] who is one of a number of leading researchers in the field (Van Berkel et al, 1995; Ersoz et al, 1995).

It was apparent that it is technically feasible to remove a large number of problem constituents from leachate (and landfill gas) using this technology. Ordinary ion exchange resins are the work horses of industry, but tend to be not particularly specific in what they exchange with. For instance a cation exchange resin will remove a range of metals from a dilute effluent. They are used in this application, for polishing effluents from plating works and recovery of precious metals from mining tailings. To regenerate the resin a clefting agent is used, for example an acid in the case of metals, which re-exchanges with the resin. The resulting material may then be processed further to recover materials, for example electrolytically in the case of metals.

The typical capital costs of a polymer supported ion exchange plant are less than those of a reverse osmosis plant, and the operation of the plant is not energy intensive.

A more advanced type of resin is a Chelating Ion Exchange Resin, again Polymer Supported. Chelating means 'crab-like' and relates to the molecular structure of the resin terminal. By careful design, the resin is capable of being much more selective.

---

[1] personal communications; formerly a student in the Department of Pure and Applied Chemistry, University of Strathclyde.
[2] Department of Pure and Applied Chemistry, University of Strathclyde.

Contact was made with a major manufacturer[1], and it was established that products are available that will for instance remove a range of metals from a dilute effluent. A particular product Purolite S930 will remove heavy metals such as copper, nickel, zinc, cobalt, cadmium and iron. The resins can be regenerated by the use of a cleaving agent, which removes the metals.

Unfortunately, the state of the art is not such that there are resins that are specific for individual components, although there are a few exceptions, notably a special resin for removal of mercury. The barrier to the creation of a large range of totally specific chelating resins is economic not technical. Currently chelation resins cost around three times as much as ordinary resins. The economics are driven by the major market which is primary manufacture. The economics in this sector, usually render recovery of low levels of material un-beneficial. However, in the waste management sector, the economics are inverted. If obliged to remove various components from a leachate, the economic question is not whether it is profitable, but what is the least expensive method of achieving the result. In this context the development of highly specialised resins may be economically feasible.

Apart from metals, various type of ion exchange resins can also be used to remove pesticides (as is being done for drinking water in East Anglia), hydrocarbons, halocarbons, nitrates, and chlorides, although it is questionable whether this is inappropriate for these latter two items.

Further development of this technology, and application to leachate treatment, could provide a far more sustainable alternative to the treatment of non-biodegradable components of leachate.

---

[1] Purolite International Limited, Cowbridge Road, Pont-y-clun, Mid Glamorgan, Wales, CF72 8YL

5.5 A Review of Recent Landfill Test Cell Research

5.5.1 Landfill 2000

Landfill 2000 was a field trial of accelerated waste stabilisation, carried out between April 1991 and March 1995, in West Yorkshire. The project was supported by the Department of the Environment, West Yorkshire Waste Management, and Yorkshire Water. A number of reports have been produced (Bradshaw, Reynolds and Blakey, 1993; Reynolds and Blakey, 1992; Blakey et al, 1996).

Project Objectives

The stated aims of the project were:

- To eliminate environmental pollution caused by existing landfilling practices and procedures.
- To provide evidence for the safe disposal of sewage sludges to landfill.
- To create an environmentally friendly "compost" suitable for land reclamation or infilling.
- To examine the economics of the scheme to show how income can be optimised by the exploration and utilisation of landfill gas.

The research objectives were defined as:

- establish optimum cell conditions that would give a three year waste degradation period.
- quantify the methane generating potential of the waste/sewage sludge mix.
- determine the biological condition of the waste digestate after a three year period and assess its suitability as an environmentally friendly soil conditioning medium.

Essentially the project consisted of two experimental cells, both containing a MSW and digested sewage sludge mix. On Cell 1 leachate recirculation would be practised, while Cell 2 would act as a control.

Cell Description

The two experimental cells were lined with 1.5mm HDPE geomembrane. The shape of the cells was rather unusual in that they were diamond shaped in cross-section. This design is not justified in the reports, although it appears to have led to some experimental difficulties, for instance with short circuiting of leachate. Each cell was 36m long, 23m wide and at its greatest depth of waste was 5m.

A 300mm thick drainage blanket of 20mm gravel was laid in the base of the cell, together with Ø180mm leachate collection pipework.

Both cells were filled with approximately 1000 tonnes of msw and digested sewage sludge. The mixture contained around 12% sewage sludge by wet mass. The emplacement density was 0.9 tonnes wet mass /m^3.

Leachate recirculation pipelines were installed in 250mm deep trenches excavated in the top of the wastemass. A 20mm gravel backfill was used. The layout consisted of three parallel pipes running the length of the cell, these were connected to a manifold at one end and were sealed at the other end.

Over the whole top surface of the wastemass a 200mm thick layer of 10mm gravel was laid, gas collection pipework was installed in this layer.

Prior to placement of a HDPE geomembrane cap, four gas and temperature probes were placed within each cell. The cells were capped in May '91.

Relevance of Landfill 2000 to Mid Auchencarroch

Scale	Landfill 2000 cells are around a quarter of the mass of those at Mid Auchencarroch. As such the problem of thermal loss will be more severe in the former.
Depth	Landfill 2000 is similar to Mid Auchencarroch in terms of waste depth: it is shallow landfill.

Waste substrate	The substrate for both cells was untreated MSW and sewage sludge. This combination of materials was not used at Mid Auchencarroch.
Leachate recirculation	A full programme of leachate recirculation was practised, utilising a sub-cap irrigation system.

Leachate Recirculation and Standing Head

Leachate recirculation was not initiated for 9 months after the cells were capped. During this period the cells were effectively duplicates.

At the onset of recirculation, in March '92, it was found that there was insufficient free leachate accumulated in the base of Cell 1. To overcome this, 70 m^3 of liquid was added in an exercise termed 'cell wetting'. The liquid used was final effluent from sewage treatment, and this was introduced to the base of the cell until there was a standing head of 1m of liquid.

Leachate recirculation then begun, at an average rate of approximately $7m^3/d$. The 'at rest' standing head of the free leachate fell as the absorptive capacity of the wastemass was satisfied, and a further 119 m^3 of final sewage effluent was added over a 65 day period to bring the level up to 1m. The 1m head was an arbitrary datum that it was decided that both cells would be maintained at.

The following year, in July '93, it was found that the standing leachate head had risen to 1.4m. The project team believe that the increase was "due to vertical and lateral infiltration, in combination with waste degradation and compaction." To restore the standing head to the target of 1m, 65 m^3 of leachate was removed. However, on further recirculation, the standing level fell, and a further 17 m^3 of final sewage effluent had to be added to regain 1m head.

The experimental regime for Cell 2, the control, was to emulate existing landfill. It was decided to emulate infiltration of precipitation through the cap, as may occur with a conventional landfill. At this time, in July '93, the standing head of leachate was unexpectedly found to be in excess of 2m. This was attributed to ingress of water over a long period. It was felt necessary to restore the level to 1 m^3 so that a proper basis for comparison with Cell 1 was maintained. This was achieved by removing 107m^3 of leachate. The simulated infiltration was achieved by pumping 37 m^3 of final sewage effluent in the leachate recirculation system, that was also fitted to Cell 2. How the quantity of 37 m^3 was arrived at, is not explained in the report. Presumably, it was the total precipitation over the plan area of the cells over the period to that date.

Over the ensuing months the standing head of leachate in both cells rose considerably, and just over one year later December '94, Cell 1 had nearly 2m standing head and Cell 2 nearly 3m.

The rises in head appeared to be at a constant rate, not exhibiting seasonal variation, which indicated that surface or groundwater ingress is not the main source. In addition typical liner leakage rates could account for only 10% of the additional liquid. The alternative explanation put forward in the report is that a reduction in porosity from 25% to 8% occurred between July '92 and December '94. In the basal saturated layer, the porosity was calculated to be as low as 3%. It should be stressed that the values presented in the report are not a result of direct measurements of porosity.

The reduction in porosity would be expected to be accompanied by a settlement in the wastemass. This is not commented upon, indeed settlement does not seem to have been a measured parameter.

Efficiency of Leachate Distribution

The cell design, and particularly that of the drainage blankets, allows some leachate to flow from the recirculation pipeline into the sump, without passing through the wastemass. The reason for this design feature is not explained, and as such may have been an oversight.

To assess the quantity of recirculated leachate that passing through the wastemass and the quantity shortcircuiting through the drainage blanket a lithium tracer test was conducted. This showed that the effective leachate recirculation rate through the wastemass was 3 m^3/d and therefore the hydraulic retention time was about 6 months.

A further test was conducted to assess whether leachate was reaching the extremities of the recirculation pipeline. The capacitive coupling method was used. This test showed that leachate reached the extremities of the system in less than one minute.

Temperature of the Wastemass

Two sensors were installed in each temperature probe at construction. In case of failure on the main sensor, the backup could be switched to.

The temperature of the wastemass was dominated by ambient conditions, showing marked seasonal variation. Temperatures began at around 25°C but after less than one year, were in the range 6 - 17°C. The relatively small mass of waste, and the high surface area to volume ratio of the cell shape led to the severe heat loss. In addition, the insulation provided by the synthetic cap was minimal.

Methane Concentration in Landfill Gas

Gas composition was measured in four probes within the wastemass of each cell and also at the vent. Methane concentration within the first 10 months after capping was poor, varying between near zero and 30%, and for a short period 40% in Cell 1. The concentration was shown to be higher by the probes within the wastemass, than in the vent.

After the initial 10 month period (to April '92, leachate recirculation having started on Cell 1in March '92) , the methane concentration increased in both cells. The concentration appeared to be much more stable in Cell 1, at a level of 55%, while

Cell 2 achieved only 45%, and was rather erratic. Leachate recirculation appears to have stabilised gas composition.

Hydrogen Concentration in Gas Probes

The removal of a quantity of leachate from the cells in July '93 resulted in an increase in organic constituents of the leachate. This in turn manifested itself as a large increase in hydrogen concentration within the wastemass, peaking in excess of 10,000 ppm.

The elevated hydrogen concentration is the result of rapid hydrogen production by fermentative bacteria, which temporarily inhibits acetogenic bacteria, leading to a build-up of the heavier intermediates such as butyric acid. The balance is restored by methanogenic bacteria utilising hydrogen. If the organic loading continues at a high rate, acidification may build up to the extent that the pH falls below 6.5 and methanogens cease to be active.

The report recommends that hydrogen be used as a parameter in a control strategy for the operation of a bioreactor landfill, to indicate organic overload.

Gas Output

The project experienced problems in measuring gas output. To begin with gas flow rates were measured using a micro pitot tube, and then a hot wire anemometer on an occasional spot measurement basis. Neither method was successful. Finally the prototype Bartington flowmeter, which works on a time of flight principle, was installed. This successfully measured gas flow on Cell 2 from October'93 to January'95. A second flow meter was installed on Cell 1 in December'94. A graph of cumulative flow is presented in the report, but daily average flows are not. Gas flow data are not provided in the appendix, so it is not possible to assess the variability of the recorded values.

On the basis of the cumulative flow, the gas yields were:

Cell 1	19.9 m^3 LFG/tonne wet msw/yr
Cell 2	8.9 m^3 LFG/tonne wet msw /yr

The mass of the sewage sludge was excluded from these calculations, although the reasons for this is not justified. The rates of gas production are much higher than would be anticipated in conventional landfill, and this is inspite of the exceptionally low temperatures of the wastemass.

Affect of Atmospheric Pressure on Gas Flow

The effect of atmospheric pressure on gas flow has been measured at Landfill 2000. Data presented showed falling pressure over a number of days had little effect on gas output, but a sudden fall in pressure of 15mbar in half a day caused a 2.5 fold increase in gas flow. The gas output peak lagged the atmospheric pressure pessimum by approximately half a day.

The subsequent immediate rise in pressure of 35mbar over 1.5 day resulted in a reduction in flow without lag. However the flow was not reduced below the previous average.

These results are important as there appears to be very little or no experimental data in the literature substantiating the commonly held opinion that, there is a direct and inverse relationship between gas flow and atmospheric pressure.

Waste Sampling

Waste was sampled from the cells in February'95, three and half years after emplacement. Two drillings were taken in each cell. A number of tests were conducted on the recovered material.

The waste was not sufficiently degraded to be of potential use as a soil conditioner. If fact paper and card had undergone little or no degradation. The moisture content was in the range 64 - 72% (dry mass basis).

A physical characterisation of the samples was carried out along the lines of those conducted on fresh waste. This showed that in comparison to characterisation of fresh waste the top of the wastemass contained more fines, and the base more putrescibles.

Leachate Quality

Leachate composition was not monitored for the first nine months after capping, in Cell 1 and not for the first 12 months in Cell 2. The reason for this is not stated.

At these nine months, prior to leachate recirculation in Cell 1, the two cells were experimentally identical. By this time the COD in Cell 1 was down to 1200 mg/l and comprised mainly acetic and propionic acids. Analysis was not conducted for Cell 2. This was a significant loss of data. To compare the two cells at that stage could have indicated the scale of variability between the cells. Instead, Cell 2 initial analysis was conducted three months later, when leachate recirculation had affected the composition of Cell 1 leachate.

Once leachate recirculation began on Cell 1, soluble constituents were flushed out of the wastemass. This manifested itself as a sharp rise in organic components as indicated by COD, BOD and VFAs. COD rose to around 22,000 mg/l over the subsequent two months, but returned to a low level over the following three months.

The team conclude that leachate recirculation helped to develop a neutral pH and distributed organic components in the leachate more evenly.

Bi-modal Activity of Wastemass

The interstitial fluid of waste samples recovered in February '95 was analysed. This showed that there were marked differences between the leachate in the wastemass, and leachate within the drainage blanket/pumping sump. The leachate in the wastemass is characteristically VFA rich, while that in the sump is methanogenic. The ratio of COD within the wastemass : sump was 20:1 and 60:1 for Cell 1 and 2 respectively. This is strong evidence of bi-modal activity of the landfill cell.

There also appears to be a vertical gradient within the wastemass, with the leachate within the base of the wastemass containing higher levels of organic components than the top of the wastemass. Ammonia shows the same trend as COD, though the differences are less extreme.

Biochemical Methane Potential

BMP analysis was conducted on the waste samples recovered in February'95. They show that a significant increase in degradation has been achieved by recirculation.

Table 5.1 Results of Biochemical Methane Potential Analysis

	Cell 1	Cell 2
BMP, m^3 LFG/t dry MSW	76	161
Total time for stabilisation, yr	6.9	17.3
LFG generated (% of total)	58	23

The calculation for 'total time to stabilisation' includes only readily degradable organic material. The calculations for 'LFG generated' utilise the average gas flow which was established for Cell 1 over a relatively short period of a few months. As such these figures probably do not represent the progress to final stage quality.

The enhancement effect of the mixture of sewage sludge with the MSW is not discussed in the reports, although it is probable that this too had an enhancing effect.

Cellulose : Lignin Ratio

The ratio of cellulose to lignin was established in the waste samples taken in February'95, as an alternative method of determining the progress of degradation. As degradation progresses the ratio decreases; cellulose degrading faster than the recalcitrant lignin.

The ratio in Cell 1 was around 0.7, whereas in Cell 2 the ratio was 0.9 - 1.3 indicating the magnitude of degradation has been greater in Cell 1.

Further Comments

An incongruous conclusion of the report is that there is little scope for the recovering the "usable gas potential" in a three year period, inspite of the fact that they have demonstrated that around 60% of the gas from readily degradable waste has been emitted during the same period. The conclusion is perhaps drawn from the fact that little or no degradation of the moderately degradable fraction, as shown by the relatively intact paper and card from the waste samples. If this is the case, then it would not be appropriate to use only the readily degradable fraction, for calculations associated with Biochemical Methane Potential. This leads to an unrealistically optimistic evaluation of the progress to stabilisation.

The strategy of leachate composition sampling and analysis was inconsistent, in particular the lack of leachate analysis for both cells, prior to leachate recirculation. Even pH was not measured for in Cell 1 prior to recirculation. After that time it was a further six months before the full suite of leachate analysis was applied.

The role of sewage sludge, and the effect that it may have had, has not been discussed in the report.

The effect of a single dose of liquor simulating infiltrated precipitation in Cell 2, the control cell, may also have had the effect of a single recirculation event. The elevation of organic components in the leachate supports this.

There appears to have been a problem with the containment in the cells. The explanation of reduced porosity is interesting, however the larger increase in standing head of leachate in Cell 2 than Cell1 is difficult to explain this way. The total accumulation of 3m of leachate in Cell 2 is not addressed.

The project may be seen as an endorsement of landfilling MSW with digested sewage sludge, as both experimental cells produced gas at a rate well in excess of that experienced in conventional landfill, despite low wastemass temperatures. However the reports does not overtly state this, because it is uncertain which of a number of factors actually created the enhanced gas production. For example, the elevation of moisture content alone may have been responsible.

Finally, the strategy of transient landfilling, which entails double handling of waste and high costs of engineering, needs to be questioned. Enhancement of degradation has been shown to be successful; however it appears that only the readily degradable fraction has been involved. More recalcitrant ligno-cellulosic materials have not been significantly degraded. This calls into question what has been achieved in what amounts to a three year long waste pretreatment process. It may well be more efficient to engineer the final repository as a bioreactor landfill, and place the waste directly in there. This would have benefits from the economies of scale of larger cells, and not have the expense of re-excavation.

The Landfill 2000 reports provided useful material when considering the design of the Mid Auchencarroch project. In particular, were the experiences of adding liquid to satisfy absorptive capacity, homogeneous distribution of leachate, and the problems of short-circuiting.

5.5.2 Brogborough

The Brogborough project is a large scale field experiment, to "evaluate practical and robust methods by which site operators may influence gas production from waste". The project was supported by the Department of Energy, which was amalgamated into the Department of Trade and Industry in 1992. There have been a considerable amount of data generated over a ten year period, and extensive analysis of this has led to the production of many reports (including Croft and Fawcett, 1993; Westlake, 1994; Maule, Luton and Sharp, 1995; Caine and Davies, 1996).

Project Description

To introduce the project, six individual test cells were constructed between 1986 and 1989. The cell were located at a commercial landfill site in Bedfordshire. The treatment applied to each of the cells is given below. The cell dimensions were 40m x 25m and 20m deep, containing approximately 15000 tonnes of waste each.

Table 5.2 Brogborough Test Cell Treatments

Cell No.	Treatment
1	Domestic waste emplaced in thin layers (current best practice)
2	Domestic waste emplaced in thick layer (old practice)
3	As cell 1, but water injection from summer `92
4	As cell 1, but air injection from summer `92
5	As cell 1, but supplemented with dewatered primary sewage sludge.
6	As cell 1, but supplemented with 45% non-hazardous industrial and commercial waste (mainly paper and card)

Cell 1 is the experimental control and the intention was that the treatment applied to Cell 2 would provide a lower density wastemass. However this turned out not to be the case and densities were similar. Therefore Cells 1 and 2 may both considered as controls.

It may be stated generally that the project did not have an easy passage during its initial few years. This was partly due to situations outside the control of the project team. The team was unfortunate in the design, selection and installation of some elements of hardware, particularly the instrumentation.

Construction of the test cells is reported to have been relatively straight forward. The project was however to be extensively revised due to a seven fold increase in waste received to the surrounding commercial landfill. This necessitated the cells, which had already been capped and instrumented, having their depth increased from 10m to 20m. Horizontal systems of gas and leachate collection had to be abandoned. Temperature probes had their wires extended and all then failed within a short time. The entire rational of monitoring and instrumentation had to be re-thought. This was undoubtedly a severe blow to the project.

During reinstallation of equipment, this time using vertical wells and borings, design errors were made, mainly though lack of experience. Settlement was given sufficient cognisance, and this led to the failure of gas extraction wells, and separate gas sampling and temperature monitoring installations. These *all* had to be reinstalled a second time, with design modifications. This was no doubt an expensive error, both in financial terms and in terms of delay of the monitoring programme.

Relevance of Brogborough to Mid Auchencarroch

While there are similarities in many aspects of both experimental projects, there are some key differences:

Scale	The mass of waste in each cell at Brogborough is much greater, resulting in a much lower surface area to volume ratio. This has significant advantages in terms of thermal loss.
Depth	The overburden resulting from 20m of waste is considerable, compared to just 5m at Mid Auchencarroch. Due to the depth of waste at Brogborough, permeability of the wastemass is likely to be considerably reduced. This has significant disbenefits in terms of homogenising moisture content and flushing of the wastemass.
Waste substrate	Untreated MSW was the main substrate, but sewage sludge and additional ligno-cellulose material were used in some treatments. Pulverised waste was not part of the project.
Leachate recirculation	Addition of water and recirculation of leachate was used.

The volume of material published about Brogborough is considerable, and therefore only topics that have significance to the Mid Auchencarroch have been chosen for discussion as follows.

Head of Free Leachate

The leachate level rose steadily in all cells, with the exception of Cell 6. The rate of rise was approximately 1m/yr.

Leachate Temperature and Composition

Leachate temperature has been maintained around the mesophilic range of 30 - 35°C.

After an initially high level of organic components in the leachate of Cell 5, the level in all cells decreased to be very similar. Until the beginning of 1994, the leachate wells were not purged prior to sampling, and therefore the value of the early data is questionable.

Gas Composition

There was little difference in methane content of the landfill gas between the cells. It has remained 55 - 59% fairly consistently.

Measurement of Gas Flow

To begin with landfill gas was vented naturally, but after the cell depth was increased to 20m, active venting was adopted, with the gas being removed from the wastemass by pump.

Initially Roots type positive displacement meters were installed. Problems were encountered that severely affected reliability. The fine tolerances within parts of the meter that encountered the gas, meant corrosion, condensate and particulates inhibited reliable operation. These meters were subsequently replaced by axial flow turbine devices, which were not positive displacement, meaning very low flow would not be registered.

Subsequently gas output was measured by a venturi meter, and checks were made using a hot wire anemometer. The pressure transducers on the venturi meter were subject to some drift, however bench tests have shown that the total error for flow measurement was less than 20%, and probably in the region of 5-10%.

From informal communications, the author understands that Bartington gas flow meters are now being fitted to these test cells.

Gas Output

Methane specific yields, in m^3/tonne wet msw/yr, over the whole length of the project were:

Cell 1, control	4.7
Cell 2, low density	4.0
Cell 3, liquid injection	5.7
Cell 4, air injection	6.7
Cell 5, sewage sludge co-disposal	5.7
Cell 6, commercial and non-hazardous co-disposal	4.9

All treatments delivered enhancement in methane yield: air injection, liquid injection, and addition of sewage sludge being the most successful.

The ratio of settlement to gas output was calculated in order to develop a relationship. The results were inconclusive.

The relationship between gas flow and atmospheric pressure was analysed. An inverse relationship was found to be present in many periods of the data. A diurnal fluctuation in atmospheric pressure was also observed at times.

Settlement

The average rate of settlement for all the cells decreased from an initial 0.23 m/yr to 0.20 m/yr. It is suggested that this indicates that settlement is greater during the predominantly acidogenic phase than the methanogenic phase.

Economic Evaluation

An economic evaluation of utilisation of landfill gas for electricity generation was made. Two scenarios were constructed, one of which included enhancement of gas generation, and one without. The model showed that there was significant economic benefit from enhancement, and that the internal rate of return rose from 15.5% to 19.5%. In addition it showed that an economic price for the electricity could be reduced from 3.5 p/kWh to 2.9 p/kWh. At this price un-subsidised production of electricity becomes realistic.

Summary of Effects of Treatments

All treatments resulted in an increase in gas output compared to the control cell. The reports suggest that the mechanisms by which the enhancements achieved this are different:

Cell 3, liquid injection	mainly a result of increased waste degradation rates
Cell 4, air injection	mainly a result of improved landfill gas recovery
Cell 5, sewage sludge co-disposal	a result of additional moisture and anaerobic inoculum within the sewage sludge
Cell 6, commercial and non-hazardous co-disposal	attributed to buffering effect of the inert materials, reducing methanogenic inhibition during acidogenic phase which usually occurs within weeks of capping.

The review of the Brogborough project during the design phase of the Mid Auchencarroch provided some salutary lessons in terms of instrumentation reliability, and in particular, measurement of the temperature of the wastemass, and the flow of landfill gas.

The project is ongoing.

5.5.3 Gas and Leachate Trends Study for Scottish Enterprise

In 1993 the Water and Environmental Management Unit of the University of Strathclyde undertook a study of a number of Scottish landfill sites on behalf of Scottish Enterprise. This analysis of the study should be read in conjunction with their report entitled 'Gas and Leachate Generation Trends at Craigmuschat Quarry and a Number of Scottish Landfill Sites in Central Scotland'(Fleming and Macdonald, 1993)

The study consists of an appraisal of the progress of degradation at each of the six sites considered. The characteristics of both gas and leachate are assessed. Further areas that are covered for research purposes are information management systems to utilise monitoring data, and the accuracy of portable gas analysing equipment. The latter is covered quite extensively but is not considered sufficiently relevant to be covered here.

Some interesting points are brought out by the study of the gas and leachate trends of the six sites. The sites are quite different in many respects, in their engineering and their waste input. Some common themes emerge, though not necessarily following the conventionally expected forms. For instance the study found the classical representation of four stages of gas production (Farqhuar and Rovers, 1973) became temporally distorted in those sites where all the factors for methanogenesis were not favourable.

Of interest with the leachate monitoring is the experience that the BOD/COD ratio was not a reliable indicator of the degradation process. From the team's involvement with the Craigmuschat site, a clear conclusion has been that depth of waste in excess of 20m does not guarantee anaerobic conditions, though this is partly due a highly efficient venting and drainage system.

The formal conclusion of the report is that landfill should be engineered to optimise early and rapid methanogenesis in order to minimise long term monitoring. If gas utilisation becomes more widespread due to greenhouse gas concerns , the control of and acceleration of the methanogenic degradative process will become an even greater necessity.

5.5.4 Bioreactor Test Cells in Australia

A bioreactor landfill research project is being conducted in Australia with the objective of achieving waste stabilisation in one generation (Van Den Broek, Lambropoulos and Haggett, 1995).

Project Description

The project consists of two experiments: a series of five large test cells, each of about 10,000 m^3 and a set of ten batch reactors, each of 160 litres.

In the initial stage of the project two of the test cells were constructed, one of which was a control and the other which will operate leachate recirculation. The subsequent test cells, which are not described here, will operate as sequential batch reactors, with the objective of achieving rapid stabilisation by optimising the methanogenic phase.

Cell Details

The cells are 45m square and 10m deep, and are artificially lined. The design incorporates a granular drainage layer at the base for leachate collection and at the top for leachate recirculation and gas collection. Leachate is also recirculated to other pipelines at five levels within the top half of the wastemass.

Interestingly, the drainage media that has been chosen is sand, rather than a gravel. The basal drainage layer is 600mm thick, and has geotextile wrapped perforated drainage pipe leading to a pumping sump. Bioclogging, which is potentially a serious threat to the operation of the drainage media and therefore the cells, does not appear to have been addressed.

The waste stream was MSW from Sydney. During emplacement the waste was subject to some mixing to help create a more homogenous wastemass. Waste was sampled on a daily basis during filling. No daily cover was used.

The leachate recirculation cell was subject to pre-saturation by a combination of fresh town water, and mature leachate, from the adjacent currently operating landfill.

Gas is passively vented. The gas collection system includes a backflow prevention device, and a flashback arrester.

Data from this interesting experiment have not been published yet.

6 EXPERIMENTAL CONCEPT, DESIGN AND METHODOLOGY

6.1 Background

In 1993 and 1994, Professor George Fleming of the Centre for Environmental Management Studies at the University of Strathclyde (CEMS) conducted an experiment in shallow landfill at Mid Auchencarroch, in association with George Munn of G & A Munn (Landfill) Ltd., a landfill operator. This experiment involved the landfilling of commercial and industrial waste, in shallow landfill, using the 'Clay Sandwich' technique developed by the former (Fleming,G 1990). The technique is essentially semi-landraise, in that only sufficient material for capping and construction of cell walls, is excavated from the thick clay drift.

This experiment showed that methanogenic conditions would develop readily in cells containing as little as 250t of commercial and industrial waste. It also showed that in the long term, heat loss was potentially a problem for shallow landfill (Wingfield-Hayes, 1994; Wingfield-Hayes, Fleming and Keenan, 1997).

Following this preliminary experiment, it was felt that sufficient experience had been gained to conduct a more detailed field scale experiment this time involving Municipal Solid Waste (MSW).

Editorial Note

Unless otherwise stated, the term 'waste' is used in subsequent parts of this thesis to mean MSW.

6.2 The Issues

The concept of the experiment revolves around three issues:

- **sustainability**
- **landfill gas**
- **appropriate technology**

These issues are dealt with separately in the following three sections.

6.2.1 Sustainability

Sustainable Development, and its importance, has been discussed at some length in Chapter 2. The application of principles of Sustainable Development to landfill, thus creating Sustainable Landfill has been discussed fairly extensively in the literature.

It has been contended in the early chapters of this thesis that landfill as a process is itself unsustainable, and so the term 'sustainable landfill' may be a misnomer. Within the landfill industry, as elsewhere, the principles of Sustainable Development have been applied such that they specifically mean:

- the consequences of actions today do not extend for more than 30 years.
- the only consequences that are considered are the direct negative effects in terms of environmental pollution. (this is a comparitively narrow definition)

Therefore, the 'Sustainable Landfill' is one in which, after 30 years, the waste will be in a benign and non-polluting state. This state is termed 'final stage quality'.

It has been suggested (Harris, Knox and Walker, 1994) that there are two strategies by which the 'Sustainable Landfill' may be achieved:

- landfill only material close to final stage quality
- speed up the process of degradation

The former strategy relies on thorough pretreatment of waste by some or all of the following methods: physical, chemical, biological, thermal. The current options available are discussed in the earlier chapters. Broadly speaking, all current methods are resource and energy intensive, therefore having a significant environmental cost in themselves. Most of the processes render the biodegradable element of the waste stream entirely or almost entirely inert, usually by an oxidation process. However, though the material is biologically inert, it may be chemically reactive, and will almost certainly contain toxic materials that will leach out. Thus, even though this material has been processed at environment cost, it is not yet at final stage quality. To achieve final stage quality, the material will need to have the soluble toxic materials flushed out, until the remaining material can only release toxic materials at a rate that can be safely assimilated by the environment.

The latter strategy, focuses on improving the landfill process, by creating conditions that are favourable for these processes. As well as speeding up degradation, a subsequent stage of flushing out of soluble toxic material is required, in order to achieve final stage quality . This type of landfill has come to be known as the 'flushing bioreactor'. Broadly speaking, this is a low input approach, which entails lower environmental overheads.

6.2.2 Landfill Gas - Composition and Output

The utilisation of landfill gas is the main method by which value can be recovered from the landfilling of waste at the moment. There are potentially other ways of recovering value, such as mining the degraded material in the future or using a nutrient rich leachate for biomass production. However, these technologies are experimental, and face many technical and economic problems.

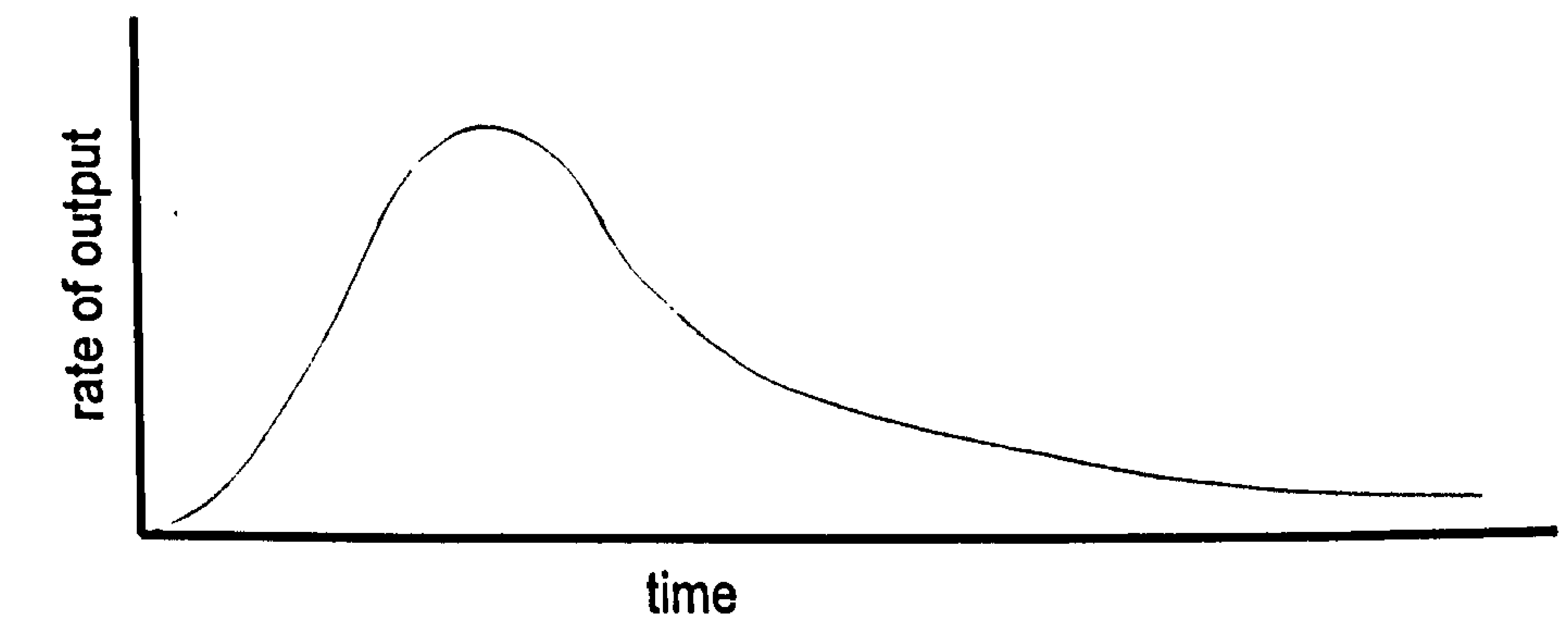
The utilisation of landfill gas, by comparison, is a mature and well established technology, and is becoming economic in the free market. It is also important that landfill gas is utilised, or oxidised in some way because of the disbenefits of its global warming contribution.

Thus utilisation of landfill gas is relatively straight forward, whereas control over production of landfill gas in the wastemass is a fledgling technology.

Production Curve

Current knowledge on landfill gas production is largely based on Farqhuar & Rovers (1973) seminal paper. From this paper, together with subsequent modelling and experiments of various sizes, a picture of landfill gas production has been established. The graphical relationship between gas output and time is shaped approximately as a left-skewed "bell" curve, as shown in Figure 6-1 below. This typical shape is drawn from both landfill gas monitoring and modelling (for example: Gasparini, Saetti and Nizzoli, 1997; Guyonnet and Come, 1997).

Figure 6-1 Typical Timing of Gas Output



The shape means that despite there being a considerable amount of gas production in the centre of the "bell", there are also significant quantities in the leading tail and particularly the trailing tail.

The long trailing tail is a manifestation of the easily degradable material having being utilised, leaving only the more refractory materials as substrate for gas production.

In terms of utilisation of landfill gas, a square production curve is desirable, that is to say that the amount of gas volume in the leading and trailing tails of the curve is minimised.

This desirable square curve would be achieved in two stages:

1. bringing gas output to the maximum steady level, at a desirable time, probably shortly after capping the landfill, once a gas collection system is implemented. This means that the immediate onset of widespread methanogenisis is not necessarily desirable, in that if it occurs prior to the installation of a gas collection system, some of the landfill gas resource will be lost to atmosphere. Effectively, what is required is a "start button".

2. maintaining gas output at the maximum steady level, until *all* the biodegradable substrate is utilised.

This amounts to a control over the landfill degradation process.

In practice, the first stage may be feasible. However, the second stage is difficult, and is probably controlled by the rate of degradation of ligno-cellulosic material.

6.2.3 Appropriate Technology

Appropriate Technology is a term most commonly associated with the developing world. In the broader sense Appropriate Technology is the application of technology that is *appropriate* to the problems and situation in which they are applied.

This has significant relevance to this project because:

1. Environmental Overhead of The Application of Technology. As landfill is a technique for disposal, there is no net benefit gained from the process; the main aim of application of technology is the minimisation of disbenefit, ie. pollution.

All applications of technology, in terms of plant and materials, have not only economic cost, but also environmental cost. Therefore, an over engineered solution to landfill will have a greater disbenefit in terms of environmental cost, than a simple but effective solution.

To sum up, design philosophy should be:

minimise environmental cost ⇒ keep it simple.

2. Evolving Techniques for Remote Communities and the Developing World. In most parts of the world the application of technology to landfill is restricted to large facilities near centres of population. Due to poor economies of scale, many smaller landfill facilities are technologically inferior, and tend to be overlooked in both funding and regulation. Taken together, they still have a significant capacity to pollute, although this occurs at disparate point sources. In terms of leachate emissions, this may be acceptable, but in terms of the atmosphere and greenhouse gases, disparate point sources are of course exactly the same as a larger single source.

The development of techniques that make small-scale shallow landfill, technically and economically feasible to remote communities and the developing world will assist in making the disposal of waste less of an environmental disbenefit.

6.3 Objectives

Stemming from the issues as described above, the broad objectives of the experiment are to develop techniques to:

1. gain a greater control over the biodegradation processes within a landfill
2. improve the ability to remove 'unbound' toxic materials from the landfilled wastemass
3. not entail excessive environmental cost in achieving the above objectives

6.3.1 Means of Achieving Objectives

It is possible to attempt to achieve the objectives as set out above, in many ways, and at different scales of size and time. Over the past two to three decades, the literature reveals that there has been a large amount of laboratory research and some field scale research, much of which has been discussed in earlier chapters. This together with experience of the Landlab facility in California (Calpoly, 1987), and the earlier experiment at the site, enabled a more ambitious experiment to embarked upon.

A research proposal was put to Dumbartonshire Enterprise in June 1994 (CEMS, 1994b), in which the potential of a number of enhancement techniques would be assessed in a field scale trial. This proposal formed the basis for a subsequent successful proposal to the Department of the Environment in October 1994 (CEMS, 1994a).

The formal objectives for the research contract were:

- demonstrate by means of a field trial that waste pulverisation combined with leachate recirculation can enhance the rate of waste stabilisation and gas production
- provide data on the effect that processing of wastes can have on waste stabilisation and production of gas from landfilled waste
- determine the impact that the flux of water within the waste can have upon waste
- study leachate quality with time to improve the prediction of leachate treatment requirements which were expected to change over the life of the lifetime of the site
- to selectively use leachate recirculation techniques to assist in understanding the impact which the water content of the waste can have upon waste stabilisation
- from information obtained from monitoring leachate recirculation, develop leachate control strategies for the protection of adjacent water courses

Not all the stated objectives for the research contract are relevant to the author's work, and in particular that of protection of water resources will not be addressed in this thesis.

Three manipulations of the landfill process were envisaged to achieve the objectives:

Manipulation of the **composition** of the waste substrate:	⇒	Addition of inert material
Manipulation of the **characteristics** of the waste substrate:	⇒	Treatment of waste prior to landfill
Manipulation of the landfill **environment** after capping:	⇒	Recirculation of leachate

By various combinations of these three manipulations, it was intended to assess their suitability in achieving the first two objectives.

Objective 3 would be satisfied by the appropriate method of implementation of the experimental landfill.

6.3.2 Raison d'Etre of Manipulations

Addition of Inert Material

The addition of inert material, may be seen to a certain extent as an emulation of co-disposal of inert and biodegradable waste streams. It is widely held view amongst legislators, particularly in the EU, that the landfilling of a heterogeneous waste stream is not desirable. In particular, the landfilling of non-hazardous commercial and industrial waste along with MSW is discouraged, and in several European nations it is outlawed.

However, there may be reasons why discouraging or outlawing this practice will make landfill less 'sustainable'. If the landfill is to operate successfully as a 'flushing bioreactor', one of the key properties required is a sufficiently permeable wastemass. By mixing MSW, with for instance a non-biodegradable granular construction or industrial waste, the permeability of the wastemass may be enhanced, so enabling greater movement of liquid.

Sand was selected as the inert material for co-disposal with MSW, as it was not expected to directly affect leachate composition, and was available from an adjacent site. The addition of sand was at a rate of 25% by volume.

Treatment of Waste Prior to Landfill

To a great extent, enhancing the rate of biodegradation in the landfill environment is about optimising conditions for the microbial population. Prior to placement of waste in the landfill, this can be done by manipulating characteristics of the waste stream. It is recognised in the literature that two of the most important parameters for microbial activity are substrate availability and moisture. Both of these may be enhanced by processing the waste stream.

In untreated waste, substrate availability may be poor because of the heterogeneity of waste, particularly wastes from household sources. For example, elements of the waste stream may be in impermeable enclosures, in the form of plastic bags. Alternatively, there may be large 'particles' of one material, for instance a wad of newspaper, for which significant microbial activity will only occur on the external surface. The pretreatment process can alter the characteristics of particle size and homogeneity. By reduction of particle size and mixing of these particles substrate availability is improved.

The pretreatment process can also be used to elevate moisture content to a beneficial level for microbes, this level is in practice taken to be approaching field capacity.

One method of pretreatment that combines these features is that of 'wet pulverisation'. This may be achieved by the 'Dano Drum', a proprietary wet pulverisation plant which is described in Section 5.1.

Leachate Recirculation

Leachate recirculation is another method of elevating moisture content in the wastemass. However, it has other functions as well; distribution of nutrients and microbial inoculate, and mobilisation of pollutants. Crucially leachate recirculation can take place over long periods of time after the landfill has been capped. Thus leachate recirculation may be used to manipulate the landfill environment in the long term.

Leachate recirculation is generally recognised as a essential tool for operation of landfill as a flushing bioreactor.

6.4 Experimental Treatments

The combination of manipulations that formed a treatment are shown in the table below. The treatments were decided upon as the optimum combination to fulfil the experimental objectives.

Table 6.1 Experimental Treatments

Treatment	1	2	3	4
Addition of inert material	✓			
Pretreatment by wet pulverisation	✓		✓	
Recirculation of leachate	✓	✓	✓	

As it can be seen, treatment combination No 4 is for comparison purposes, and is in effect emulating the current practice of landfilling untreated waste. No 2 reflects landfilling untreated waste as well, but includes leachate recirculation. No 1 and 3 have both pulverised waste as well as leachate recirculation, but No 1 has the addition of inert material.

Replication

Replication is desirable in any experiment. Unfortunately, the scale and the cost of each test cell meant that this could not be justified at full scale. A proposal for 5 smaller test cells for each treatment was considered. However, additional fixed costs, difficulties of construction, measurement of small gas flows and the potential pitfalls of scaling experimental data up to full scale landfill meant that this idea was abandoned at an early stage.

In addition, it was felt that the relatively large size of the cells in comparison to the size of elements of the waste stream, would mean that heterogeneity of the waste stream would not adversely affect a cell.

It was therefore decided, after consultation with the funding partners, that only one landfill test cell would be constructed for each of the four treatment combinations. The four test cells were numbered according to the same numbering as the treatment combinations that were applied; ie treatment combination 1 was in Cell 1, etc.

6.5 Design of the Experiment Landfill

The design philosophy was that of simplicity, efficient use of resources and technology appropriate to the application.

6.5.1 Design Criteria

The criteria that were considered during the design process were:

Scale

Each test cell should be of sufficient size that full scale landfill conditions are emulated faithfully, so data obtained will not be subject to uncertainties when scaling up.

Gas Production

Measurement of the production of landfill gas is a key method of directly assessing the progress of the microbiological degradation process occurring in the landfilled wastemass. It is of importance in terms of the experiment because it shows how successful the various treatment combinations are compared to one another. It is also important in terms of absolute value because from it we are able to calculate the progression to final stage quality - using a mass balance approach.

For these reasons, it was considered absolutely crucial to have full time monitoring of gas production. It was further intended that this would provide accurate, real landfill data to put a timescale on Farqhuar & Rovers (1973) seminal work.

Gas Collection

A passive, that is unpumped, system for collection and venting of gas was envisaged. An active, pumped, system was rejected not only on grounds of cost, but also because a low head loss passive system should more accurately represent the pattern of production of landfill gas.

A further reason for a low head loss system is that in order to assess the gas production accurately, collection of *all* the gas is necessary. In addition, the containment should not be pressurised, and the path of least resistance for gas being produced in any part of the wastemass should be to the collection system.

Distribution of Recirculated Leachate

The irrigation of leachate should provide even distribution through the whole of the wastemass.

Prevention of Shortcircuiting

The Landfill 2000 (Bradshaw, Reynolds and Blakey, 1993; reviewed in Section 5.5.1) test cells encountered problems of shortcircuiting[1] around the periphery of the wastemass. This appears to have been mainly due to the unconventional, diamond section, shape of the cells. Shortcircuiting of this type is a more serious problem within a test cell compared to a full scale landfill, because in the test cell the volume of leachate passed through the wastemass needs to be measured. Therefore it is important matter of design to prevent shortcircuiting.

---

[1] see glossary for 'shortcircuiting' and 'preferential drainage path'

Physical and Chemical Effects on Leachate during Recirculation

During the process of recirculation, changes in physical and chemical characteristics of the leachate should be minimised. Of particular note are thermal loss, air stripping of ammonia, and creation of aerobic conditions.

Significant Amount of Free Leachate Available For Leachate Recirculation

An efficient leachate collection and storage system that enables a significant amount of leachate to be pumped from base of cell at a high rate, is desirable.

Measurement of Settlement of Wastemass

The ability to measure the settlement of the wastemass, in order to record the progress of physical stabilisation, is necessary.

Accommodation of Settlement

The design of cell features, and in particular gas collection system, leachate irrigation system and wellheads should be such that they should be unaffected by the settlement of the wastemass.

Ability to Obtain Samples of Degrading Waste

The ability to obtain samples of degrading waste is desirable in order to assess the progress of biodegradation, or to measure other specific parameters in the degrading waste, for instance microbial populations. However, the facility to obtain these samples should not compromise the integrity of the cap, nor should it cause anaerobic conditions in the wastemass.

It would be useful to be able to obtain samples of waste from both the saturated zone and the unsaturated zone of each cell.

Containment

Containment to provide minimal ingress of surface and groundwater and minimal egress of leachate.

Density of Wastemass

To improve the hydraulic characteristics, the density of the wastemass should not be excessive, and for this work it is desirable to make it lower than that normally achieved in full scale landfill.

Homogeneity of Wastemass

On a whole cell scale, it is desirable to achieve a homogeneous wastemass. In particular the introduction of layers of low permeability material, in the form of daily cover, is not desirable.

Bioclogging

The accumulation of material in and around some of the engineering features of a landfill is now being recognised as a major long term problem (Rowe et al, 1997). The design of the experimental landfill should make allowance for this, both in terms of its operation and for research.

Vandalism

There is an acknowledged problem of vandalism and theft over the whole of the landfill site. Outside hours of operation, the site is unattended, and being an upland location, is not overlooked by any dwellings.

Power Supply

There is no mains power available on site. A genset is available, but cannot be left on site overnight for reasons of vandalism, and theft.

Agricultural After Use of Revegetated Landfill

When construction of the experimental landfill is complete, the revegetated landfill surface will be turned over for agricultural use by the landfill operator George Munn, who is also a sheep and cattle farmer.

This has two main implications for design:

1. The restored surface should allow operations with agricultural machinery

2. Installations at the surface should be capable of withstanding the attentions of cattle and sheep. The mass of the former can be in excess of 600kg.

6.5.2 Method of Measurement of Gas Production

Measurement of gas production are the single most important parameter of the experimental monitoring. Therefore, it will be dealt with in more depth:

Collection of Gas

To enable the rate of landfill gas production to be assessed, the test cells were designed with a collection system in which it was intended that all the gas should aggregate. The collection system is described below. From the collection system the gas is piped to a location above the cap at which a metering device may be operated.

Nature of the Gas

Landfill gas is a potentially explosive, corrosive, hot gas, often saturated with moisture, containing particulates, and of variable composition and density. As such it is difficult to devise an instrument to measure the flowrate with accuracy and reliability over long periods unattended.

Gas Flowmeters

A study (Fletcher,P 1992) compared the available devices for measuring landfill gas flow. This study together with experience on other test cell projects[1], showed that many of the devices were not particularly accurate or reliable. Most were originally designed for another purpose and were modified for landfill gas application. Some devices were accurate irrespective of variable gas parameters, for instance a 'Roots blower' type flowmeter, but were unreliable because of particulates and corrosion. Others, generally those with no moving parts, were reliable, for instance the orifice

---

[1] see Section 5.5

plate, but are liable to drifts in accuracy with changes in temperature, composition and density.

A further problem was that most of the devices create a significant pressure drop across them. This may be acceptable in landfill gas systems in which the gas is pumped out of the cell, but not in a passively vented system such as this experimental landfill.

A considerable amount of effort was put into researching the landfill gas flowmeter market by the author, in order to select a device that would be suitable for our requirements. The Schlumberger INTEX-VF Vortex Flowmeter[1] was initially selected. This utilises the phenomena of vortex shedding on a bluff object in the flowstream. Above a threshold value flow speed, vortices are shed off alternate sides of the bluff object. The rate of shedding is proportional to the flow. The flowmeter has no moving parts and has a very low head loss. A turndown ratio (ie. the maximum value divided by the minimum value) of 40:1 is possible.

Prior to purchase of the Schlumberger flowmeters, a new type of flowmeter was brought to the attention of the author by Nick Blakey of WRc. This was the Bartington flowmeter, and though not commercially available at that time, was designed specifically for landfill gas. It was developed with WRc and was used on the 'Landfill 2000' test cells. After consultation with the manufacturer, and a visit to an existing installation on a landfill site, it was decided that the Bartington device had significant advantages.

The Bartington Landfill Gas Flowmeter

The Bartington flowmeter were developed originally at the University of Essex in association with WRc. The patent is now owned by British Technology Group (1995). Prototypes were used on the Landfill 2000 test cell project, and on the

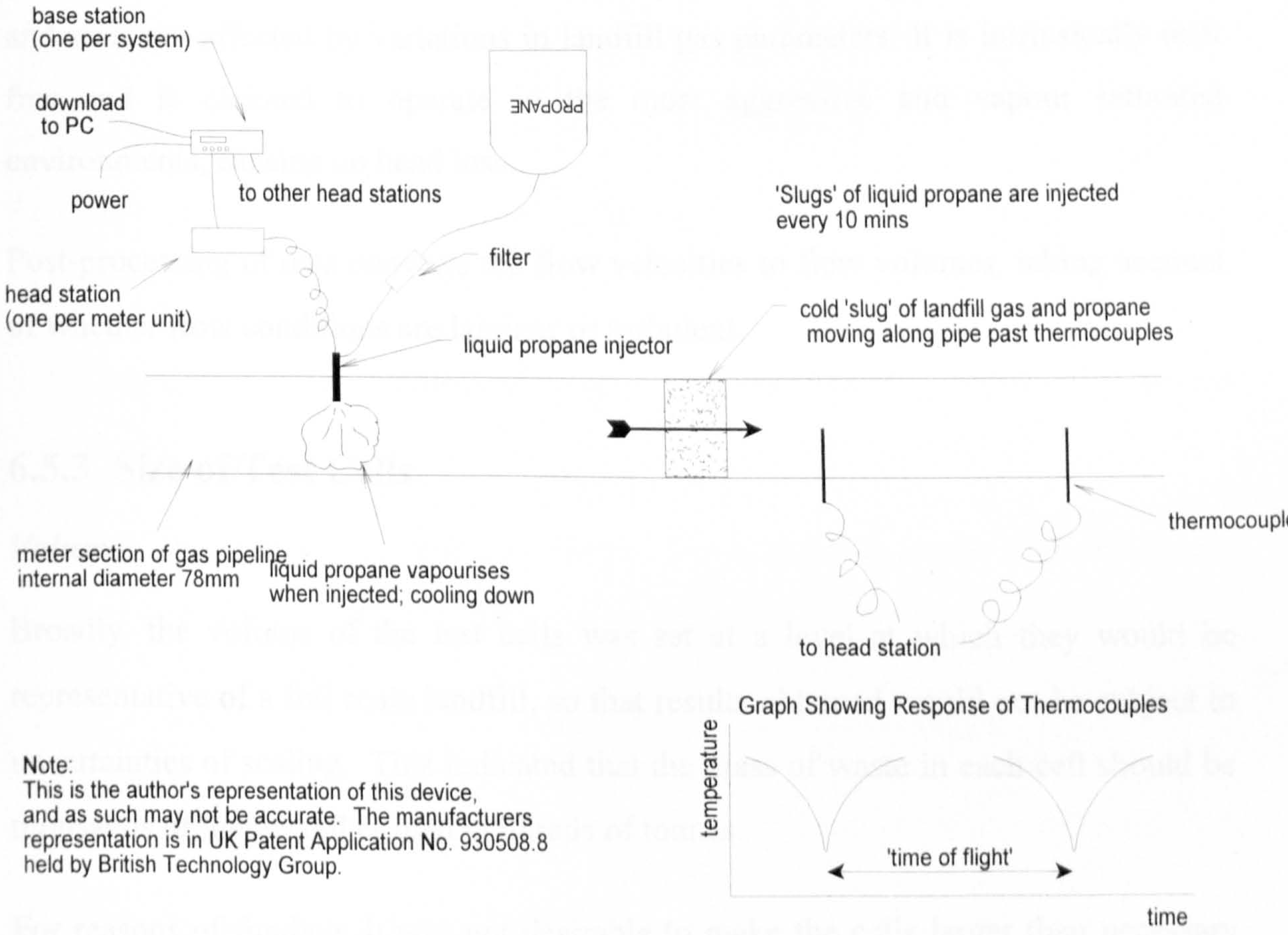
---

[1] Schlumberger Measurement & Systems, Salmon Fields, Royton, Oldham, Lancs, OL2 68X.

Mucking Marsh Recirculation Trials, the latter of which are on going. The flowmeter works in a novel way and is in fact a *velocity* measuring device.

The figure below shows how they work in the Mid Auchencarroch installation.

Figure 6-2 Bartington Gas Flow Meter



A small 'slug' of liquid propane (hence the bottle is inverted) is injected into the landfill gas stream within the pipe. The propane vapourises, cooling down, due to the thermal energy required for latent heat of vapourisation. This creates a cold slug in the landfill gas stream, which continues downstream past the two thermocouples. The meter calculates the velocity of the gas from the 'time of flight' between the two thermocouples, a known distance apart. More precisely, it looks at the time from pessimum temperature to pessimum temperature at the thermocouples.

The system is controlled by a datalogger at the Base Station. Injections of propane are programmed to occur every ten minutes, so the meter is in effect taking a spot reading every ten minutes, and not truly measuring the total volume flow (in comparison to a positive displacement meter which does).

The accuracy of the meter is claimed to be independent of the gas being measured, and so is not affected by variations in landfill gas parameters. It is intrinsically drift free and is claimed to operate in the most aggressive and vapour saturated environments, causing no head loss.

Post-processing of data converts the flow velocities to flow volumes, taking account of whether flow conditions are laminar or turbulent.

6.5.3 Size of Test Cells

Volume

Broadly, the volume of the test cells was set at a level at which they would be representative of a full scale landfill, so that results obtained would not be subject to uncertainties of scaling. This indicated that the mass of waste in each cell should be thousands of tonnes rather than hundreds of tonnes.

For reasons of funding, it was not desirable to make the cells larger than necessary for the experimental criteria. The specific factor that set the minimum cell size was that of measurement of gas production.

The cell dimensions were originally established before the Bartington Flowmeter was known of. The minimum flow that other suitable flowmeters were able measure was 6 m^3/h.

Gas yield data published from the Brogborough Test Cells (Croft and Fawcett, 1993), showed that the range of gas production was 0.4 - 3.0 l/h/tonne of waste. This indicated a cell wastemass of at least 4500 tonnes. The bulk density of the placed waste was expected to be around 0.9 t/m^3. Therefore the proposed cell volume was

5000 m^3. Even with this quantity of waste it was realised that some of the low flow data would not be recorded.

However, it was subsequently possible to reduce the cell volume and acquire more of the low flow data, once the Bartington Flowmeter became known of; the new device had a flow measurement threshold that was much lower, at 1 m^3/h. The cell volume was reduced to 4000 m^3.

Dimensions

Experience with the previous experimental landfill site at Mid Auchencarroch had shown that shallow landfill of around 5m depth of waste was feasible.

It was decided that the waste depth in the proposed test cells should also be 5m because:

- knowledge that the higher thermal losses associated with shallow landfill, did not preclude methanogenic activity.
- suitable for construction using the clay sandwich technique.
- superior hydraulic properties of a thinner and less compact wastemass
- leachate recirculation; greater infiltration area to waste volume ratio
- flushing wastemass; shorter flow path through waste from injection to collection, therefore faster flushing.

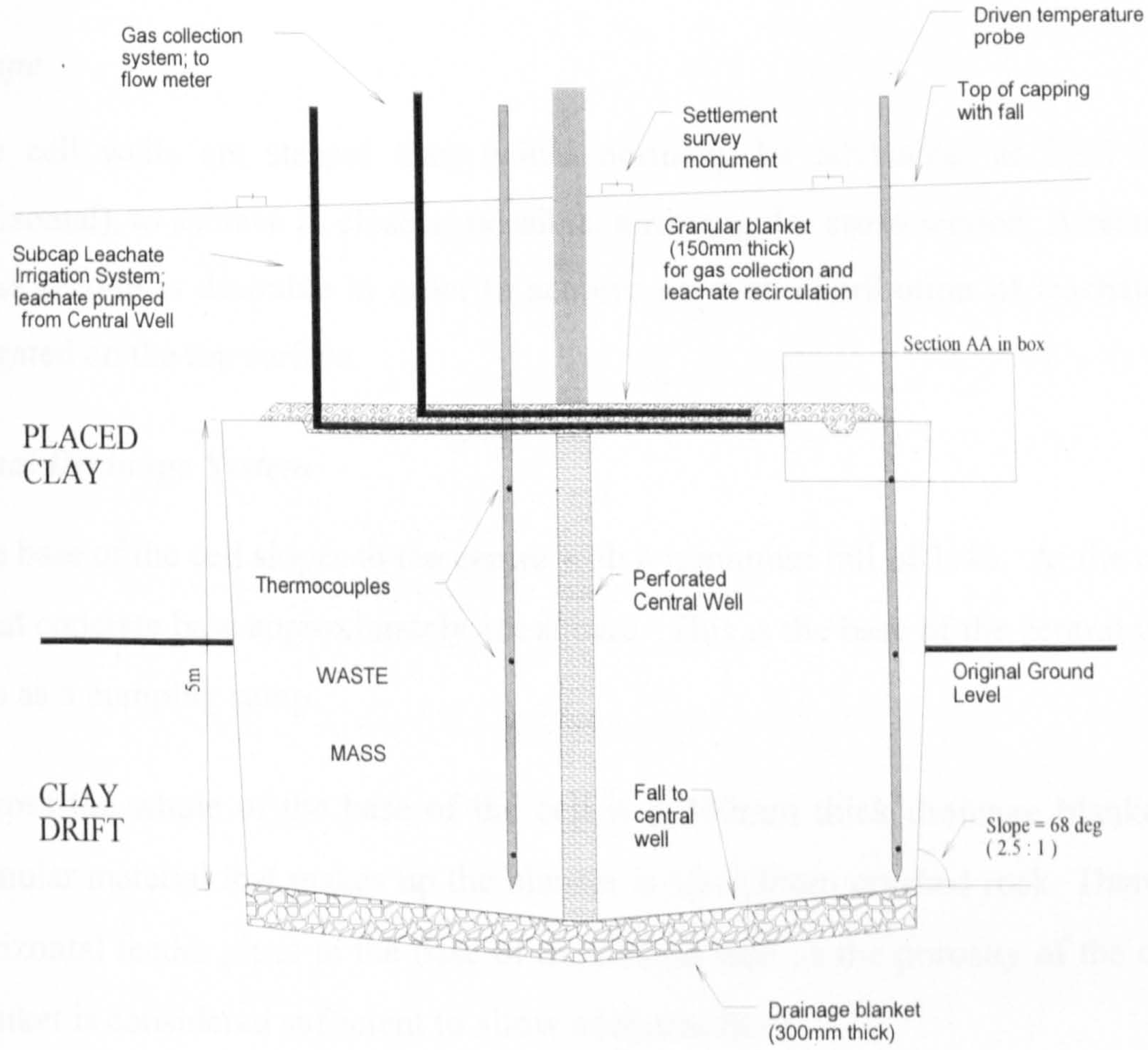
The cell plan dimension were decided on the basis of convenience of site layout, and were set at 28 x 30 m.

6.5.4 Design and Engineering Features

Careful design and engineering of the cells was considered to be important, so that an effective design was arrived at without excessive construction costs. Shallow landfill is particularly sensitive in this respect due to the higher plan area / volume ratio.

Figure 6-3 Schematic Diagram of Cell Design

Cross Section of Cell



Plan View of Top Blanket and Pipework

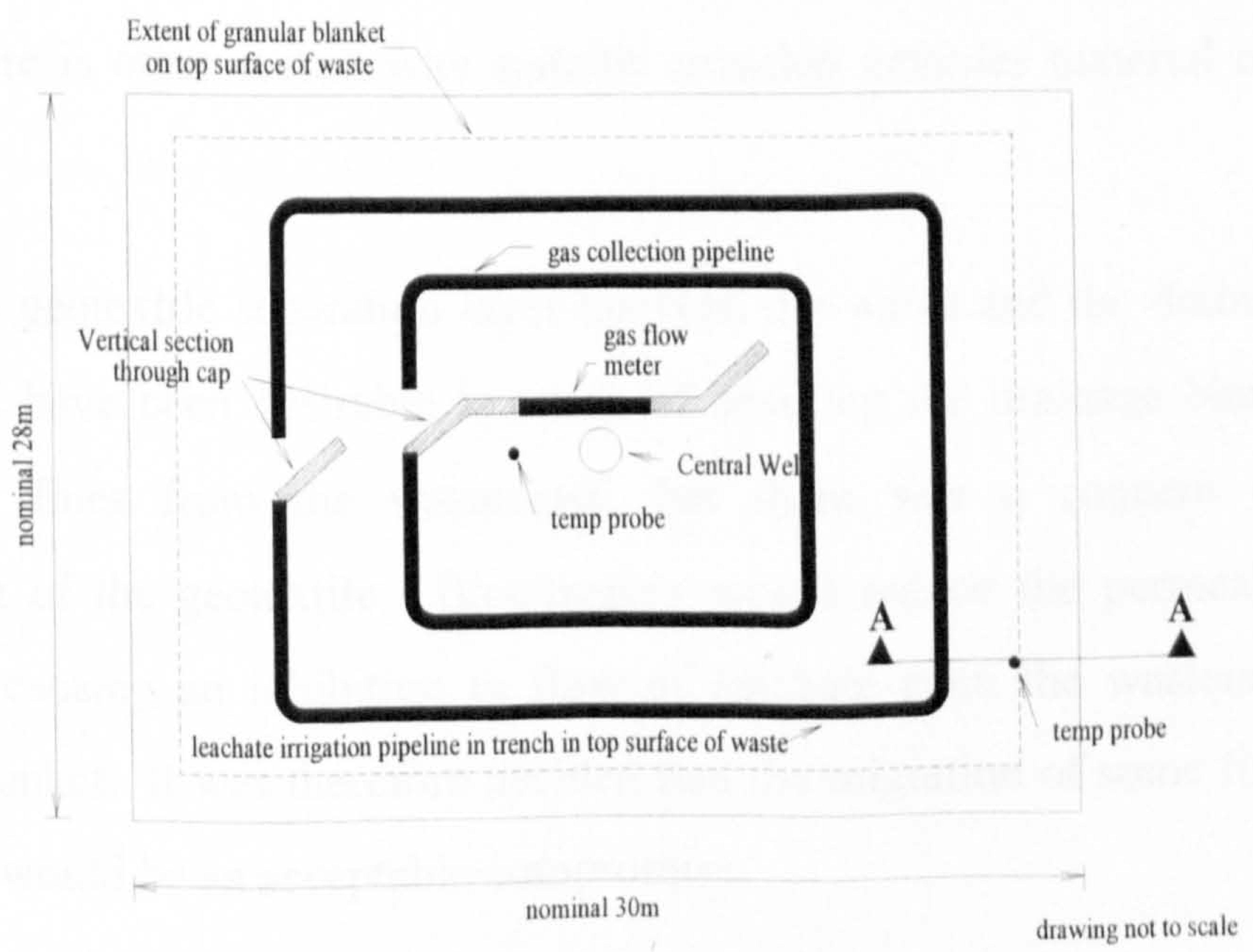


Figure 6-3 above shows the cell design. The aspect ratio of the cell cross-section has been distorted for clarity. With reference to the figure, the following design features are discussed:

Shape

The cell walls are steeper than would normally be advisable, at 2½:1 (68° to horizontal), to achieve as close as possible, a rectangular cross-section. A rectangular cross section is desirable in order to achieve an even distribution of leachate when irrigated on the top surface.

Basal Drainage System

The base of the cell slopes to the centre with a minimum fall of 1:40. At the centre is a flat concrete base approximately 1m square. This is the base of the central well and acts as a pumping sump.

Across the whole of the base of the cell is a 300mm thick drainage blanket. The granular material that makes up the blanket is 50-100mm crushed rock. There are no horizontal feeder pipes to the base of the central well as the porosity of the drainage blanket is considered sufficient to allow adequate flow.

Although new crushed rock was used in the experiment, for reasons of quality control, there is other reason why suitable recycled granular material could not be used.

There is no geotextile separation layer between the waste and the drainage blanket. This would have been desirable in terms of ensuring the drainage blanket did not accumulate fines from the wastemass, but there was a concern of potential bioclogging of the geotextile. Bioclogging would reduce the permeability of the geotextile, causing an inhibition to flow of leachate from the wastemass into the drainage blanket. It was therefore decided that the migration of some fines from the wastemass would be an acceptable compromise.

A geotextile separation layer, or a geogrid, beneath the drainage blanket would help to prevent some loss of the efficacy of the blanket. The loss may be expected due to the rock particles 'punching in' to the clay base, or due to fines migration when leachate was flowing along the base of the blanket. The potential for loss of efficacy was not considered great, and so on grounds of cost and benefit, a geotextile was not used.

Leachate Reservoir

The basal drainage blanket acts as a reservoir for leachate, from which it may be pumped for recirculation. The advantage of using a high capacity basal drainage blanket as a reservoir are:

- the rate of pumping is not limited by the hydraulic conductivity of the wastemass
- leachate is stored in anaerobic, landfill conditions
- leachate remains at the landfill temperature

The porosity of a drainage blanket was measured in a laboratory test which is described in the following chapter. The porosity was found to be 0.4. Thus theoretically the basal drainage blanket has a void volume of around 70 m^3. In practice and over time, bioclogging and accumulation of fines may reduce this by an estimated 50% to around 35 m^3. The latter figure is satisfactory in terms of volume available to pump for leachate recirculation.

Central Well

The central well is a vertical perforated twin wall pipe of diameter 200mm. It would be installed in the first lift of waste, and subsequent lifts would be placed around it. It has a number of functions. It provides access to the base of the cell to pump and sample leachate, it allows leachate in the wastemass to drain into it, and it allows gas at the base of the cell to move up into the top granular blanket.

Top Granular Blanket

The top surface of the wastemass had to fulfill two functions:

1. accept recirculated leachate
2. allow generated gas in the wastemass to migrate to the collection pipework

A 150mm thick blanket of granular material was considered to be the solution. The granular material was the same as that used in the basal drainage blanket. The top surface of the waste would be levelled, and the blanket laid across the whole surface, with the exception of a peripheral 2m strip. In this strip the capping would be placed directly on the waste. The purpose of the strip was to prevent the shortcircuiting of recirculated leachate down the cell wall.

The granular blanket was covered by a geotextile separation layer, which prevents fines from migrating from the clay capping into the blanket. The geotextile that was selected was Polyfelt TS 420. It is a polypropylene, non-woven and needle punched type. It was supplied by Polyfelt Geosythetics[1] at reduced cost because of the research status of the project.

The theoretical void volume of the top granular blanket is 30 m^3. The effective volume is likely to be around 20 m^3 once aggregate 'punch in' on the waste surface is taken into account.

Leachate Irrigation Pipeline

The idea for a sub-cap leachate irrigation pipeline was borrowed from the agricultural practice of sub-surface irrigation of some crops with permeable pipe, together with the experiences of the Landfill 2000 test cells[2].

---

[1] Polyfelt Geosynthetics (UK) Ltd., 460 Palatine Road, Manchester, M22 4DJ
[2] see Section 5.5.1

The leachate irrigation pipeline is ∅100mm perforated twin wall pipe, with a permeable area of 4200mm^2/m. The location of the pipe run is shown in Figure 6-3 above.

The pipe run is continuous, with no junctions. There are two reasons that this design has been adopted: access and distribution

> **Access** to the interior of the whole pipeline is much simplified if it is one continuos run. It was envisaged that in the future a CCTV[1] survey might be conducted, to assess bioclogging of the pipeline. The minimum diameter of pipeline[2] that it was possible to conduct such a survey, was 100mm. The bends in the pipeline are long radius and not ordinary elbows for the same reason. As well enabling CCTV access, this pipeline design meant that if cleaning was necessary, a jetting operation could be conducted.

> **Distribution of leachate** is uncertain in a herringbone irrigation system. It is unlikely that distribution will be homogenous. In a single continuous pipeline the leachate will be present along the whole length.

The pipeline is placed in a trench excavated in the top of the wastemass, which is 300mm wide and 300mm deep. The trench is backfilled with crushed rock as per the top blanket. The top blanket is laid over the top of the filled trench so that the granular material in the trench and the blanket are one continuous mass.

Pipework through the cap and above the cap is unperforated. The leachate is introduced into the pipeline from a wellhead above the capping and top soil. The leachate flows around the pipeline, filling the trench first. When full, the leachate will overflow into the top blanket and spread over the top surface of the wastemass. This is intended to provide a large surface area for infiltration, and an even distribution of leachate across the top of the wastemass.

---

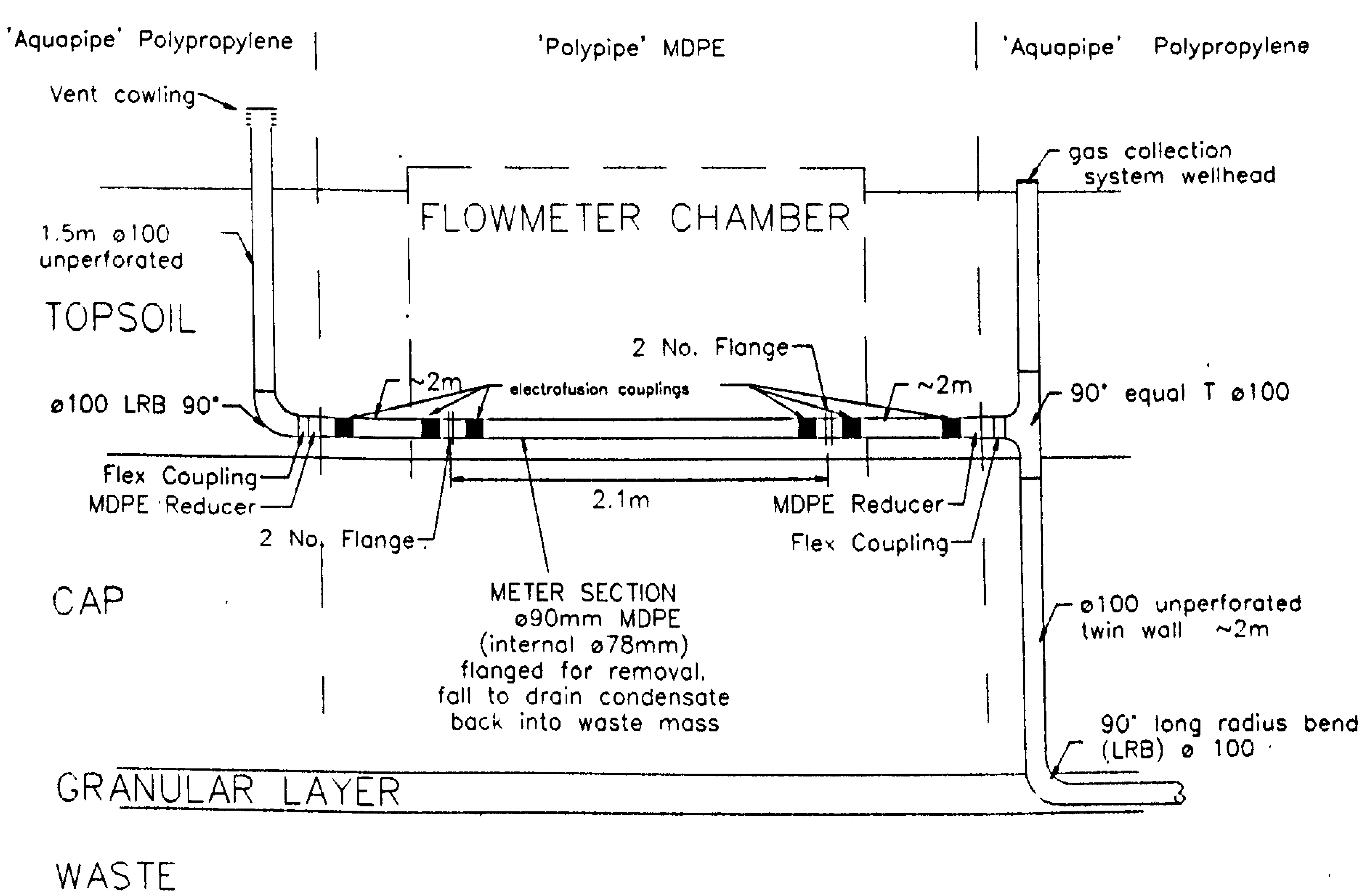
[1] Closed Circuit TeleVision
[2] Technology on the market in early 1995

Gas Collection Pipeline

The gas collection system consists of the top granular blanket, the central well and the gas collection pipeline. The pipeline is ∅100mm perforated twin wall as used for the leachate irrigation and is laid in the top granular blanket. For the same reasons of access as the leachate irrigation pipeline, it is one continuous run without junctions. The layout is shown in Figure 6-3 above. It is separated from the leachate irrigation pipeline both horizontally and vertically.

The gas collection pipeline passes up through the cap to a wellhead. Below the wellhead, just above the cap, a 90° T junction allows gas into the metering section and thence to the vent. The wellhead is provided because access through the flow metering section is not possible.

Figure 6-4 Gas Meter and Venting Pipework Detail



Drawn: EnviroCentre

Gas Metering and Venting Pipeline

Above the cap, the pipe line is partly unperforated twin wall polypropylene and partly ∅78mm (internal) medium density polyethylene (MDPE) as shown in the figure above.

The MDPE section of pipe is required for measuring flow. The bore of the pipe is smoother and more accurately engineered. The wall is thicker, which allows components of the flowmeter to be mounted through the pipe wall, for example, the injector. There is a requirement to have a straight run of pipe before and after the flowmeter, so that turbulence of flow is not artificially increased. The standard specification is a length equal to 25 diameters upstream and 10 diameters downstream. To reduce the adverse and unpredictable effects of wind on a passively vented system, a greater length of downstream straight run was provided.

After the straight metering section the pipeline turns to the vertical, to emerge from the topsoil with a vent to atmosphere. The vent terminates in a standard ∅100mm domestic gas heating cowl.

Pipework Selection

Twin wall polypropylene pipe was used for all sub-cap pipework installation. Twin wall pipe is suited to non-pressurised applications, such as ours. It has an excellent strength to mass ratio, therefore less material has to be used for the same duty. It is available in both perforated and unperforated form.

Polypropylene has good performance against degradation in the landfill environment. PVC was excluded because performance is not as good, and because degradation components of PVC in the wastemass would be measured as part of the experiment. In addition it has doubtful environmental credentials. An added bonus of using polypropylene was that the particular manufacturer, Aqua Pipes Ltd[1], uses recycled polymer to produce the pipes.

Leachate Recirculation Regime

The leachate recirculation regime is based on two considerations:

1. The quantity of leachate that it is desirable to recirculate

2. The quantity of leachate that it is possible of recirculate

Research work indicates that between five and seven 'bed volumes' of leachate need to be passed through the wastemass in order to flush out soluble pollutants, before a final stage quality can be reached (Knox,K 1996). This therefore is the desirable quantity to recirculate over a period of less than 30 years, to fulfil the aims of sustainable landfill.

The quantity possible to recirculate will be dependent on the hydraulic characteristics of the wastemass. Of prime importance will be infiltration and permeability.

Neither size of the bed volume nor empirical knowledge of the hydraulic properties of the wastemass were known prior to construction of the experiment. Originally a monthly recirculation was scheduled, but this was subsequently changed to a weekly event.

Recirculation was conducted on a batch basis rather than on a continuous or semi-continuous basis. Apart from the cost of automation, mains power was not available on the site, and it was not considered feasible to leave the genset on site unattended due to vandalism. Batch recirculation, did also have advantages in terms of distribution of leachate. Inevitably a batch system requires a higher flow into the leachate irrigation pipeline than a continuous or semi-continuous system which can trickle leachate in. If leachate is trickle fed into the irrigation pipeline it may

---

[1] Aqua Pipes Ltd., Darlingscott Road, Shipston-on-Stour, Warwickshire, CV36 4DZ

accumalate and infiltrate in just one area, but if it fed in fast, there is is a greater certainty of achieving leachate distribution over the whole of the waste surface.

Leachate Pumping

Prior to construction of the experimental site, the landfill operator had agreed to provide a 5 m^3 vacuum tanker in order to collect leachate from the central well and pump it in to the leachate irrigation system. However once the site was constructed and leachate recirculation by this method attempted, it became apparent that it would not be feasible. The suction head of 6-7m proved too great for the equipment.

Subsequently, a number of pumps were assessed. This is described in Section 8.4 titled Leachate Recirculation Trials. A Calpeda MXSM 404 electric submersible pump, which is capable of fitting down the ∅200mm central well, was finally selected. It is a multistage centrifugal type, with stainless steel impellers and body. Output with a static head of 6 - 7m is around 7 m^3/hr.

Leachate is pumped directly from the sump at the base of the central well, out of the wellhead and into the leachate irrigation pipeline. The leachate spends only a few seconds outside the cell, thus not losing heat. The discharge end of the pump delivery hose is pushed down to the level of the top granular blanket so that leachate is discharged into the anaerobic landfill environment.

Volume of Leachate Recirculated

Instruments to measure the flow of leachate were investigated. All were found to be either inaccurate or unreliable, some were both. The nature of leachate tends to make meters with moving parts (e.g. axial flow turbines) unreliable, while the variable composition can make non-intrusive meters (e.g. magnetic Doppler effect type) grossly inaccurate[1].

---

[1] anecdotal evidence from personal communications with Chris Parry, Landfill Processes Manager, UK Waste Ltd, Warrington, WA3 6EW.

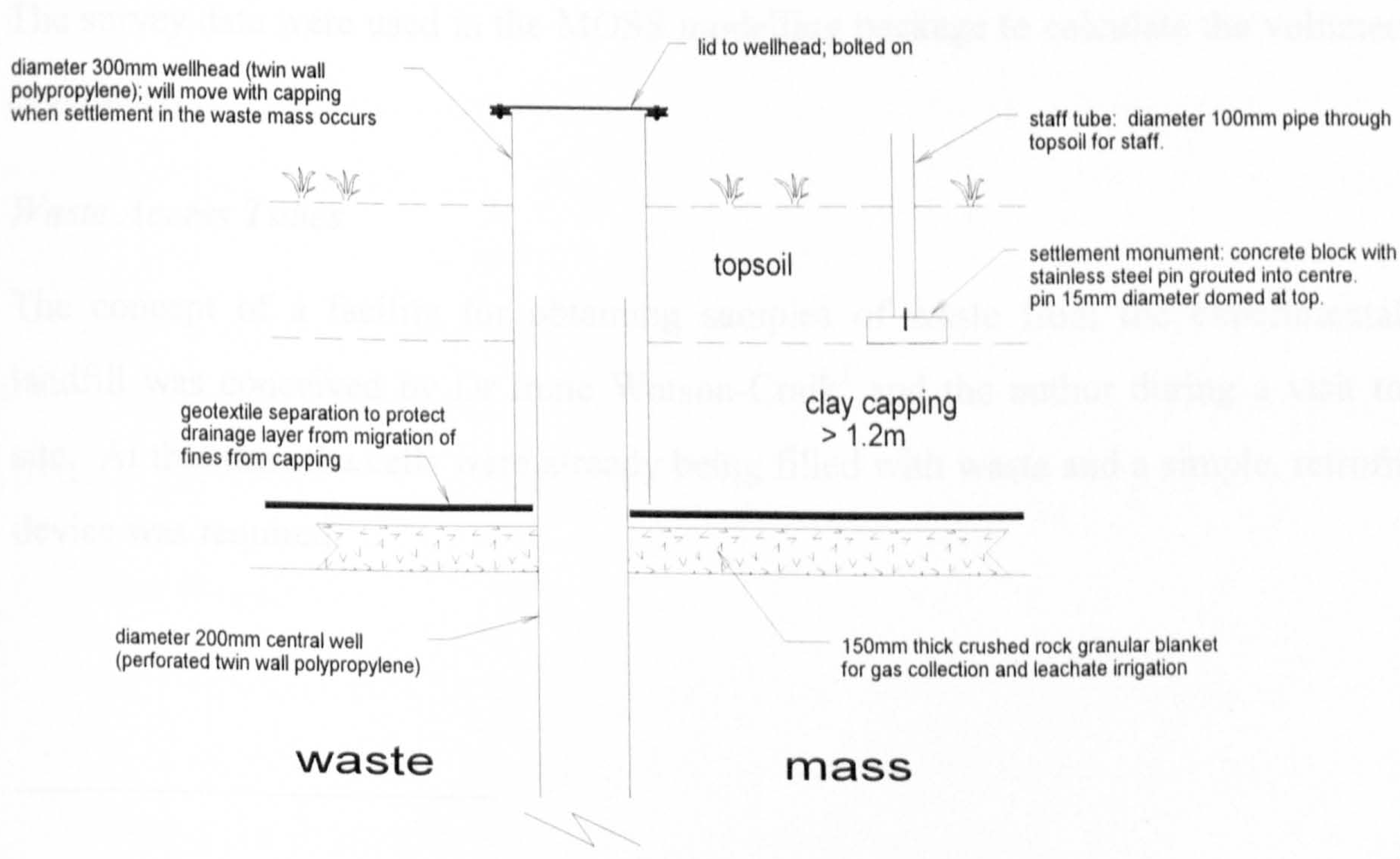
A 205 litre steel drum was calibrated in the departmental hydraulics laboratory. During the initial period of recirculation with the submersible pump, flow rate was established by the time required to fill this calibrated container. It was found that the flow rate varied insignificantly over the small head changes associated with central well drawdown experienced in the experimental cells - effectively the pump output was constant during the recirculation operations.

For the purposes of the experiment, the precise rates of flow are not important. The parameter that needs to be measured is volume recirculated. Given the above, it was therefore decided to calculate the volume recirculated from the duration of pumping alone. Regular checks on pump output are made to ensure efficiency has not altered.

Settlement

Settlement of the whole of the wastemass should not affect the capping, blanket and pipework systems as the whole unit moves together. The central well has a floating wellhead to accommodate movement. Settlement is monitored by six concrete monuments per cell, located on the capping surface. The floating wellhead and settlement monuments are shown in the diagram below.

Figure 6-5 Floating Wellhead and Settlement Monument Detail



The elevation of the settlement monuments is periodically recorded by level survey.

Temperature

To measure wastemass temperature, a driven temperature probe was developed with a removable string of thermocouples to allow maintenance or replacement. There are two probes in each cell; one at the centre and one at the periphery. On each thermocouple string there are three thermocouples, near the top, middle and bottom of the wastemass. The development of the temperature probe is described in detail below, in Section 6.5.6.

Measurement of Cell Volume

To determine the density of the whole wastemass in each cell, the volume of the cell needs to be measured. This was achieved by detailed surveys at two stages of construction of the experiment. The first stage was when the cell is excavated, with drainage blanket in place ready to receive waste. The second was when the cell had been filled with waste, had been trimmed level, and was ready to have the top granular blanket placed.

The survey data were used in the MOSS modelling package to calculate the volumes accurately.

Waste Access Tubes

The concept of a facility for obtaining samples of waste from the experimental landfill was conceived by Dr Irene Watson-Craik[1] and the author during a visit to site. At that time the cells were already being filled with waste and a simple, retrofit device was required.

---

[1] Department of Bioscience and Biotechnology, University of Strathclyde.

Three Ø150mm twin wall unperforated pipes were inserted into the wastemass of each cell. Each of the three pipes was a different length, and went down to a different level within the wastemass. Thus it was hoped to have a least one tube in the saturated zone and one in the unsaturated zone. The top end of the three tubes was housed in a floating wellhead, in a similar way to the central well.

Containment

Pending the site investigation, it was intended that the experimental landfill be constructed in the indigenous clay, following other landfill operations on the site. Previous laboratory tests on remoulded samples from adjacent areas indicate that permeability is less than 10^{-9} m/s.

Infiltration of effective precipitation is limited by having a fall on the capping and topsoil. A compromise of a moderate 1:50 slope has been selected. A larger slope would have been desirable for a well vegetated topsoil, but would cause excessive erosion on the bare cap.

Surface water from other areas is prevented from coming on to the experimental site by a cut off drain.

Layout of 'Cell Top Furniture'

The wellheads, gas flow meter chambers and settlement monument access shafts, etc. are collectively known as the 'Cell Top Furniture'. They have been laid out in three distinct lines so that agricultural machines can operate down the length of Cells 1 - 3. Agricultural operations that are envisaged are: 1. Revegetation of topsoil, including cultivations and sowing seed; 2. Maintenance of vegetation, including topping and fertiliser application.

Chamber Design

The chambers that house the gas flowmeters (gfm) and the automatic weather station (AWS) were designed to be generous in space and protect the equipment. The requirement for protection came from vandalism/theft threat, and they had to be strong enough to withstand being stood on by farm animals. They were fabricated from 1/8th gauge steel plate. The whole top of the chamber opens as a lid(s), using heavy integral hinges. Two padlocks secure the lid. Rust protection is provided by cold galvanising paint. Hot galvanising is superior, but the cost was prohibitive.

A step and propane bottle holder are provided in the gfm chambers. The weather station chamber has a floor, while the gfm chambers do not, as they had to lowered over the gas pipeline, for which arch shape cutouts are provided at each end.

The gas flow meters are mounted on a 2.1m flanged section of pipe. Therefore the chambers are 2.5m long. They sit on the surface of the cap over the gas pipeline. The chambers are 1.2m high and are surrounded by 0.8 - 1.0m of topsoil. They are also 1.2m wide to provide room to work inside the chamber. The chambers also serve as a protected area for the gas sampling ports and the inner temperature probe.

The AWS chamber is a cube of side 1.2m. It houses the AWS electronics enclosure and two lead acid batteries. It is a little larger than necessary but was designed and constructed before the final location of the AWS was decided. The edge of an field was an alternative location, which would have required it to be more prominent, and set into the ground.

6.5.5 Preliminary Water Balance

A water balance was calculated at the design stage (CEMS, 1995). It was carried out according to the method described in Waste Management Paper 26 (Great Britain. DoE, 1986). The liquid input was considered to be precipitation only, as there was no liquid waste input, and negligible expected surface or groundwater ingress. A worst case scenario of a cell being open for six months, May to October, was taken. Precipitation was not measured on the site, and therefore 'long term average' data from the Killearn Sewage Works (OS grid ref NS518844), some 12km away, was used. This showed the precipitation total for this period to be 632mm. Effective precipitation was calculated by subtracting the 'long term potential evapotranspiration' over the same period. The LTPE data was from Glasgow Airport.

The literature[1] suggests a typical absorptive capacity of waste to be between 0.12 - 1.3 m^3 water/ m^3 waste. As water is added during the waste pulverisation process, thereby satisfying some absorptive capacity, a conservative figure of 0.1 m^3water/ m^3waste was used.

The calculations showed that free leachate would not be generated. This is discussed further in Section 10.1, together with retrospective liquid balance calculations.

6.5.6 Development of Driven Temperature Probe

Measurement of the temperature of the wastemass was considered essential in order to assess thermal loss and to monitor the temperature at which degradation proceeds. The temperature distribution within the wastemass was also considered to be of interest.

Background

Embedding thermocouples in the wastemass appears to be the cheapest and easiest method of measuring temperature in three dimensions. However, reports from other test cell projects, including Brogborough (Croft and Fawcett, 1993) show that thermocouples can be unreliable in these conditions. This is probably due to the single filament wires being fragile.

For these reasons it was decided that the thermocouples would be installed in the wastemass *after* capping the landfill, and in addition that the thermocouples would be removable for repair or replacement.

Installation of a temperature probe after capping of the landfill cell would normally entail drilling. This was not desirable on grounds of cost and disturbance of the

---

[1] see Section 5.3.4 and 5.3.5

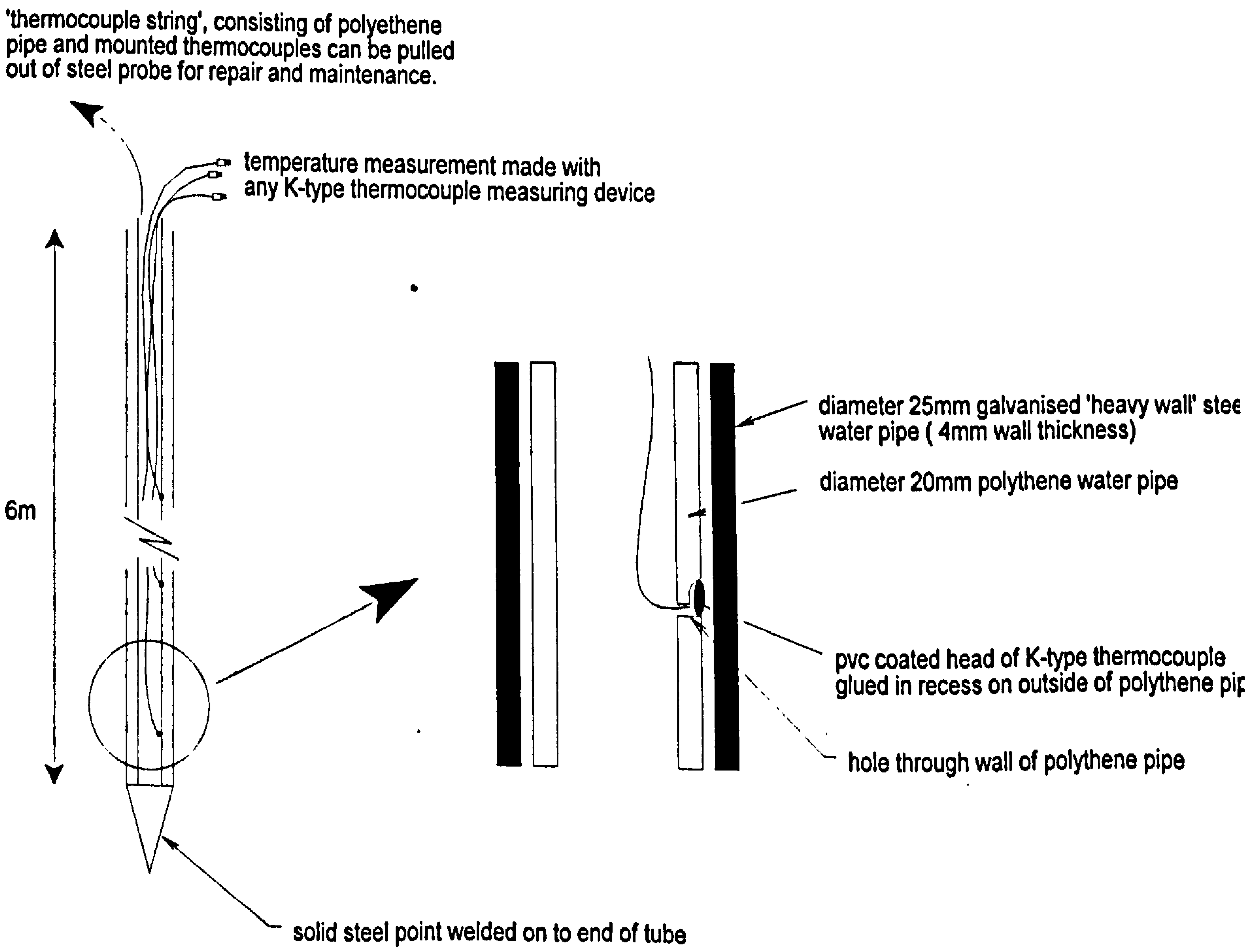
wastemass. An additional consideration was the problem of how to backfill the borehole created, so as to mimic the degrading wastemass whose temperature was being measured. A further problem was the potential to create a preferential flow path for leachate.. Therefore access to the wastemass by drilling was not considered an appropriate method.

The solution was a hollow steel probe driven through the cap and down into the wastemass.. Once the hollow probe was installed, a 'string' of thermocouples could be lowered down into it.

Development of Steel Probe

Prior to the construction of the test cells, a prototype probe was designed and fabricated in department workshops. It was then tested on an existing landfill cell.

Figure 6-6 Driven Temperature Probe



The steel tube was driven through the cap and down through several metres of waste by a hydraulic breaker, with an adapted coupling. The breaker was operated from an access platform. The prototype was successful, but showed that standard wall water pipe was not really adequate, and therefore 'heavy wall' tube (wall thickness 4mm) was used subsequently.

A single 6m length of tube was difficult to install, and therefore two 3m sections were used. Once the first section had been driven, the second section was fitted to it with a threaded connector. When this was assembled the connector was also welded.

Development of Thermocouple String

The prototype thermocouple string worked well, being sufficiently robust and easy to install and remove. There were concerns over thermal conduction along the steel tube, which may have led to an inaccurate representation of the temperature at a spot in the wastemass. Data from the prototype, which had six thermocouples in the string, showed that 'blurring' of measurements due to conduction along the probe did not appear to be a problem. Discrete temperatures were recorded over relatively small distances. An example of this is shown in the adjacent box. The data were collected in March, with snow on the ground.

depth (m)	temperature (°C)
1.0	-4.2
1.5	15.4
2.5	31.6
3.5	32.4
4.3	28.3
5.3	22.3

Three thermocouples were used on the strings that were installed in the test cells. This was considered sufficient to measure the temperature at the top, middle and bottom of the wastemass.

Location of Probes

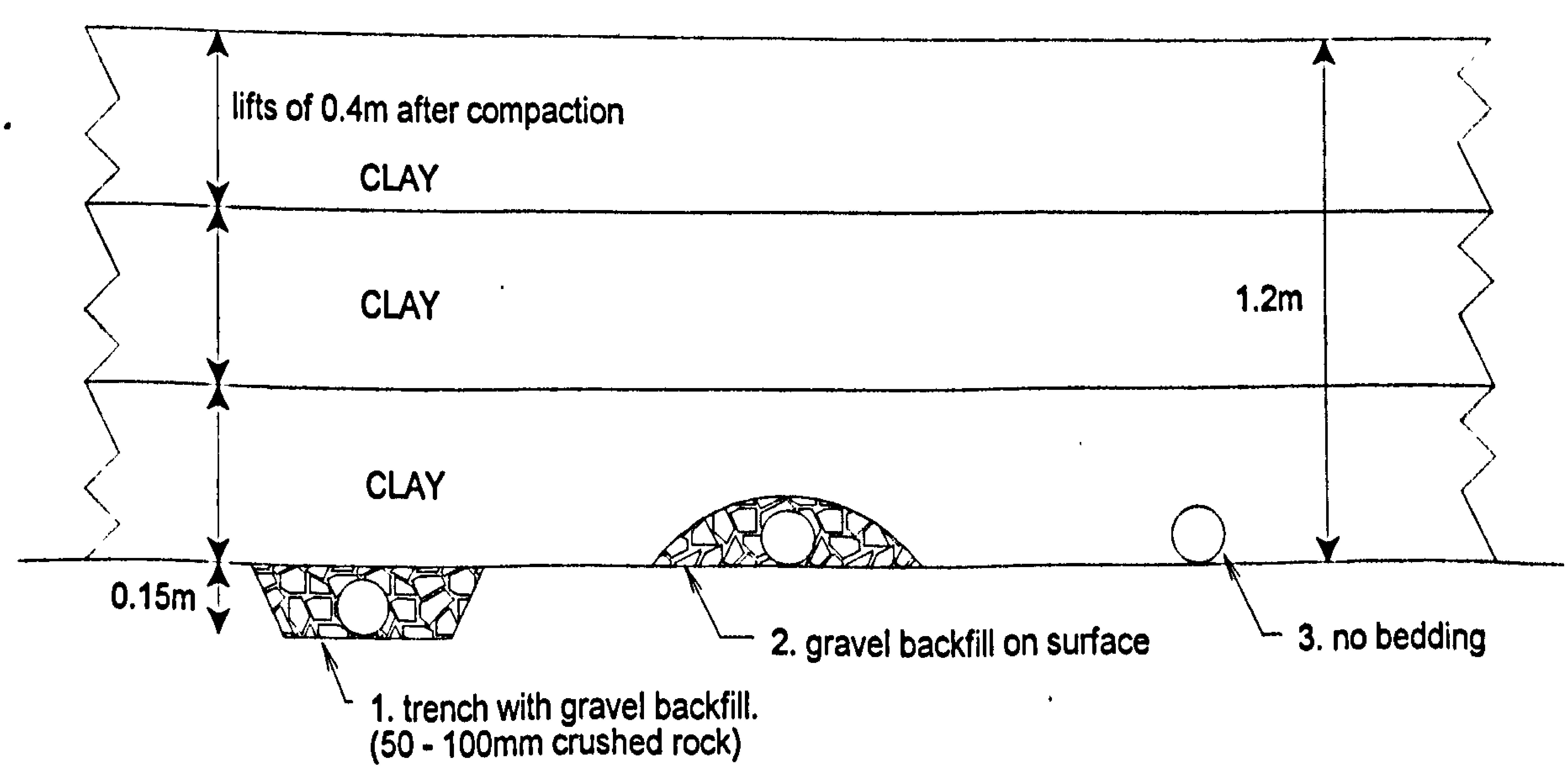
Spatial temperature variation in the vertical plane was measured by having three thermocouples on a string. Spatial temperature variation in the horizontal plane was established by having one probe near the centre of each and one near the cell wall.

6.5.7 Trial to Assess Structural Suitability of Twin Wall Polypropylene for Sub-cap Pipework

Design manuals for un-pressurised pipework in the ground, tend to be orientated towards installation of the pipe in a trench, surrounded by a gravel packing. When the sub-cap leachate irrigation and gas collection pipelines were being designed, there was some concern over their strength in our particular situation.

Twin wall polypropylene pipe had been selected as most appropriate on a number of criteria as detailed elsewhere. To assess the suitability of this pipe, a trial embankment was constructed, to emulate conditions beneath the landfill cap. Three different situations were appraised, as shown in the figure below. Situation number 3, in which there was no bedding, was not considered a potential construction technique, but was included as an extreme test of the pipe strength. This would enable us to judge what safety margin was available with the other situations.

Figure 6-7 Cross-section of Trial Embankment



Notes:
Pipes were 100mm diameter twin wall polypropylene in 6m lengths.
Embankment of compacted clay was 4m wide and around 8m long.

The construction of the clay embankment was carried out in the same way that it was envisaged for the capping of the landfill. Each of the three lifts of clay were compacted by at least two passes of tracking, by the excavator. Finally the whole embankment had a further two passes with a steel wheel compactor.

Deformation of the pipes was assessed visually, severe crushing being considered as a failure. On inspection of the pipes it was found that none of them had failed. Although the pipe in situation 3 had deformed significantly, to be elliptical in section, it was not close to failure.

From this trial, it was concluded that there would be a large safety margin for strength if we used these pipes within gravel bedding beneath the cap.

6.5.8 Measurement of Voids Ratio of Granular Blankets

The blankets of granular material that constitute the basal drainage system, and the gas collection and leachate irrigation systems were a crushed basaltic rock. The material all came from one source, a quarry working a volcanic vent feature on the north bank of the Clyde at Bowling. The nominal grading of the material was 50-100mm.

A bulk sample of the material that made up the granular blankets was taken on 1st November 1995. The voids ratio of the aggregate was determined in the departmental structures laboratory.

Method

A cylindrical steel mould of average diameter 254.6mm and average height 280mm was used. The mould was weighed. The mould was filled with water and re-weighed. The empty mould was filled with the sample material. It was compacted in 3 layers with a tamping rod, and the full mould was put on a vibrating table for 1 minute. The mould, full of rock was weighed. Water was added to the mould filling the interstices, until the water reached the top of the mould. The mould plus rock plus water were weighed.

Results

Porosity (α): volume of voids/total volume = 0.40

Voids Ratio (e): volume of voids/volume of solids = 0.66

Bulk Density = 1.53 Mg/m^3

6.6 Measurement of Meteorological Parameters

The literature and experience shows that meteorological parameters have an effect on landfill, especially passively vented landfill.

Meteorological data are required as part of the research project to conduct:

- water balances
- thermal balances
- correlate landfill parameters, such as gas output, with met. parameters, such as temperature, barometric pressure or wind speed

The location and exposure of the site meant that no suitable local or site similar source for the data existed. Therefore a weather station on site was required.

Meteorological Office Involvement

The Meteorological Office in Edinburgh were contacted for advice on siting and selecting an automatic weather station. Mike Porter, Superintendent Edinburgh, visited the site on 20th April 1995. In his written report, he advised on the suitability of a number of proposed locations, together with information about specification and maintenance. He suggested that in addition to an automatic weather station, a manual raingauge should be installed, as a check for the automatic device.

We were also advised of an informal co-operative arrangement that we could enter into with the Met. Office. Data from the weather station could be passed to the Met. Office to become part of their National Climatological Archive. For this to happen the data would have to be in their specific format. Given the data, a series of quality control procedures would be applied, that would look not only for errors (for example, out of range readings), but also measurement drift. We would receive the dataset back after it had been quality checked. It was agreed to enter this arrangement with the Met. Office.

Measurement Standards

In general the Met. Office standards have been adhered to for measurement of the various parameters. Wind speed and direction are measured at 10m. Temperature, relative humidity and net radiation would normally be measured at 1.2m. Historical experience of vandalism on the site showed that these sensors would need to be mounted well out of reach. They were therefore mounted at 4.0m above ground level, and as such, the measurement of these parameters in non standard. This does have negative implications for comparison of data with other sites, and means that these parameters will not be included in the National Climatological Archive.

Power Supply

No mains power existed on site. Lead acid batteries would be used to power the system. They would be replaced with charged units periodically.

Datalogger Specification

In 1995 there was no established standard for measuring and processing data with an automatic weather station. That is to say, there was no standard methodology for arriving at an hourly mean for a parameter like temperature, when the sensor may take a measurement once a minute or once every 5 seconds. The Met. Office were in the process of producing a standardised methodology, and were likely to issue this as a software package. The datalogger on which the Met. Office had developed and would be running their software was the Campbell Scientific CR10. It was therefore felt important to specify this as a datalogger, so that in future the system could be upgraded.

System Selection

There are several packaged unit automatic weather stations (AWS) on the market. They vary considerably in quality and price. A thorough investigation of the market was conducted and a unit from Didcot Instruments was selected. Didcot is a well respected company that has made AWS for the Institute of Hydrology for some years. They were also able to accommodate our requirement of having a Campbell CR10 datalogger, at the heart of the system.

A Munro heated, tipping bucket automatic raingauge was available from the Department of Civil Engineering. This was loaned to the project.

Lightning Protection

Lightning protection is essential in this exposed upland location. The structure of the mast was protected by a 1m air terminal at the top of the mast, which is connected to a substantial earthing spike a few metres away from the base of the mast.

The wires from the sensors at the top of the mast, viz. for wind speed and direction, have special inline circuit breakers. These circuit breakers are located at the base of the mast in the electronics enclosure, in order to protect against induced currents from the mast earthing system. Both systems were supplied by Furse.

Data Output

Data collection and processing is described in detail in Chapter 8. For data to be accepted by the Met. Office, in the arrangement that is described at the beginning of this section, data need to be presented to them in a specific software format. This is known as CAWS format (Met. Office, 1990). It specifies header fields and field codes for particular parameters in the dataset.

Manual Raingauge

A Met. Office Mark 11, 5 inch raingauge was selected as a manual raingauge. A 10mm tapered-base glass measuring cylinder was used to measure collected precipitation to 0.1mm and a 50mm flat base cylinder to measure to 1mm.

A hasp and staple were brazed on the raingauge in the departmental hydraulics workshop. The funnel was padlocked on to the base, so that interference was prevented.

6.7 Waste Stream

Apart from the addition of inert material in Cell 1, this experiment is concerned exclusively with Municipal Solid Waste (MSW).

6.7.1 Waste Sources

MSW from three sources was used in the experimental cells, as shown in the table below:

Table 6.2 Sources of Waste

Source:	Per Capita arisings kg/year	Type:	Used in Cells:
Dumbarton District Council	538	untreated	2 & 4
Inverclyde District Council	460	untreated	2 & 4
Cunninghame District Council	699	pulverised	1 & 3

Notes: Per capita arisings calculated from figures provided by council sources cited in following section. Does not include trade and industrial waste from private sources, but does include MSW receipts other than domestic.

6.7.2 Profile of Sources

The organisations that provided the waste had varying knowledge of the situation in their areas.

Dumbarton District Council

Dumbarton is located on the north bank of the Clyde, 25km west of Glasgow. Dumbarton District Council (DDC) covers an area stretching north up the Vale of Leven, and to the west to Loch Long. A variety of socio-economic groups are located in the area, parts of which suffer from high rates of unemployment.

DDC consigned[1] 43,000 tonnes of MSW in the year April'95 to March'96. They estimate from government statistics, and their own statistics on car and van consignments to their waste transfer station (years 1992 and 1993), that 56% of waste stream is from domestic sources. The population is approximately 80,000 and they consider the holiday boost in population not be significant.

The waste that was consigned to the experimental site was delivered directly from waste collection vehicles, and is therefore not typical of the whole MSW stream for Dumbarton District. Vehicles that had been on a variety of collection runs delivered waste to the experimental site. Examples of runs: Dumbarton, Helensburgh shops, housing estates in the Vale of Leven, 'country runs'. The collection runs were recorded for the majority of consignments.

Inverclyde District Council

Inverclyde District Council (IDC) covers an area centred around Greenock on the south side of the Clyde estuary, around 25 km west of Glasgow. The area has a population of 89,000. Socio-economically statistics[2] show that the area is mixed, but the majority of households are not wealthy. 53% of households have no car, and 81% of houses are in the council tax band less than £45,000. Heavy industry used to dominate, in the form of shipbuilding and docks. These industries have declined dramatically, although they have not disappeared. Services industries are replacing the traditional employers; now 78% of jobs are in the service sector.

---

[1] Information from telephone interview with Graham Pollock, Dumbarton D.C. on 13/5/96
[2] Statistics supplied by John Robinson, Inverclyde D.C.

All domestic waste collections, council department waste and civic amenity waste is brought to the transfer station at Port Glasgow, near Greenock. At the transfer station, the waste is mixed by a loading shovel, to increase its density for transit. The material is transferred to high capacity vehicles for consignment to landfill.

The mixing has a tendency to open bin bags and to a minor extent homogenises the waste. A number of the collection vehicles are the 'Vario-Press' type, which has a rotating drum compaction system. It is evident when comparing the waste discharged from these, with the waste discharged from conventional 'linear compaction' vehicles, that the rotary machine breaks open the bin bags and mixes the waste.

This bag opening and minor homogenisation of waste (frame8)[1], by various methods, has implications for landfill degradation, and could be considered a partial pretreatment, in the author's opinion.

Table 6.3 Sources of Waste at Inverclyde Transfer Station by Sector, 1995-96

Sector	Mass (tonnes)	%
Domestic	24,425	58.7
Trade/Commercial	5,839	14.0
Container Hires	1,740	4.2
Civic Amenity/Flying Squads	7,571	18.2
Other Council Departments	1,554	3.7
Private Sector	501	1.2
Total	41,630	

The whole fraction of the MSW stream was consigned to the experimental cells, including the odd washing machine and sofa.

[1] see software appendix for photographs

Cunninghame District Council

Cunninghame District is on the Ayrshire coast, around 45 km south-west of Glasgow. The main town is Irvine, a substantial part of which is 'new town' comprising housing, commerce and light industry, some of which in relatively affluent. The District[1] has a population of 138,000, but coastal areas experience a holiday boost in population of around a third - perhaps a further 20,000 people. The higher per capita arisings for Cunninghame District Council (CDC), as shown in Table 6.2 above, are perhaps a manifestation of the affluence of the area and the holiday boost.

Recorded waste arisings are shown in Table 6.4 below. CDC have their own landfill sites, which receive private commercial and industrial waste, which would not normally be recorded as MSW. Therefore, the Private waste stream has been excluded from the calculations in the table.

Table 6.4 Sources of Waste Disposed of by Cunninghame D.C., 1995-96

Sector	Mass (tonnes)	% *
Domestic to Pulveriser	45,000	43.5
Domestic direct to landfill	9,500	9.2
Commercial	8,000	7.7
Parks & Gardens Dept	5,400	5.2
Other Council Dept's	6,600	6.4
Civic Amenity (bring)	29,000	28.0
Private Trade/Industrial	28,000	
Total	103,500*	

* Private Trade/Industrial omitted from calculation.

Only the waste processed at the Council's pulverisation at Shewalton, was consigned to the experimental cells. This was predominantly household waste, but also included commercial waste collected by the Council's refuse collection vehicles. Elements of the waste stream which were present in the Inverclyde waste stream, but

---

[1] Information from telephone interview with John Curry, Cunninghame D.C. on 2/5/96

were omitted from that received from Cunninghame, were; Parks and Gardens, Other Council Departments (e.g. Building Maintenance) and Civic Amenity (bring).

6.7.3 Waste Characterisation

A characterisation of the waste streams was conducted in order that a comparison between the streams could be made. This was carried out as part of the experimental design to show that there were no significant differences in the waste stream, which could become a 'confounding factor' in the analysis of experimental data. Therefore the characterisation of the pulverised waste stream was conducted prior to pulverisation.

Characterisation of the three waste streams was conduct between 19th September and 3rd October 1995, during the period that the experimental cells were being filled. Some of the results of these characterisations have been reported previously (McSherry,V 1996).

Equipment

A cubic wooden box of side 1m, with a hinged, drop down front. Kindly lent by Inverclyde District Council.

500 kg platform scales and 20kg balance from departmental laboratories.

Protective clothing

Method

The $1m^3$ empty box was weighed on the platform scales. It was then filled with sample by a loading shovel. The sample was not compacted more than by hand with a spade. Excess material was struck off, so that the top surface of the cube was level. The box was re-weighed (frame9).

Material in the box was then separated by hand (frame10) into the 11 main categories used in the National Household Waste Analysis programme (Warren Spring Laboratory and Aspinwall & Co, 1993). The mass of material in each category was then recorded, together with notes about the contents.

This process was repeated, so that each source had categorisations carried out on two samples. It was possible to categorise two samples in one day.

Dumbarton Source

Waste characterisation for the Dumbarton D.C. source was carried out at Mid Auchencarroch in an empty barn, kindly provided by George Munn. The samples was taken at the experimental cells, because the collection vehicle delivered the material directly. A consignment was mixed by the bucket of the compactor, and then the 1m^3 box was filled. A tractor and trailer transported the full box to the barn, where it was lifted onto the platform scales by a forklift. The characterisation is given in the table below:

Table 6.5 Characterisation of Waste Stream from Dumbarton

Category	1st Box Mass (kg)	%	2nd Box Mass (kg)	%	Average %
Paper/Card	73.1	35.1	62.9	31.0	**33.0**
Plastic Film	14.4	6.9	13.0	6.4	**6.7**
Dense Plastic	15.3	7.3	11.6	5.7	**6.5**
Textiles	5.0	2.4	9.5	4.7	**3.5**
Misc. Combustibles	10.0	4.8	8.5	4.2	**4.5**
Misc. Non-Combus.	0.6	0.3	0.5	0.2	**0.3**
Glass	10.8	5.2	13.4	6.6	**5.9**
Putrescibles	61.3	29.4	68.2	33.6	**31.5**
Ferrous Metal	12.8	6.1	10.5	5.2	**5.7**
Non-Ferrous Metal	1.8	0.8	2.8	1.4	**1.1**
Fines (<10mm)	3.4	1.6	2.0	1.0	**1.3**
Total Mass	208.5		202.9		
Sample Density (t/m^3)	0.21		0.20		

Box 1 sample came from a house collection run at Dumbarton, and Box 2 from Helensburgh which can be considered a more affluent area. Observations:

Paper/Card: newspapers and food cartons

Plastic Film:	carrier bags and food packaging
Dense Plastic:	food, milk and household cleaning fluid containers
Textiles:	Box 1 contained a bag of clean sound clothes
Misc. Combustibles:	nappies
Glass:	spirits bottles, several whisky in Box 2
Putrescibles:	Box 1 mainly kitchen waste, Box 2 some garden waste as well
Ferrous Metal:	beer cans, food cans, aerosols; Box 1 vacuum cleaner motor
Non-Ferrous Metal:	mainly soft drink cans

Categorisation of the two samples broadly agrees. The Helensburgh sample contains more putrescible material and more glass, including whisky bottles - possibly a indication of the higher socio-economic status of the residents. The Dumbarton sample contains more nappies, more plastic bottles and more newspaper.

Inverclyde Source

Characterisation was carried out at the waste transfer station at Port Glasgow. The sample box was filled by the loading shovel that mixed the waste, and therefore the sample was not attributable to one collection run.

Table 6.6 Characterisation of Waste Stream from Inverclyde

	1st Box		2nd Box		Average
Category	Mass (kg)	%	Mass (kg)	%	%
Paper/Card	39.7	25.0	43.5	24.8	**24.9**
Plastic Film	8.9	5.6	8.5	4.8	**5.2**
Dense Plastic	7.6	4.8	7.9	4.5	**4.6**
Textiles	6.2	3.9	6.2	3.5	**3.7**
Misc. Combustibles	5.0	3.2	5.5	3.1	**3.1**
Misc. Non-Combus.	1.0	0.6	1.0	0.6	**0.6**
Glass	6.4	4.0	7.6	4.3	**4.2**
Putrescibles	70.5	44.4	66.7	38.0	**41.2**
Ferrous Metal	7.0	4.4	13.2	7.5	**6.0**
Non-Ferrous Metal	1.1	0.7	1.5	0.9	**0.8**
Fines (<10mm)	5.5	3.5	13.8	7.8	**5.7**
Total Mass	158.7		175.2		
Sample Density (t/m^3)	0.16		0.18		

Observations during characterisation:

Paper/Card:	cardboard packaging and newspaper
Dense Plastic:	soft drinks bottles
Misc. Combustibles:	nappies
Glass:	very few spirits bottles, mainly food jars
Putrescibles:	kitchen waste, quite a lot of green garden waste
Ferrous Metal:	beer cans
Fines (<10mm):	mainly ashes, probably domestic fires

Both samples were taken from waste that had been mixed. They broadly agree, although Box 2 had a significantly more ferrous metal and fines. Inverclyde includes areas where coal fires are still used for heating, hence the ash constituent of the fines category.

Cunninghame Source

The characterisation was conducted at the Shewalton pulverisation plant. The material was sampled by loading shovel in the waste reception hall, **prior to being pulverised.** The loading shovel mixed a number of consignments, before filling the sample box.

Table 6.7 Characterisation of Waste Stream from Cunninghame

	1st Box		2nd Box		Average
Category	Mass (kg)	%	Mass (kg)	%	%
Paper/Card	65.8	33.4	50.4	31.9	**32.7**
Plastic Film	14.6	7.4	11.3	7.1	**7.3**
Dense Plastic	21.4	10.9	9.1	5.8	**8.4**
Textiles	6.8	3.4	6.2	3.9	**3.7**
Misc. Combustibles	8.8	4.4	4.0	2.5	**3.5**
Misc. Non-Combus.	1.6	0.8	4.2	2.7	**1.8**
Glass	15.0	7.6	8.2	5.2	**6.4**
Putrescibles	44.3	22.5	42.4	26.8	**24.7**
Ferrous Metal	13.2	6.7	14.9	9.4	**8.1**
Non-Ferrous Metal	2.5	1.3	2.9	1.8	**1.6**
Fines (<10mm)	3.2	1.6	4.5	2.8	**2.2**
Total Mass	197.1		158.2		
Sample Density (t/m^3)	0.20		0.16		

Observations:

Paper/Card:	newspaper, food packaging, cardboard,
Plastic Film:	bags and food wrapping
Dense Plastic:	mainly soft drinks bottles, milk bottles, food packaging, Box 1 contained a telephone, a clock radio. Box 2 contained a bag of polystyrene - from a shop?
Textiles:	clothes
Misc. Combustibles:	nappies
Misc. Non-Combus.:	some clinker
Glass:	many spirits bottles, especially vodka in Box 1. beer bottles in Box 2. some food jars
Putrescibles:	mainly kitchen waste, little garden waste.
Ferrous Metal:	beer and food cans. pet food cans
Non-Ferrous Metal:	beer and soft drink cans
Fines (<10mm):	Box 2 contained two bags of ashes

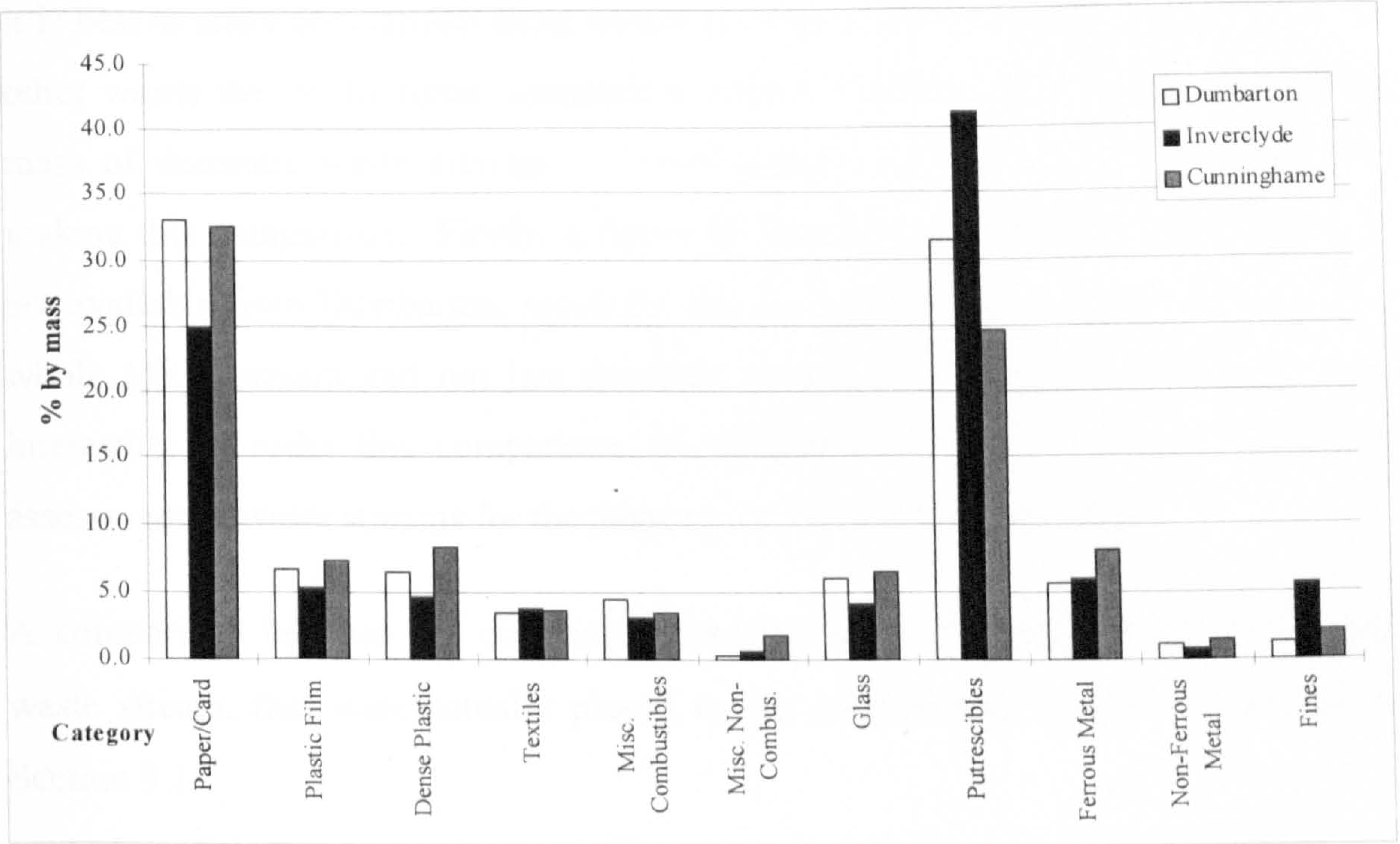
The density of the two samples was significantly different. This appears to be mainly attributable to Box 1 having larger masses of paper/card, dense plastic, textiles, nappies and glass. The reason for the difference in density is not known, nor is it evident what occupied the space without contributing to the mass. The bag of polystyrene is probably partly the cause.

Comparison of Sources

Sample densities varied quite considerably, although the waste stream cannot be exclusively attributed as the cause. The range experienced may also be due to experimental procedure.

The graph below shows the comparison of the waste streams on a '% by mass' basis. This is the most effective method of comparison as far as input to the experimental cells is concerned.

Figure 6-8 Comparison of Waste Stream Characterisations



The most notable difference is between the Inverclyde source and the other two. Inverclyde appears to contain much less paper/card fraction, and much more putrescible material and fines. An explanation for the larger putrescible fraction is the inclusion of the Inverclyde's Parks and Gardens Department waste, whereas this is excluded from the other two waste streams. An explanation for the larger fines fraction is coal fire heating in Inverclyde, whereas the other two areas have more modern or affluent housing that has electric or central heating.

The lack of glass beverage bottles in the Inverclyde waste samples was particularly noticeable. This may be due to good access to bottle banks, or could be an indicator of the different socio-economic group in the Inverclyde catchment.

The comparison shows that the Cunninghame source has a low putrescible fraction, while having more plastic bottle and more steel can - pet food cans were especially noticeable.

Comparison of the three waste streams is useful for assessing the waste stream input to the experiment, but can distort the picture if one is trying to gain some insight into the socio-economic connections that there may be with the waste stream. In this case it is best to make comparison using annual per capita waste arisings, by category - in other words the '% by mass' comparison above, weighted for the total per capita mass of domestic waste arisings . Unfortunately, there are two impediments to making this comparison. Firstly, a figure for the annual *domestic* waste arisings is not available from Dumbarton, secondly, the characterisation for Inverclyde was the whole MSW stream and not just domestic waste. Although it would have been interesting to make this comparison, its omission does not adversely affect the assessment of waste streams for the purposes of the experimental cells.

A comparison between the combined untreated waste streams and the pulverised waste stream, that were actually placed in the experimental cells, is presented in Section 9.1.

6.7.4 Waste Pretreatment

Waste from the Cunninghame source was pretreated by 'Dano Drum'[1] wet pulverisation prior to transportation to the experimental cells. The plant is located at Shewalton in the Cunninghame District, beside the Council's main landfill site.

The generic Dano Drum process is described in Section 5.1.2. Plant specific details are added here.

Shewalton Pulverisation Process

Only domestic waste arrives at the plant. The material is loaded into a conveyor hopper that feeds the Dano Drum. As the material enters the drum, approximately 225 litres of mains water are added per tonne of waste. The Dano Drum operates as a continuous process, the residence time in the drum is 4 hours.

Although the name pulveriser suggests an aggressive reduction in particle size, the Dano Drum has a tumbling action, similar to a clothes washing machine, although it

[1] Head Office: Dano A.G., PO Box 4, Logans Rd., Motherwell ML1 3NP, Scotland

does not contra-rotate. Therefore impact resistant elements of the waste and those that have wet strength, are not greatly affected by the process.

Normally a perforated screen at the outlet from the drum, separates the pulverised waste into a coarse and fine fraction. During the pulverisation of waste for the experimental cells, these screens were blanked off, and the whole mixed fraction was taken. Ferrous metal is removed by drum magnet over the discharge conveyor. The removal efficiency is estimated by the plant manager to be only 60%.

Product

The material that is produced by the pulveriser is substantially different than the waste input, although some elements, such as plastic beverage bottles are unaffected (frame11). Glass bottles and jars are reduced to small fragments, and there is very little food waste that is recognisable. Loose newspaper and paper wrappings are fragmented, but cardboard and larger masses of paper remain whole as a wet lump.

The principal effects are:

- particle size reduction
- increase in moisture content
- homogenisation of materials

A particle size distribution of the product was not conducted, but operational experience indicates that 40% of the product passes a Ø50mm round orifice.

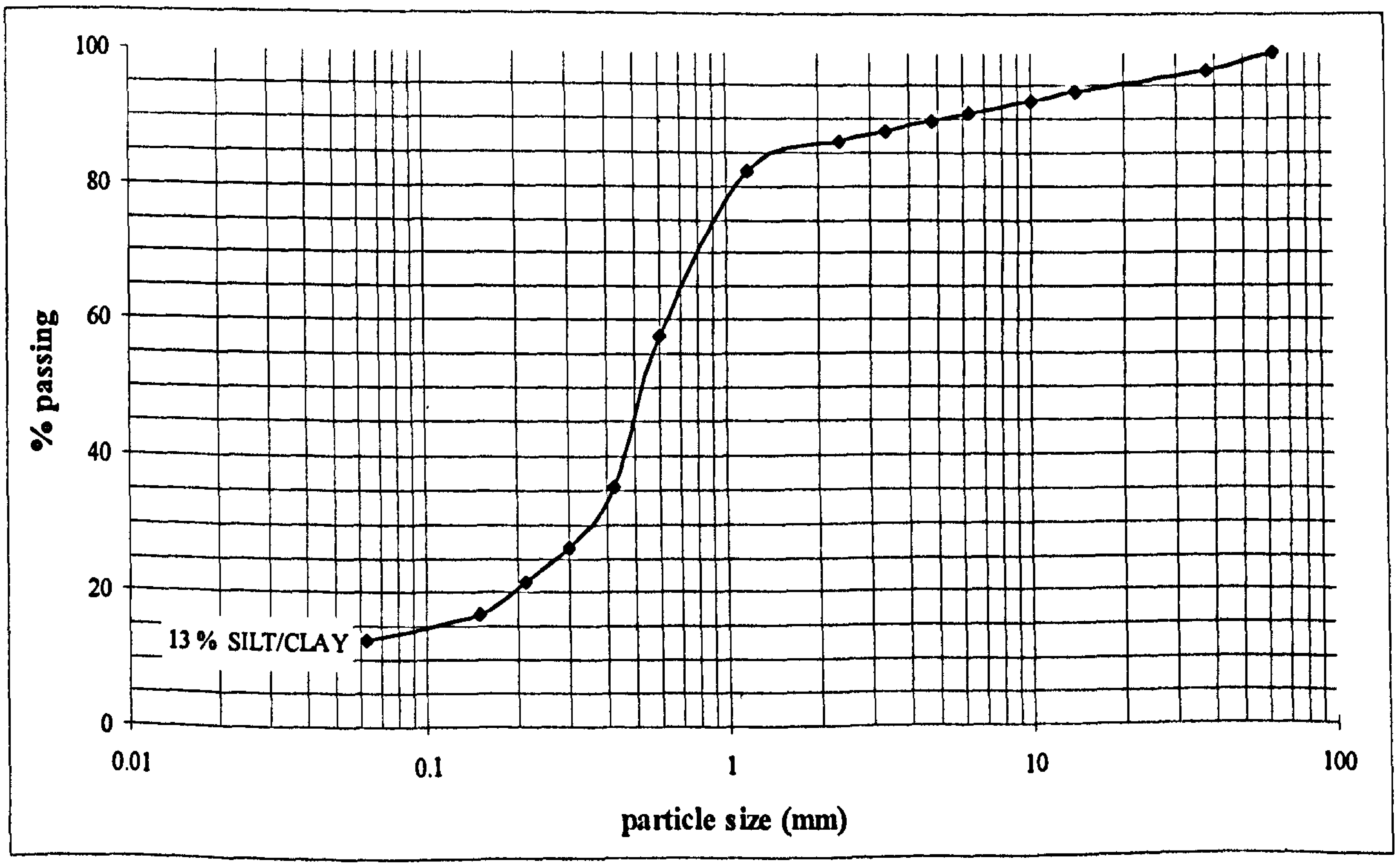
6.7.5 Inert Material

Prior to construction of the experimental cells, a number of sources and types of inert material were considered. Concrete and brick demolition waste was a possibility, but was not available in sufficient quantity at the time required. Sand, was however freely available on site, and this was used as the inert material. Experimentally, the sand has probably been a better choice in terms of homogeneity. Demolition material, due to its coarser particle size, would have probably been better in terms of improving the permeability. The alkaline nature of concrete and mortar would have had an effect on leachate pH, and plaster would have increased the buffering capacity of the leachate.

Material Analysis

Description:	Red SAND with gravel sized particles of weathered sandstone and gravel sized clay pockets.
Natural moisture content	13 % dry mass
Bulk density	1.76 Mg/m3
Dry density	1.57 Mg/m3

Figure 6-9 Particle Size Distribution of Sand used as 'Inert Material'



The grading shows that the material consists of 73% by mass sand-sized particles, while 14% is gravel-sized particles and 13% silt and clay.

Testing was carried out in the departmental geotechnical laboratory. Moisture content and particle size distribution analysis was conducted in accordance with BS1377: Part 2: 1990, Method 3. The density was determined according to BS1377:

Part 4: 1990, Method 3.3 (2.5kg rammer in a 1litre mould), but modified to a single point test. BS 5930:1981 provided the method of soil description.

7 CONSTRUCTION OF THE EXPERIMENTAL FACILITY

Photographic Records

Numerous still photographs and some video were taken to record the progress of construction. Photographs are contained in software appendix, on disc, found inside the back cover. Photographs in this appendix are referenced by number, for example "(frame24)", and should be viewed concurrently with the text.

7.1 Site Selection

Through the previous landfill experiment (Fleming,G 1990; Wingfield-Hayes, 1994), and landfill consultancy (Fleming,G 1988b), the University of Strathclyde and EnviroCentre have a good relationship with G&A Munn & Son (Landfill)Ltd. The Munn family are farmers as well as landfill operators. The landfill and farm are located at Mid Auchencarroch, near Alexandria, in Dunbartonshire, some 40km west of Glasgow.

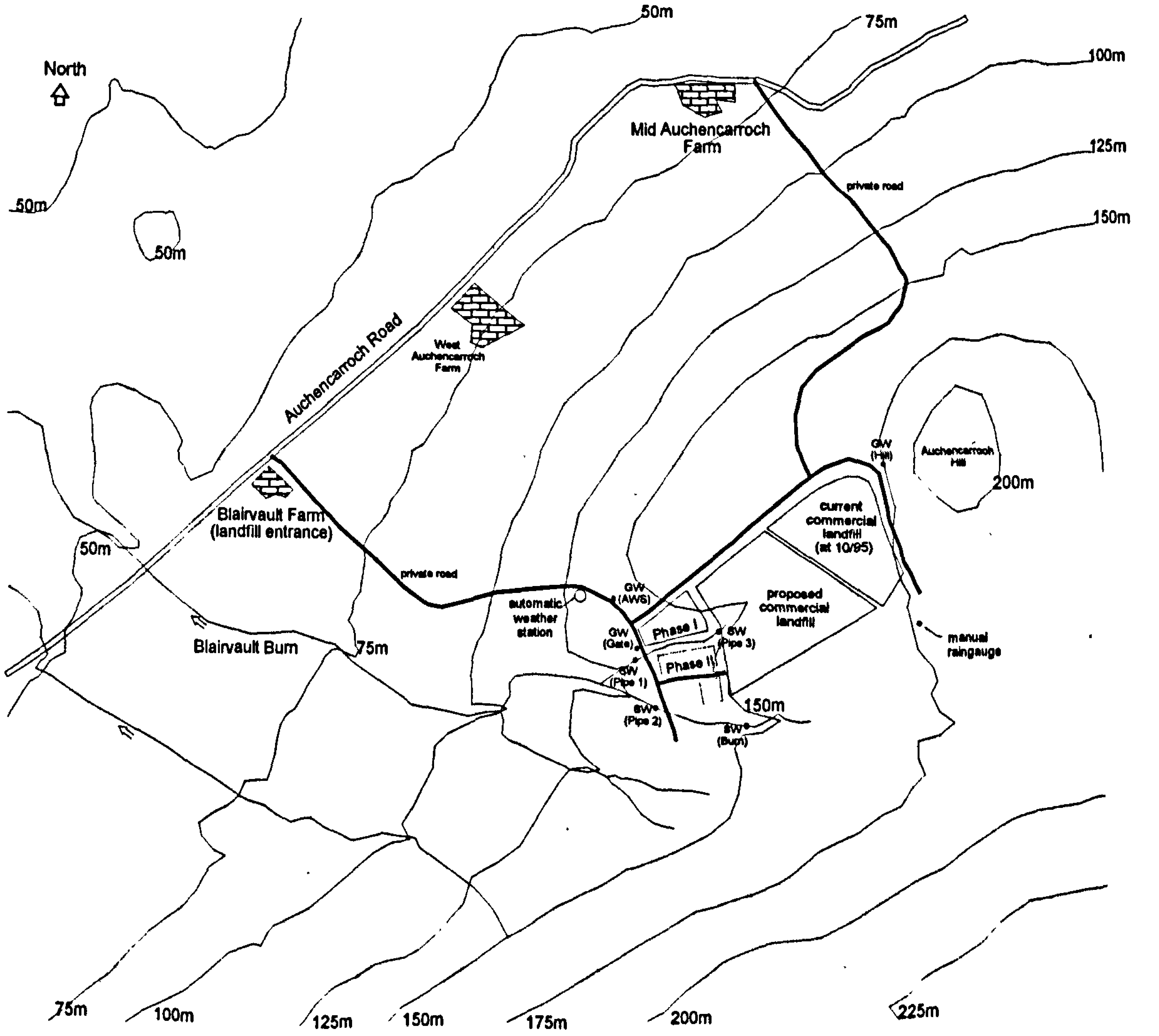
Experience of the site indicated good geological conditions for landfill. George Munn agreed to allow a further experimental facility to be built at Mid Auchencarroch on land adjacent to his commercial landfill site and the previous experimental landfill, Mid Auchencarroch Phase I . Mid Auchencarroch Landfill is located at Ordnance Survey grid reference NS420813, and the situation is shown in Figure 7-1.

The landfill is situated on an exposed upland moor, at an altitude of approximately 150m above ordnance datum and overlooks the Vale of Leven, to the west.

7.1.1 Site Geology

The geology of the area is formally given in the solid and drift editions of the relevant geological maps (British Geological Survey, 1958, 1961). This shows that the solid, that is underlying, geology of the area is Upper Old Red Sandstone, and in fact a sandstone quarry existed approximately 1km from the site.

Figure 7-1 Situation of Experimental Site



The nearby Auchencarroch Hill is a volcanic vent feature consisting of basaltic agglomerate with a small lense shaped dyke of olivine-basalt on the north side. The volcanic features are considered to be of little direct significance to the geology of the experimental site specifically.

The drift, that is surface deposits, are more variable. The area surrounding Auchencarroch Hill, to the east, south and west is boulder clay. In places it is overlain by peat. Further to the south the Old Red Sandstone outcrops, again in places with a peat covering. To the north of Auchencarroch Hill there are moundy deposits of moranic drift.

To summarise, in the area that was considered for the construction of a new experimental landfill the ground investigation anticipated finding boulder clay overlying sandstone.

7.1.2 Ground Investigation

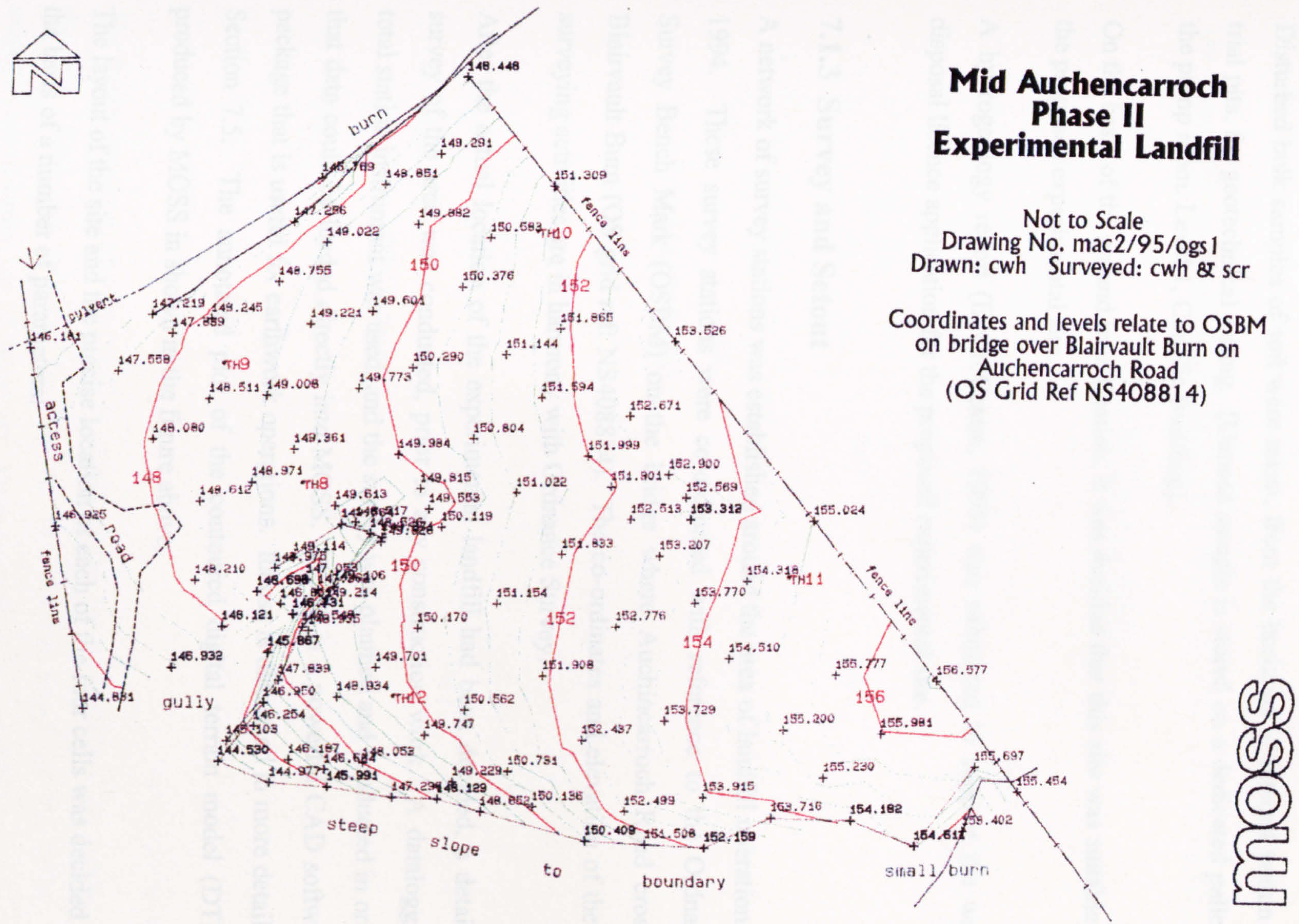
A hydrogeological report of the area had already been conducted for commercial landfill activities in the area (Fleming,G 1988b). Experience of the surrounding ground conditions was drawn from the adjacent landfill activities on the commercial landfill site and also from the experience gained with the Phase I Experimental site. Both of these landfill sites operate on the "containment" principle, the containing media being the natural in situ clay.

A trial pitting operation was undertaken to investigate the ground conditions in the area of the proposed experimental site.

The initial area under consideration was covered by TH 1 - 7. This area proved to be unsuitable for the experiment because the thickness of clay was insufficient and variable. Rockhead was encountered at 3.6m in TH 2 and 3. Attention was turned to a different area, also adjacent to the Phase I Experimental Site. TH 8- 12 were conducted in this second area (frame1). Logs for all the trial pits are shown in the software appendix. This area has a good thickness of clay which continued to the extent of excavation of the trial pits (4.1~5.6m). Generally the drift in this area would be described as: Stiff, fissured, brown CLAY with some gravel (frame2).

The locations of trial pits TH 8 - 12 are shown on the Original Ground Survey, in Figure 7-2 overleaf.

Figure 7-2 Original Ground Survey



Disturbed bulk samples of soil were taken, from the horizons of interest within the trial pits, for geotechnical testing. [Unused sample is stored on a dedicated pallet in the pump room, Level 1, Colville Building].

On the basis of the ground investigation, it was decided that this site was suitable for the proposed experimental site.

A hydrogeology report (EnviroCentre, 1995) was submitted to support the waste disposal licence application for the proposed experimental site.

7.1.3 Survey and Setout

A network of survey stations was established around the area of landfill operations in 1994. These survey stations were co-ordinated with reference to the Ordnance Survey Bench Mark (OSBM) on the bridge where Auchincarroch Road crosses Blairvault Burn (OS grid ref: NS408814). The co-ordinates and elevation of the all surveying activities are in harmony with Ordnance Survey.

After the actual location of the experimental landfill had been decided, a detailed survey of the area was conducted, prior to any construction work. A datalogging total station instrument was used, and the survey was planned and conducted in order that data could be loaded directly into MOSS. MOSS is a powerful CAD software package that is useful for earthwork operations. Its use is discussed in more detail in Section 7.5. The annotated plot of the contoured digital terrain model (DTM) produced by MOSS in shown in the figure above.

The layout of the site and the precise location of each of the four cells was decided on the basis of a number of parameters:

1. spatial and topographic limitations of area available

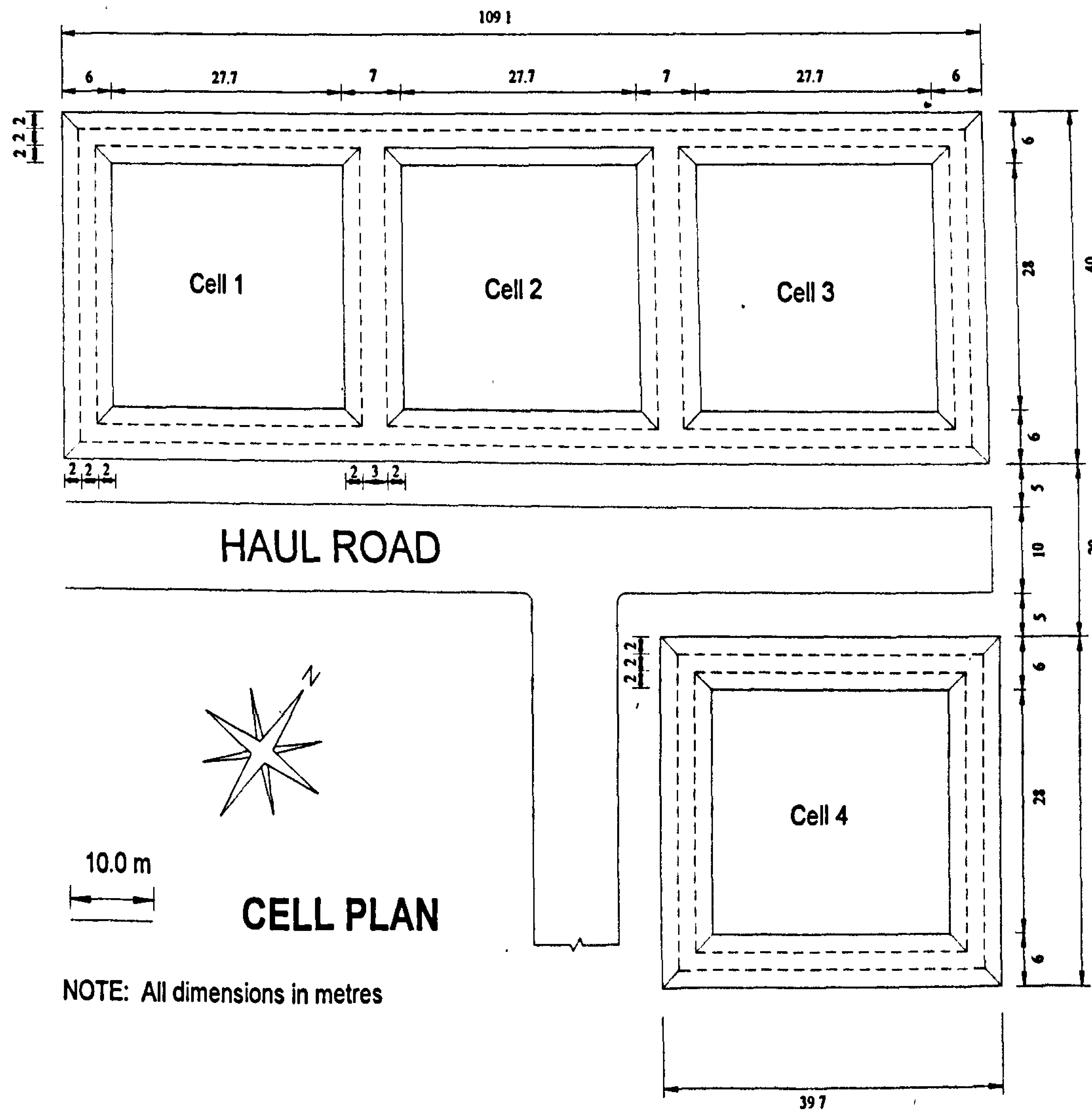
2. minimisation of muckshifting

3. suitable location of stockpiles/borrowpits

4. vehicular access for waste input.

The layout that was proposed, is shown in the figure below (not drawn in MOSS).

Figure 7-3 Layout of Cells



Drawn: EnviroCentre

The digital terrain model was used to generate plan co-ordinates (x,y) for setting out the site. This was achieved by drawing "construction lines" on the DTM, for example, toe of batter, top of batter, etc. From these lines, a output file of set-out co-ordinates was created.

The set-out co-ordinate data were loaded on to the Total Station datalogger. Once the instrument was set up on a suitable station overlooking the site, the datalogger calculated bearings and distances for each of the points. Thus, with a detail pole, the location of each point was found, and the set-out achieved. Set-out was conducted on 25th May '95.

The powerful combination of CAD software and a Total Station instrument with datalogger has been made use of throughout the project. The original ground survey and subsequent set-out were the first stage. Further surveys were conducted at important stages during the construction process; these and their use is described in 7.5 Surveying and Digital Terrain Modelling.

7.2 Establishment of Weather Station

7.2.1 Manual Raingauge

The 5 inch manual gauge was established on 25th May 1995. It was located on the heather moor approximately 250m north of the experimental site (frame6). This location was chosen as it was away from both the experimental cells and the Automatic Weather Station (AWS), where it may have received more attention as a target for vandalism.

7.2.2 Automatic Weather Station

It was intended to have the automatic weather station installed and commissioned prior to the filling of the experimental cells. This would have enabled a more accurate water balance to be calculated. In the event, the AWS was several weeks late in delivery. Added to this, there was a communications problem between the datalogger and the laptop PC, which was eventually tracked down to a faulty interface device on the AWS. This delayed the commissioning of the AWS until the 12th October 1995. General view (frame7).

AWS Mast

A 10m telegraph pole was used as the mast. This was held between two steel stanchions set in concrete to a depth of 2m below ground level. The mast is hinged at approximately 1.5m above ground level and may be lowered with the assistance of a machine. The lower 4m section of the mast is greased to deter unwanted climbers.

Automatic Raingauge Emplacement

Due to the exposed windy location, a turf wall was constructed on the basis of Met. Office specification (Met. Office, 1981) to protect the raingauge. The instrument was bolted onto a concrete plinth in the centre of the turf wall emplacement.

A drainage pipe was placed under the turf wall in 1997, as the soakaway was found to be inadequate at times.

Chamber

The datalogger and battery power supply were housed in a steel chamber at the base of the mast. The chamber was manufactured by a local blacksmith.

7.3 Cell Construction

The design of the cells has been discussed in the previous chapter. The implementation of the design and the construction of the four experimental landfill cells began on 22nd May '95, with stripping of the construction area.

7.3.1 Vegetation and Topsoil Strip

There were a number of small silver birch trees on the site. These were stunted due to the predominantly water logged conditions in which they were growing. The trees were removed with a large lump of soil, and stored for subsequent replanting around the site.

The topsoil was around half a metre thick in most areas. Initially stripping the topsoil and the vegetation was attempted using a tracked excavator and dump trucks.

Mobility for the dump trucks proved too difficult in the soft and damp conditions on the moor. The dump trucks were replaced with a dozer with 1m wide tracks. The topsoil strip was completed on 30th May, despite some wet weather over the intervening weekend (frame12). The peat topsoil proved to be quite a sensitive soil, and when overworked after the heavy rain, it quickly became a slurry. Thus the final material to be stripped was poorly stockpiled, and occupied a larger area than was planned.

7.3.2 Excavation of Cells

The start of excavation for cell construction was deferred until 17th July '95, while waiting for the issue of the site licence.

Two excavators shifted the approximately 2500 m^3 of material per cell (frame13). From the formation level, which was effectively the level of stripped site, the cells were excavated 3m below and bunds constructed 2m above, using the spoil from excavation. The bunds were constructed by compacting material in 0.3 - 0.5 m lifts (frame14). The excavated clay was at a moisture content below, but close to optimum, which made it suitably workable. Compaction was achieved by tracking a number of passes (frame15). The prior construction of a trial embankment (detailed in the previous chapter) had shown that effective compaction could be achieved using this method. The width of the bunds was overbuilt, and after compaction was trimmed to the correct dimensions.

A steep ramp was left in one corner of each cell to allow exit and entry for the excavators (frame16).

The base of the cells was surveyed and marked out to be trimmed for a minimum 1 in 40 fall to the centre of the cell (frame17). At the centre a concrete block, approximately 1m square was countersunk so that the upper surface would act as the base of the central well pumping sump.

A 5m gap in the constructed bund was provided at the same corner as the ramp (frame18). Apart from machine access, the main function of these gaps was to provide an entrance to the cells for granular material and then waste.

Concurrent with the excavation of the cells, was the construction of the access road to the cell entrances (frame18). The road consisted of ≈1m thick layer of concrete demolition material placed on the stripped ground surface.

7.3.3 Basal Drainage Blanket

The 300mm thick basal drainage was laid over the entire base of the cell (frame19). The material was 50 - 100 mm, no fines, new crushed basalt, imported from a local quarry at Bowling. New crushed rock was used for the experimental landfill, rather than recycled granular material, to be certain of not introducing unknown confounding factors in the bioreactor system. The use of recycled granular material is not precluded for a successful enhanced landfill bioreactor.

The drainage blanket was not protected by geotextile, for reasons discussed in the previous chapter. Waste was placed directly on the granular material.

7.3.4 Waste Input

The Municipal Solid Waste that filled the cells for this experiment came from three sources. The sources of waste are described in the previous chapter and the characterisation and quantity of each waste stream is presented in the next chapter.

The pulverised material was delivered from Cunninghame District Council's Shewalton plant by haulage contractor in articulated and rigid chassis, high capacity tippers (frame20). Despite the large volumes of these vehicles, they were unable to achieve a full load in terms of mass, due to the low density of uncompacted waste.

The untreated waste from Dumbarton District Council was conveyed direct to site in refuse collection vehicles (frame21). The second source of untreated waste, from Inverclyde District Council, was delivered to site in their own articulated, 54 m^3

ejector vehicles (frame22). These vehicles were loaded with premixed MSW at their waste transfer station in Port Glasgow.

The drainage blanket was completed on Cell 1 on the 31st of July '95. The first consignment of pulverised waste was delivered the following morning. Cell 2 was ready on 3rd August '95, and received the first consignment of untreated waste from Dumbarton D.C. on 7th August. The first consignment from Inverclyde D.C. was on 31st August '95.

The waste was deposited from the delivery vehicle directly into the cell, or into the cell entrance. A compactor then spread each consignment (frame23).

The first lift of ≈1m of waste was placed in all the cells as soon as possible after construction. There were two reasons for this:

1. To stabilise the very steep cell walls by surcharging the toe of the batter
2. To provide an 'absorbent mattress' of material for any precipitation, so that runoff (from precipitation water) would not accumulate in drainage blanket and central well sump.

7.3.5 Well Installation

The lower section of the Central Well was installed in each cell when the first lift of waste was complete. This lower section consisted of a 6m length of twin wall perforated polypropylene pipe, of internal diameter 200mm. The pipe was stood upright on the block of concrete in the base of the cell, at its centre. Waste was pushed up against the pipe to hold it in a vertical position. Filling of the cell then continued around the Central Well. Though this method obviates the need to drill, movement of waste during compaction inevitably means that the well will not remain absolutely straight. This is not of consequence for most of the Central Well operations.

The cluster of three Ø150mm pipes that from the Waste Access Tube facility were installed in the same way (frame27, frame28).

7.3.6 Spreading and Compaction

Spreading and compaction were achieved by a steel wheel compactor (JCB 428), the gross mass of which is 21 tonnes. Excessive compaction was discouraged. During the spreading and compaction operation there was also a degree of homogenisation, particle size reduction and waste container opening. This appears to particularly relevant to the untreated waste, with bin bags being torn open, large pieces of material being broken up and some of mixing of the resulting material. This homogenisation was not conducted to any greater extent than waste placed in an ordinary landfill.

It was planned to place the waste in discrete lifts of ≈1.5m. Due to space and access constraints, virtually every consignment of waste had to be moved before the next one could be deposited at that cell. Therefore in practice each lift was composed of a number layers, and there may have been a greater degree of stratification imparted to the waste than would normally be the case in a commercial operation.

7.3.7 Addition of Inert Material to Cell 1

Inert material was mixed with the waste. The intention was to make the addition of ≈25 % by volume. The addition was made on a volume basis as there was not a weighbridge on site.

Only Cell 1 received this treatment. Analysis of the inert material is reported in Section 6.7.5.

Measurement of Volume

Sand was consigned to Cell 1 in dump trucks, each consignment being recorded. The basis of measurement was the volume was the bucket of the excavator which loaded the dump trucks.

The volume of the excavator bucket was determined by filling a tipping trailer with a number of buckets. The sand was not compacted, but just levelled off. The interior of the trailer load box was rectanguloid, thus making it easy to determine its volume. On this basis, the volume of one 'domed' bucket of sand was determined as 0.92 m^3.

A large dump truck contained 33 buckets full, a small dump truck, 17. A total of 1134 m^3 of inert material was added.

Mixing

Two methods of mixing were utilised. Method 1 was adopted for the first lift only. Method 2 was used for the subsequent lifts.

Method 1. Bulk Addition. Place a lift of waste. When the lift is complete add an appropriate depth of inert material over whole layer (frame24). Using an excavator mix waste and inert material thoroughly (frame25).

Method 2. Per Consignment Addition. For each consignment of waste add an appropriate volume of inert material, the amount depending on the size of consignment. Machine operators were a given table of quantities to determine amount of material to add for each delivery vehicle size. Inert material was spread on top of each consignment, and then mixed in during blading out by compactor.

Method 1 proved to be laborious and slow, not to mention unpleasant for the excavator operator, the pulverised waste having begun to degrade. This led to the adoption of Method 2. According to visual observation, both methods achieved a fairly homogeneous mixture (frame26).

The total depth of the first lift and inert material was ≈2m. On the first lift, using Method 1, it was found that was slightly in excess of a 25% admixture. To compensate for this the subsequent 3m was given an admixture of ≈21% by volume.

7.3.8 Top Granular Blanket

Cells 1 & 3 were full of pulverised waste on the 29th September 1995, while Cells 2 & 4 were full of untreated waste on 4th October 1995. Trimming and laying the granular blanket began immediately.

Once the last lift of waste had been placed and the cell was full, it was trimmed to the horizontal by the excavator. This was checked and amended where necessary, using a survey instrument (frame29).

The crushed rock that forms the top granular blanket was place on the trimmed surface of the waste (frame30). The surface was sufficiently firm for road tippers to traffic it.

Prior to spreading the crushed rock, the leachate irrigation pipeline was installed in a trench in the waste surface. The trench was backfilled with the granular material. The 150mm thick granular blanket was then spread over the whole surface of the waste (frame31), with the exception of the peripheral 2m wide strip. The gas collection pipeline was then installed in the blanket (frame32).

The top granular blanket was protected from migration of fines from the clay cap by a geotextile separation layer (frame33).

7.3.9 Capping

Wellheads were installed prior to placing of the cap (frame34), and the clay was carefully compacted around these features to effect a good seal. The outer wall of the twin wall pipe has a serrated section which allows a good key between capping and pipe.

The capping was placed entirely by excavator. There were no dump trucks used. The cap was placed in two lifts, and the excavators did not traffic the top granular blanket, working only on the clay that they had placed ahead of themselves (frame35).

Cells 1,2 & 3 were capped first. The first lift was laid on all three cells before the second was started in order to seal the cells (frame36). The first lift was completed on Cells 1- 3 on 19th October 1995. This is effectively the date that they were sealed.

Poor weather halted earthmoving operations on site until 3rd November 1995. Cell 4 had the first lift of capping completed on 8th November 1995, some 19 days after Cells 1 - 3. The second lifts were placed on to all the cells, completing the capping (frame37). During the final stages placing the second lift of the cap, a wide tracked blade was used, because weather conditions prevented the excavators trafficking the cap.

The elevation of capping around the wellheads was slightly higher so that the surface runoff would not accumulate around them, with the potential for infiltration into the cell.

Some additional material was required for the capping, as in practice the mass balance had fallen slightly short. Additional material was sourced from borrow pits adjacent to the cells.

7.3.10 Installation of Gas Flowmeters

The super-cap pipework for the gas flow meters was installed in early January 1996. When the gas collection pipeline emerges through the capping, a T-piece allows the pipe to the gas flow meter to be connected (frame38). A flexible coupling connects the twin wall pipe to the solid wall MDPE which makes up the metering section (frame39). The meters are housed in a 2.5m long chambers that sit on top of the capping. The chambers were manufactured by a local blacksmith. The meters are linked together by an armoured communications cable which is in a shallow trench in the top of the capping (frame40).

To accommodate settlement which may draw more cable, each chamber has loops containing several metres of slack cable. The cable passes through a ∅100mm duct between Cell 3 and Cell 4.

The gas flow meters were installed and commissioned by the manufacturer and supplier Bartington Associates Ltd. This was conducted on 24th January 1996.

Each cell has a meter, each meter having a Head Station. The Head Stations are controlled by one Base Station, which was initially located in the chamber on Cell 2, along with the battery power supply. The Head Stations and the Base Station were initially mounted on the meter section of the gas pipe (frame41). The Base Station has an interactive display.

After the gas passes through the flow meter section of pipeline, it turns through 90° to a vertical vent, approximately 1m above the topsoil surface. The vent terminates in a cowl (frame42).

7.3.11 Installation of Temperature Probes

The temperature probes were fabricated in the departmental hydraulics workshop. They were installed at the end of January 1996, taking advantage of frozen ground for access onto the cells. The probe at the centre of the cell was placed inside the gas flow meter chamber, to protect the thermocouple wires emanating from the top from unwanted interference. The steel tube that forms the outer shell of the probe was driven with a hydraulic breaker (frame43). After driving the steel tube, the thermocouple string is inserted (frame44).

The thermocouple string has three thermocouples at different locations down the string. The thermocouple head comes through the wall of the plastic tube that forms the string and is glued in a recess on the outside (frame45).

The outer probe is placed near the periphery of the cell. It is installed in the same way, but has a housing at the top of the steel tube to store and protect the emanating wires (frame46).

The temperatures can be read using any K-type thermocouple reading device (frame47). Should any thermocouple in a string fail, the string can simply be withdrawn for repair or replacement (frame48).

7.3.12 Topsoil Placement and Revegetation

The bare capping was subject to erosion due to surface runoff. This problem was acute at the lower end of Cell 1 where runoff from Cell 2 & 3 was also flowing. To protect the cap it was necessary to place the topsoil as soon as possible.

Prior to placement of the topsoil, drainage for the gas flow meter chambers was installed. This was necessary in order to prevent submersion of the gas flow meter. The drainage consisted of ∅60mm single wall field drainage pipe which was laid from the chamber to the edge of the cell where it discharged. The pipe was laid across the surface of the capping, no bedding was used (frame49).

Topsoil was placed on the cells during a cold spell of weather at the end of January, and beginning of February 1996, again taking advantage of the frozen cap and frozen topsoil (frame50). Heavy earthmoving plant was not suitable for the conditions, so agricultural tractors and trailers were used (frame51)(frame52). The topsoil was spread out by an excavator.

Once thawed after the cold weather of January and February 1996, the topsoil was not sufficiently dry to traffic until late summer. In early August 1996, the topsoil was worked to a seedbed and a grass seed mixture was broadcast (frame53). Some fertiliser was also broadcast and the seedbed was harrowed and rolled. A few weeks later there was good germination evident across all cells (frame54).

7.4 Waste In Situ Density Tests

Background

The density of the wastemass on a whole cell basis was calculated, and is described in Section 7.5. In addition to this, an in situ density test was conducted in the top of the final lift of waste in each cell. This determination would act as a comparison for the whole cell figure and would give some indication of increase in density with depth.

Methodology

The 'particle size' of MSW meant that the sort of test that would normally be used for a soil fill, e.g. sand replacement test, was not suitable. The possibility of using a nuclear density gauge was investigated, but the author could find no written or colloquial reports of this being attempted on waste before. The general opinion was that effective calibration of the device would be difficult, and the heterogeneity of moisture content of various elements of the wastemass would render results dubious.

Finally, the water replacement method of in situ density test was used. The method used was based on Test 2.3 of BS1337:Part 9: 1990 (BSI, 1990). Again there appears to be no written or colloquial evidence, that the author could locate, that this test has been used on a landfilled wastemass before. The test was developed for use on very coarse grained soils, for example measuring the density of boulder and earth fill in a dam structure.

Essentially the test procedure is as follows: Excavate a hole in the material that density is to be measured. Determine the mass of the material that has been removed. Line the hole with a water retaining membrane, e.g. plastic sheet. Fill the lined hole with water, using a method that allows the determination of the amount of water required. Determination of amount of water required to fill the hole enables calculation of the volume of the hole, and thus with the mass of removed material, calculation of the density is straightforward.

Equipment

It was envisaged that approximately 1 m^3 excavations would be made in the wastemass to conduct the tests. The quantity of material excavated dictated that determination of mass had to be conducted on site. Conditions on site meant that platform scales or the like would be unsuitable. The problem was solved by using a 50kN load cell, borrowed from the departmental geotechnical laboratory. The load cell was of the temperature compensated strain gauge type operating as a Wheatstone Bridge. Calibration was conducted both while loading and unloading, to check for hysteresis. The calibration data were plotted on a spreadsheet and linear regression analysis used to establish a numerical relationship between applied load and measured voltage.

Procedure

The tests were conducted on Sunday 1st October 1995. One test was conducted in each of the four cells. It would have been desirable to conduct two or three tests on each cell, but limitation of time prevented this.

A hole was excavated in the top surface of the wastemass with a 1m wide bucket on the excavator. Attempts were made to keep the boundaries of the excavated hole as discrete as possible. This was difficult due to the nature of the material, particularly the plastic film in the waste. The excavated material was placed directly into large bags (frame55). The bags were weighed using the loadcell (frame56). The water tank was filled from a vacuum tanker (frame57), and was weighed.

The hole was lined with plastic sheet, and water introduced (frame58). When the lined hole was full of water, the water tank was re-weighed (frame59).

After the test was complete the plastic lining was ruptured with the excavator bucket, to allow the water to drain away into the wastemass. The excavated waste was returned to the hole and compacted.

Results of the tests are presented in Section 9.1.4.

7.5 Surveying and Digital Terrain Modelling

The highways and earthworks CAD package MOSS was used to create digital terrain models (DTM) of various stages of the construction process. Using a CAD system such as this, the survey stage becomes an integral part of modelling, and is in effect the creation of the model.

Feature Coding and Strings

MOSS has a powerful feature coding system that enables each surveyed point to labelled with a code. Thus features such as fences, watercourses and spot levels, have different features codes. Points on any feature could be surveyed in any order, provided the correct code was applied to that particular observation.

When the survey data are subsequently input to a computer, the MOSS software recognises the individual points, but associates those with common feature codes, and forms them into separate 'strings' (of points).

Survey Equipment

In the field, a total station instrument, the Sokkia SET3, was used in conjunction with a dedicated datalogger, the SDR 20 and later the SDR 31 (SDR = Sokkia Data Recorder). The final survey of the topsoiled cells was conducted using a new integral datalogger/total station, the Sokkia Powerset 2000.

Conducting the Survey

Feature coding is the essence of creating a model in the field. Therefore prior to survey, the creation of the model must be considered, and feature codes planned. Examples of the 4 character codes that were used are:

MP21	Master String Code - centre of access road
L251	Line Code - toe of batter, Cells 1-3
PCWT	Point Code - Central Well Top (top of wellheads)

The first character of the code controls to how MOSS will interpret the string point. The subsequent 3 characters are for user identification, and are alphanumeric. For instance, a string with a code beginning with L will have a plain line drawn through the points automatically, and the level of each point will be assumed to be on the surface being surveyed. It will therefore be used in triangulation operations that are conducted by MOSS.

Conversely, a P string is considered as point information only, although there may be a collection of these points. The point is not used in triangulation of the surface, as the elevation is considered as not necessarily indicative of the surface. P strings are useful for a series of individual features.

When each observation is taken, a code is prompted for. It is also possible to load a set of codes into the datalogger and select one of them for each observation.

The dataloggers are capable of calculating point co-ordinates of an observation in real time. However, for input into MOSS, the raw data format is preferred. This is in the form of slope distance and vertical angle (SDVA)

Transfer of Data

The collected raw data from each survey are downloaded to a PC running SDRMAP. SDRMAP passes the raw data into a file in MOSS input format. It also stores a separate version with co-ordinates calculated, in SDR format. The latter is not used.

Creation of a DTM

The MOSS input file is loaded on to the university's Sun workstation network. Once the data were input to MOSS, the software calculates the co-ordinates (x,y,z) of each surveyed point. The 'string' codes associated with each point enables the appropriate points to be strung together, and a digital terrain model (DTM) is created showing features on the ground.

This should be a straight forward process that is automatic. However it was found that the SDRMAP software did not produce a perfect MOSS input file. After some research of the MOSS manuals, and trial and error amendments, a methodology for correcting files was developed. The main problems were missing commands and missing fields.

Models

Survey data were acquired at four main junctures of the construction of the experimental cells:

1. The original topography of the area on which the cells were constructed

2. The excavated cells, with the basal drainage blanket in place, prior to filling

3. The cells full of waste, with the final lift trimmed level, ready to have the top granular blanket placed.

4. The final topsoiled topography, including locating all the cell top 'furniture'

Models were created for each of these stages.

MOSS interprets the surface of the digital terrain model by triangulating all the points that have relevant elevation data. The whole surface is covered in irregular triangles that are drawn between a point and any two adjacent points. MOSS can therefore interpolate between points and calculate an elevation for any location on the DTM surface.

The triangulated surfaced is then used for further functions; such as contouring or volume calculations.

Setting Out

The model of the original ground survey was used to create a setting out dataset. Lines were drawn in the model denoting setting out features, such as top and bottom of batter for the cell walls. Points on these lines were output as a dataset.

The dataset was fed into the SDR 20 datalogger; this and the SET3 were used to set out the site. The datalogger and total station instrument were operated in 'Setout' mode. The detail pole was placed roughly in the correct location. A shot was taken from the instrument which then gave instructions to the instrument operator, on where and how far the detail pole should be moved. This information was relayed by radio, the detail pole moved, and a confirmatory shot taken.

Contouring

The software is capable of generating contours for the triangulated surface of the DTM. The models of the original ground and of the final topsoiled were contoured in this way. Figure 7-2, shows the Original Ground Survey.

Volume Calculation

MOSS can use several methods for calculating volumes. Essentially the volume to be measured is the difference between two DTM surfaces. In this case the difference between the empty cell and the cell full of waste. The isopachyte method was used because it is a much more accurate method of measuring the volume of non-linear features, than by taking sections.

The isopachyte method creates irregular prismatic elements between one point on one DTM surface and three points on the other DTM surface. This process is replicated for all points on each surface, until the volume between the surfaces in filled. The volume of each irregular prism is calculated and a total found.

Sub-models were created for each of the cells so that each could be measured individually. The results from the modelling exercise and volume calculations were used to determine the waste density, given in Section 9.1.4.

7.6 Monitoring Equipment

7.6.1 Gas Temperature Measurement

Gas composition and temperature are measured on site using a Geotechnical Instruments GA94. The instrument is connected to a self sealing port on the gas pipeline (frame65). Temperature can be measured by a separate probe that plugs into the side of the instrument. This is convenient for measuring the temperature in an open vent, but it is not possible with a self sealing port.

Geotechnical Instruments were contacted to seek a solution, but stated that there was no other model of temperature probe. They did however provide a thermistor in order that a device could be fabricated (frame66). This was carried out in the departmental electronics workshop. The device is a simple construction that holds the thermistor in the stream of gas, that is being drawn up by the GA94.

7.6.2 Gas Logging

A requirement was identified for the GA94 instrument to run for 7 days continuous field operation, logging gas parameters. The internal batteries were sufficient for a few hours only. Therefore an external power supply to float charge the internal battery was necessary. This was achieved using a 12v lead acid battery and modified 'model car' charger that reduced the voltage to around 8v.

Unfortunately the GA94 uses a common electrical port to measure temperature and receive power from an external source. Again Geotechnical Instrument did not have a solution for this problem. Investigations showed that both operations could be conducted concurrently. Modifications were carried out in the departmental electronics laboratory.

The instrument is shown in use (frame67). In the foreground is the battery with the voltage reducing device sitting on top of it. The GA94 is hanging from the propane cylinder, above ground level in case of chamber flooding. The sampling tube is connected to self sealing coupling on the gas pipeline. The exhaust gas from the instrument is piped out of the chamber so that an explosive mixture is not allowed to develop inside the closed chamber.

7.6.3 Development of Waste Sampling Apparatus

The Waste Access Tubes were successfully installed during the construction of the cell. At that stage, apparatus for sampling the waste had not been designed or made. In 1996, after the waste had been in the experimental cells for around six months, a sampling programme was established.

The three ∅150mm tubes, which go down to different depths, are housed within a ∅450mm wellhead (frame68). Waste is sampled from the bottom end of each tube, which is 3.5 - 7.5m below the wellhead rim.

On the 5th July 96 the first attempt to recover waste was made. The sample recovery apparatus operated by impaling waste with a barbed pronged device on the end of steel rods (frame69). This device worked in the shallowest of the tubes, but was unsuccessful on the deeper tubes. It appeared that the waste was too tightly compacted in the wastemass to be torn out using this device.

A reappraisal was conducted that resulted in a two stage approach to sampling. Firstly, loosen and break up the waste at the base of the hole with a powered rotary device, then recover the fragments of material.

Available in the department was a steel hand drilling set, complete with strings and 4 inch core barrel. A Kango 637 rotary/percussive drill was also available. An adaptor from the Kango to the drill set was made in the departmental hydraulics workshop, as well as long handle for torque transfer (frame70). Sampling with this apparatus was attempted on 18th July 1996. The Kango (750W) proved to have insufficient torque to drive the core barrel, once it was in work. However the technique looked promising.

The apparatus was modified to be driven by the more powerful Hilti TE74 rotary/percussive drill (1050W). Sampling with this apparatus was carried out on 7th & 8th August 1996 (frame71). Although more powerful than the Kango, the Hilti did struggle at times to core a sample. This is perhaps not surprising, considering the rapid rate of wear on the core barrel leading edges. A further problem was retention of sample within the core barrel when the drill string was removed. In the deeper tubes, in which sampling was occurring below several metres of leachate, there was a tendency for the core to fall out of the barrel. Recovery of a good sample using the barbed prong device was not successful in these submerged conditions.

The next modifications were to weld sample retention fins on the inside of the core barrel, and fit a larger rotary driver. The latter seems an obvious move, but for most plant hire companies, the TE74 is the most powerful hand held rotary drill. However, a larger one was found - the 1.5kW Bosch GBH10DC. This set of apparatus was used on site on 3rd September 1996. The Bosch drill was suitably powerful, and was being used in all the deepest of the tubes, in which the superseded apparatus had been unsuccessful in sampling.

During drilling for a sample in Cell 1, the drill string fractured at around 3.5m below the wellhead rim. The steel drill string is heavy and slow to use, but would probably be strong enough if there was no percussive element of the drill action. Unfortunately, with none of these drills is it possible to switch off the percussive action.

At the time of writing, no further development work has been conducted. Samples had been recovered from every cell, if not every tube, and therefore it was felt that development work could be suspended. Further development work will be conducted when the next set of samples is required.

7.7 Subsequent Construction Events

7.7.1 Failure of Gas Flow Meters due to Flooding

At the time of installation of the gas flow meters, the manufacturer and supplier, Bartington Associates Ltd, made it clear that the Base Station and Head Stations should not be submerged. At installation, Bartington Associates were requested to move the Base and Head Stations from a pipe mounting which was below final ground level, to a side of chamber mounting which was above the ground level. This was not done, due to their time constraints.

Flooding Incident

The chamber drainage worked well, however during heavy rainfall on 17th and the early morning of 18th April 1996, which totalled nearly 50mm, the chamber on Cell 2 flooded. A scheduled site visit discovered the flooded chamber on the 18th. Marks on the side to the chamber wall indicated that the flowmeters had been subjected to around 300mm submersion, probably for a few hours.

Water was bailed out of the chamber, and the lids of Base Station and Head Station instrument enclosures removed. These enclosures were waterlogged. Moreover when the enclosure of the headstation on Cell 1 was opened (which is ≈ 1m lower in elevation, but some 35m away), it was also found to have a small pool of water in it. This water was emerging from the communications cable that connected it to the system Base Station on Cell 2.

The chamber drainage pipe was rodded. There appeared to be a partial blockage, which under normal conditions allowed sufficient water to pass, but under extreme conditions caused water to accumulate.

The Base Station and Head Station on Cell 2 were removed, and returned to the university. Inspection by the departmental electronics technician, indicated that corrosion of the printed circuit boards was too severe for repair. The instruments were returned to Bartington Associates. They confirmed that total replacement was the only realistic option.

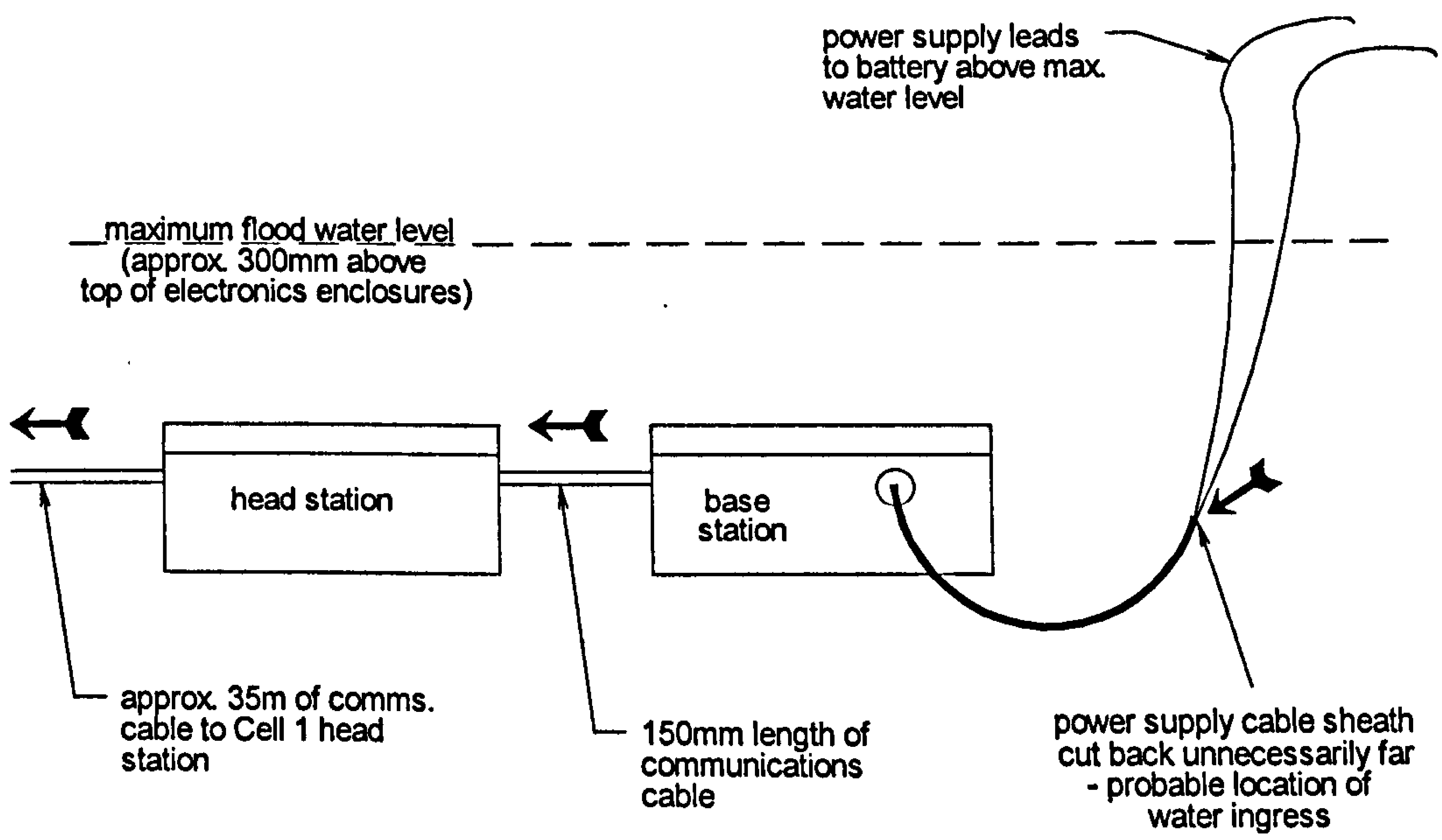
Mode of Failure - An Error of Design ?

The question of how these instrument enclosures failed arises. They were rated to IP65 (BSI, 1992), which means that they were dust tight and had water protection against water jets, so they were not designed to be immersed. When a flow metering device was being selected, a visit was made to another Bartington Associates installation at Mucking Marsh. There the rating was given as IP67, dust tight and water protection against the effects of brief immersion. At the time of specification of our installation, the significance of this downgrading of enclosure rating was not appreciated by the project team.

Inspite of the fact that IP65 was not designed for immersion, the author's opinion is that the failure occurred, not because of the enclosure itself, but was due to the cables attached to them. This opinion is based on the amount of water in the enclosures, and inspection of the inside of the cable glands.

Figure 7-4 below shows the probable mode of failure. Water entered the power cable sheath that had been cut back unnecessarily far. The power cable was not sealed internally on entry to the enclosure. Therefore, when the cutback sheath became submerged, the cable acted as a duct to let water in. Lack of internal sealing on the communications cable from the Base Station to the headstation, allowed the cable to act as a duct, thus water logging the Head Station as well.

Figure 7-4 Water Ingress into Flow Meter Electronics Enclosures



The exit of the communications cable that went to the Head Station on Cell 1 was also unsealed. This allowed water to flow down the cable to that Head Station. Fortunately, the problem was identified immediately the flooding was discovered. The flow rate of water down the communications cable was sufficiently slow that the unit on Cell 1 was dried out before damage could occur.

Had the circuit boards been protected by a gel coating, the consequences of inundation would not have been a total loss.

The primary cause of flowmeter failure was obviously the flooding of the chamber in which they were located. However, it is the author's opinion, that the evidence shows that temporary flooding of the chamber would not have caused failure but for some serious design and installation oversights on the part of Bartington Associates.

Specification of Electronic Enclosures in Sub-surface Landfill Applications

Landfill sites, like many large scale earthworks projects, are particularly prone to flash flooding. This is primarily due to unvegetated soils of low permeability allowing rapid surface runoff and short time of concentration.

The specification of electronics enclosures that are installed below ground should take account of this tendency for periodic but temporary flooding. Therefore, it would appear that IP67 is appropriate. Where more than brief immersion is to be expected, IP68 is appropriate (dust tight and water protection from full submersion).

For above ground applications IP65 is satisfactory.

Resiting of Gas Flow Meter Base & Head Stations

Following the flooding the remaining Head Stations were resited to the walls of the chambers, above ground level (frame73).

Re-Installation of Base Station and Cell 2 Head Station

Quotation for repair and replacement of the damaged parts of the system was requested from the manufacturer. Funding for this unbudgeted occurrence was then sought. The system was re-installed and commissioned on 27th September 1996.

The incident resulted in the loss of approximately six months of gas flow data.

7.7.2 Further Maintenance on Gas Flow Meters

Further work was carried out on the gas flow meters, after a set of tests confirmed unsatisfactory operation in early 1997. The tests are described in the following chapter in Section 8.6.

A service visit to the installation was made by Bartington Associates on 17th June 1997. New amplifiers were fitted to all head stations to improve the performance of the meters. One of thermocouples on Cell 2 was found to be faulty, and was replaced. The thermocouples on Cell 4 had the probe tips cut back to increase sensitivity. In addition to this, injectors were cleaned, and software and electronic circuits were checked and reported to be operating correctly.

The effective operation of the flowmeters, as measured by the % of successful spot readings (the 'hit rate'), showed a huge increase after this maintenance visit. This indicates that there had been some avoidable loss of data. It is a matter of conjecture how much has been lost; statistical analysis of the data may help to indicate the scale of loss. The variability of readings was also greatly reduced after this maintenance visit.

8 MONITORING AND TRIALS

8.1 Monitoring Schedule

Routine monitoring encompasses measuring parameters of the landfill gas, leachate, wastemass and climate on a regular basis. The table below gives details:

Table 8.1 Monitored Parameters and Frequency

	Continuous	*Weekly*	*Monthly*	*Quarterly*	*Annually*
Gas	volumetric - output	methane carbon dioxide oxygen temperature	methane carbon dioxide oxygen nitrogen (by GC in lab) hydrogen hydrogen sulphide		
Leachate		depth volume - recirculated	temperature pH sodium magnesium potassium calcium electrical conductivity sulphate alkalinity chloride chemical oxygen demand biological oxygen demand total organic carbon ammonia nitrate nitrite	iron manganese total organic - nitrogen volatile fatty acids ortho-phosphate	cadmium zinc chromium copper nickel lead
Wastemass		temperature	settlement		
Climatic	precipitation temperature humidity wind speed wind direction barom. pressure net radiation	manual rain gauge			

Surface and ground water are also monitored around the site on a monthly basis. This ensures that any breach of the containment system is apparent immediately.

This monitoring, as well as much on the above table is required to comply with the site's Waste Management Licence.

8.2 Attendance on Site

Routine monitoring fieldwork centred around a weekly site visit, usually a Wednesday. Before leachate recirculation commenced in November 1996, one to two people were able to do the work in one day, depending on the tasks to be done in a specific week. Once leachate recirculation had started, two people were required for a whole day each week. The author worked in a team with EnviroCentre staff to cover the monitoring fieldwork for the project.

As discussed in the following section, some tasks were carried out on a weekly basis, some on a monthly basis, and others on demand. Work was scheduled in order that it was evenly spread through the month.

8.3 Methodology of Routine Monitoring and Maintenance

8.3.1 Gas Flow

Data

Spot readings of gas flow are taken every 10 minutes for each cell and recorded by a datalogger. At the beginning of every month, the data were downloaded onto a laptop PC (frame72).

The data were in the form of a record of the velocity of gas in the metering section. The minimum velocity is 0.1m/s. The collected data took the form of a time duration in units of 120ms counts. The collected data were sent to the meter manufacturer to be processed. The processing converted time to flow rate, and made a correction for laminar, turbulent or transition flow conditions according to empirically derived constants. These constants have been determined by Professor John Barnard in laboratory tests at Essex University.

Not every attempt to record a spot flow reading was successful. Typical errors were that one or both thermocouples had failed to detect the passage of the cold slug of gas. Theoretically, reasons for failure to read successfully are; flow below meter threshold of 0.8 m^3/h, and unstable or reverse flow conditions in meter section of the pipeline. The latter can be caused by meteorological conditions, such as wind and changing barometric pressure.

An indicator of the performance of the flowmeter is the amount of times that the meter is successful in taking a spot reading. This success is recorded as a % Hit Rate, the closer to 100% the better.

The raw data contained diagnostic error messages when readings were unsuccessful. The processed data assigned the unsuccessful readings a null value.

A daily 'average' of gas flow was also created during processing, which is presented as a separate datafile. This appears to be a simple average of the successful readings on that day.

It has not been possible to obtain the precise methodology of the data processing from Bartington Associates, and thus it is not known.

Unavoidable Interruptions to Gas Flow

When a wellhead is opened, for instance while recirculating leachate, some gas can exit from the cell without passing through the flowmeter. The times that wellheads are open was recorded.

Gas bypassing the flowmeter is effectively a loss of data, and could potentially create problems for data analysis; for example when conducting a carbon mass balance on a cell. However, wellheads were open for around just 1% of the time, and as such this does not represent a significant loss of data.

Maintenance

The gas flow meters were powered by two lead acid batteries. There were two sets of batteries, only one in use at one time. The depleted set was changed for the recharged set each week.

8.3.2 Gas Composition and Temperature

A self sealing port in the gas pipeline was used as a sampling point. The port is located ≈0.5m upstream of the propane injector of the gas flow meter (frame65).

The macro-constituents of the landfill gas were measured on site using a Geotechnical Instruments GA94. This device has an infra-red sensor to measure methane and carbon dioxide, and an electro-chemical sensor to measure oxygen. It also records barometric pressure and gas temperature.

Once a month, gas samples were taken in SKC Tedlar sample bags. They were filled from the exhaust port of the GA94. One bag of gas was returned to the Water and Environmental Management Unit (WEMU) laboratory for confirmatory analysis by gas chromatography. This was carried out as a matter of quality control, as the field instrument does not differentiate between methane and similar VOCs. The GC also determined levels of nitrogen.

Another bag was used to provide a gas reservoir for Dräger tube Accuro hand pump apparatus. The level of Hydrogen Sulphide in the gas was measured on site in this way. The tubes were Dräger 81 01 831 and measured in a range of 1-200ppm.

Hydrogen was measured using an add-on pod for the GA94. The pod was capable of measuring hydrogen in the range 1-1000ppm.

8.3.3 Leachate Composition and Temperature

Duplication

All leachate sampling and laboratory testing was conducted in duplicate.

Sampling

Samples of leachate were first taken on 22nd November 1995, and thereafter on a monthly basis. The samples were taken from the central well. A minimum of three 'well volumes' of leachate was purged from the well before sampling. This was done to ensure a 'fresh' sample was collected.

The samples were collected in plastic 1 litre bottles. Two litres were collected for each duplicate. Samples for volatile fatty acids were taken in additional 1litre glass bottles. Samples were stored on site and in transit, in coolboxes with 'icepaks' surrounding them. The target was to have one icepak per sample bottle.

The purged leachate was returned to the cells via the leachate recirculation pipeline in the case of Cells 1-3. Recirculation was not a treatment for Cell 4, and so the leachate was stored on the surface, and poured back down the central well after sampling had been carried out. Returning leachate to the central well was not an ideal solution in terms of obtaining a fresh sample, but appears to be the most realistic solution in terms of maintaining Cell 4 for comparison.

Initially, purging and sampling was conducted using Waterra tube pumps, which are hand operated and work on the principle of inertia. A dedicated tube pump was used for each cell. After leachate recirculation began on the 14th November 1996, the purging and sampling was carried out using the submersible pump. In practice this meant that a much larger volume was purged from the wells. For Cells 1-3 between 0.7 and 10 m^3 was pumped prior to sampling. For Cell 4, a 205 litre drum was filled before sampling.

On Site Measurements

Leachate temperature was measured as samples were taken, using a hand held electronic thermometer.

The presence of nitrate and nitrite was tested for using Merkoquant 1.10020.001 'Nitrat-Test' indicator strips. This was to confirm that nitrate was not present, as some of the early laboratory test results indicated that there was. Some oxidation of the ammonia, during sampling, transport and storage, was implicated. The sampling and transport procedures were improved and the problem did not reoccur.

Laboratory Testing

Table 8.2 shows the type of method used for each determinant. The detailed methods are mostly documented in-house modifications of published methods.

Table 8.2 Leachate Laboratory Test Methods

Determinant	Method
alkalinity	titration, range pH 4.5 - 8.3
ammonia	multiple known addition using an ammonia selective probe
Biochemical Oxygen Demand	depletion of dissolved oxygen after incubation of microbiologically seeded specimen. nitrification inhibitor used, so that only carbonaceous BOD measured.
Ca, Mg, $S0_4$, Na, K, Ni, Zn, Cu, Pb, Cd, Cr, Fe, Mn	inductively coupled plasma optical emission spectrometry
Chemical Oxygen Demand	acid digest, colourmetric measurement of unreacted reagent
chloride	quantative addition of reagents
Electrical Conductivity	conductivity probe
nitrate	multiple known addition using an ion selective probe
nitrite	spectrophotometrically after addition of reagent
ortho-phosphate	colourmetrically after addition of reagent
pH	electrochemical probe
Total Organic Carbon	infrared measurement of carbon dioxide after oxidation of organic carbon by sodium persulphate
Volatile Fatty Acids	gas chromatography

Laboratory testing was conducted by TES Bretby Ltd, a NAMAS accredited test house. The samples were transported from the site to their laboratory in Burton-on-

Trent by overnight parcel service, and were delivered to them before 10am the day following sampling.

TES Bretby state that the samples are filtered, usually on the day of arrival, and stored in a refrigerator. Apart from refrigeration, no specific sample preservation technique was used. Analysis was carried out within 10 days of receipt.

8.3.4 Leachate Recirculation

Recirculation involves pumping leachate from the base of the cell up into the top granular blanket. The process and means are discussed in detail elsewhere. Leachate recirculation began on 14th November 1996, approximately one year after the waste was placed and capped. Recirculation was conducted on a weekly, batch basis.

Volume Recirculated

The volume of leachate recirculated was determined on a duration of pumping basis. The volume of leachate recirculated was calculated, as follows. The time during which leachate was pumped is recorded. The flow output of the pump was measured regularly, using a calibrated container. From this, the total volume was found. If a significant amount of shortcircuiting, from the top blanket down the central well, had occurred an appropriate reduction was made.

8.3.5 Wastemass Temperature

Readings were taken from the temperature probes using a K-type thermocouple measuring device. These temperatures were recorded manually on a dedicated form.

8.3.6 Manual Raingauge

Two dedicated glass measuring cylinders were used to measure the water collected. They are calibrated for the diameter of the gauge and read depth of precipitation. The 10mm measuring cylinder measures to 0.1mm. The 50mm cylinder measures to 0.5mm.

A record was made of whether it was raining hard when the reading was taken, and at what time the reading was taken. This information is useful when comparing manual rain gauge data with automatic raingauge data. If the manual raingauge was not read exactly on the hour, and it was raining heavily, there will be a discrepancy, which can be eliminated with this additional information.

8.3.7 Automatic Weather Station

Data Collection

Data were collected on the first visit to site after the end of the month. A laptop PC collected the data, via a serial lead to the weather station datalogger.

Maintenance

Power was supplied from two lead acid batteries, which were replaced with a recharged set on a monthly basis.

There is a water reservoir in the temperature sensor so that relative humidity and wet bulb temperature can be measured. This reservoir was filled with distilled water on a monthly basis.

The white screen on the temperature sensor was cleaned to maintain a high albedo. The transparent plastic domes on the net radiometer were cleaned to prevent drift.

Debris in the automatic rain gauge funnel was removed.

8.3.8 Surface and Groundwater

Up and downstream surface and groundwater was monitored for a range of parameters to confirm effective containment, and to comply with licence requirements.

The results indicate that the containment was secure. Further than this, surface and groundwater data are not within the scope of this work on sustainable landfill, and therefore are not discussed in this thesis.

8.4 Leachate Recirculation Trials

Four pumping systems have been evaluated for leachate recirculation at Mid Auchencarroch. They are:

1. Vacuum tanker, $4m^3$ in volume
2. Solo II pneumatic displacement submersible pump
3. Sykes surface mounted, vacuum assisted, single stage centrifugal pump
4. Calpeda electric, multistage centrifugal, submersible pump

The vacuum tanker (frame60) proved to be unsuitable due to the high static suction head of nearly 7.5m. As a pressure vessel it was only to be operated at pressures of -0.5 bar, equating to -5m head of water. Thus it was able to operate to some extent on Cells 1 & 3, but not at all on Cell 2.

The concept of recirculation changed during the project. The original objective was to enhance degradation conditions by homogenising moisture content. It was also hoped that there may have been some transport of nutrients and microbial inoculants. The objective evolved to embrace the flushing bioreactor concept. That is leachate was to be passed through the waste at high rates in order to flush out pollutants. DoE guidelines suggested that one bed volume be recirculated within a period of one to five years (Great Britain. DoE, 1996d). The broad implications of this for the experimental cells is that at least 30 m^3 of leachate should be recirculated per month in each cell.

The vacuum tanker proved not to be suitable for recirculation on this scale.

The pneumatic displacement pump (frame61) worked satisfactorily but was too slow at 0.6 m^3/h. Had a permanent power or compressed air supply been available on site, it would have been possible to leave it running continuously, although this low rate would have had negative implications for even leachate distribution.

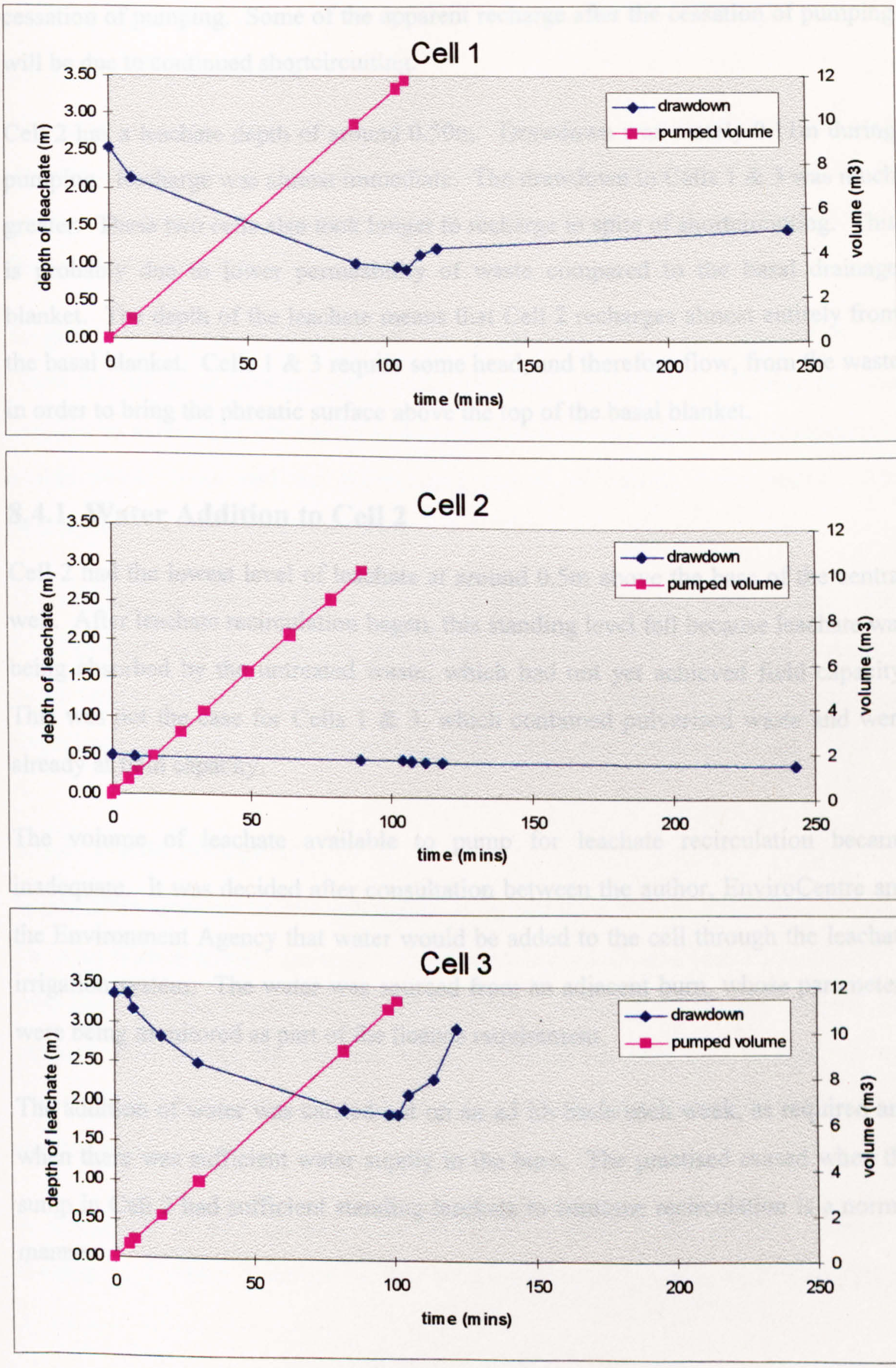
The surface mounted centrifugal pump suffered (frame62) from the same problems as the vacuum tanker, namely high suction head. This was predictable, but the plant hire company were convinced it would work and provided the pump on the basis that if it did not work, no charge would be made.

The pump would prime, then pump for a few minutes before de-priming. The de-priming was probably due to the increasing suction head as well drawdown occurred. On Cells 1 & 3 the output, when pumping, was around 11 m^3/h.

The Calpeda submersible pump (frame63) was sourced by EnviroCentre, the author providing a technical specification. The unit has an intake at the base, which was a key parameter to enable pumping from the low leachate head in Cell 2. Subsequently, a 100mm high stainless steel 'stirrup' was attached to the base of the pump (frame64), to lift the intake out of detritus at the base of the central wells.

The pump outputs around 6 - 7 m^3/h. This has proved to be a satisfactory rate for leachate to enter the central well pumping sump. Graphs showing a recirculation event are shown in Figure 8-5 below.

Figure 8-5 Leachate Recirculation Event of 14/11/96



It should be noted that Cells 1 & 3 were shortcircuiting to the central well at the cessation of pumping. Some of the apparent recharge after the cessation of pumping will be due to continued shortcircuiting.

Cell 2 has a leachate depth of around 0.50m. Drawdown was merely 0.11m during pumping. Recharge was almost immediate. The drawdown in Cells 1 & 3 was much greater. These two cells also took longer to recharge in spite of shortcircuiting. This is probably due to lower permeability of waste compared to the basal drainage blanket. The depth of the leachate means that Cell 2 recharges almost entirely from the basal blanket. Cells 1 & 3 require some head, and therefore flow, from the waste in order to bring the phreatic surface above the top of the basal blanket.

8.4.1 Water Addition to Cell 2

Cell 2 had the lowest level of leachate at around 0.5m above the base of the central well. After leachate recirculation began, this standing level fell because leachate was being absorbed by the untreated waste, which had not yet achieved field capacity. This was not the case for Cells 1 & 3, which contained pulverised waste and were already at field capacity.

The volume of leachate available to pump for leachate recirculation became inadequate. It was decided after consultation between the author, EnviroCentre and the Environment Agency that water would be added to the cell through the leachate irrigation system. The water was sourced from an adjacent burn, whose parameters were being monitored as part of the licence requirement.

The addition of water was carried out on an ad lib basis each week, as required and when there was sufficient water supply in the burn. The practised ceased when the sump in Cell 2 had sufficient standing leachate to continue recirculation is a normal manner.

8.5 Non-Routine Monitoring

8.5.1 Gas Composition

Gas composition is monitored routinely as stated above. These readings are spot samples of a potential datastream, and as such might not represent it accurately. In addition, monitoring is always conducted in the daytime, and the possibility of diurnal fluctuations exists.

To gain a better picture of the variability of gas composition and temperature, the GA94 was set up on each cell for a week's duration, logging every 20 minutes. This required an external power supply and modification of the instruments peripherals to enable power input and the temperature sensor to operate concurrently. The development of this is described in Section 7.7.2.

The logging was timed so that it was out of phase with the gas flow meters, which inject propane near the sampling port every 10 minutes. The instrument was set to pump sample gas for 90 seconds, record a reading and switch off until the next log. Experience has shown that 90 seconds is sufficient to gain a stable reading.

8.5.2 Waste Sampling

In mid 1996, after the landfill cell had been capped for 6 months, discussion between Dr Irene Watson-Craik[1], the author and EnviroCentre indicated that a set of samples from the degrading wastemass should be taken. Although no sample analysis was planned immediately, the samples would be frozen for long term storage. It was envisaged that these samples would provide a valuable baseline for future research on the degrading wastemass.

A description of how samples were recovered is given in the previous chapter in Section 7.7.3, which describes the development of waste sampling apparatus. During

---

[1] Dr Irene Watson-Craik of the Department of Bioscience and Biotechnology, University of Strathclyde. A member of the project's Scientific Advisory Group.

the sampling procedure, a number of other parameters were recorded. These were: depth to waste, depth to leachate, leachate temperature, temperature of gas 0.5m above leachate surface, and gas composition. The latter was measured with the Geotechnical Instruments GA94. The temperatures were measured using 25m borehole probe that was made in the departmental hydraulics workshop.

The size of samples that were recovered was not very large, at around 1 - 3kg. They are unlikely to be representative in terms of physical constituents of the wastemass. It is understood that they are expected to be representative in terms of microbiology and degradation dynamics.

8.6 Gas Flow Meter Testing

Towards the end of 1996, there was concern that the gas flow meters were not functioning well. In particular Cell 4 rarely recorded any gas flow, but a crude field test of holding a bin bag over the vent indicated that there was gas output.

The manufacturer of the meters was contacted on a number of occasions, their standard response being that gas flow was below the stated threshold of the meter.

Two possible situations existed:

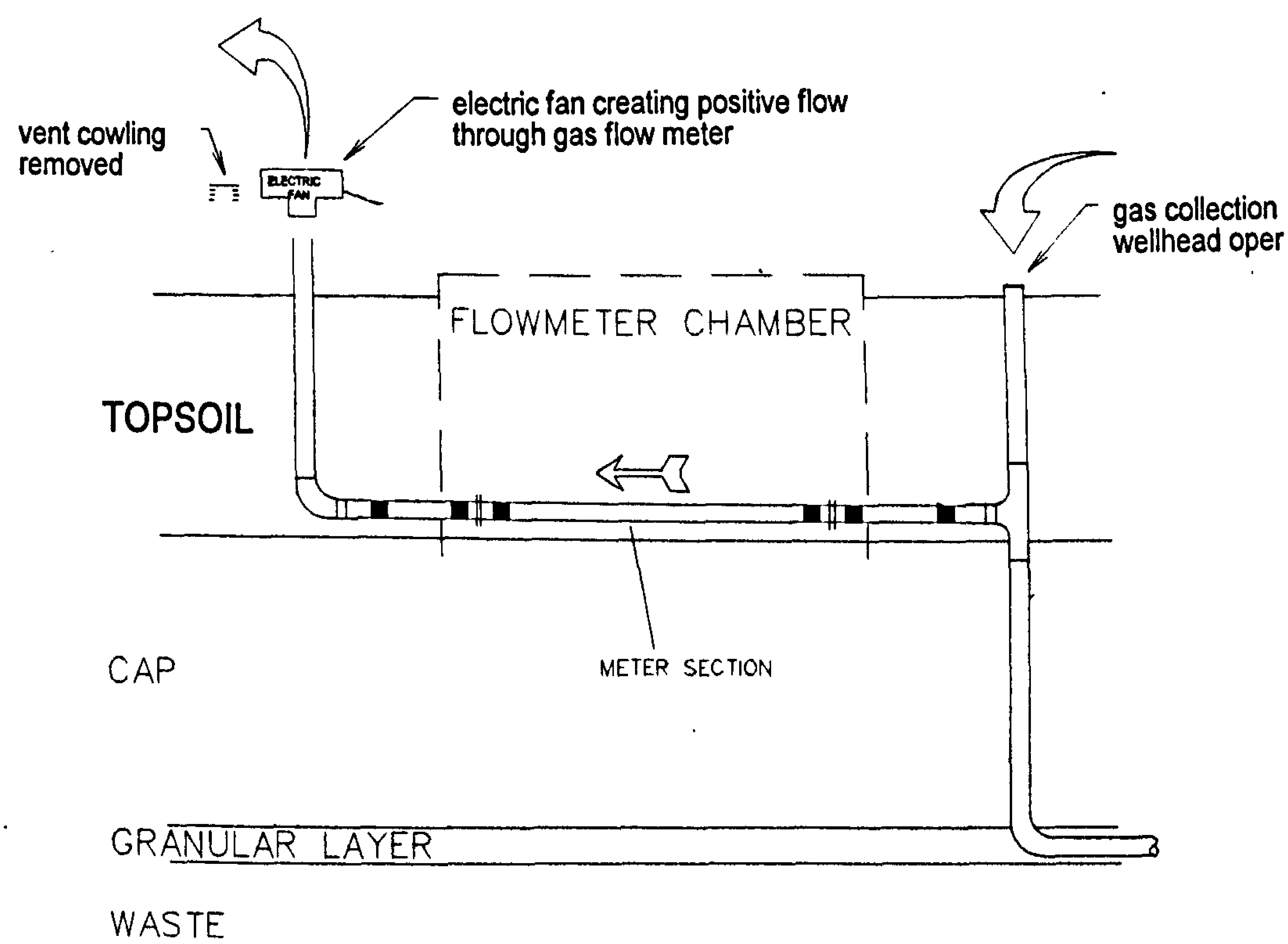
- either the gas flow meters were operating satisfactorily, and the gas output was below their threshold
- or there was a fault with gas flow meters

The former could be solved by reducing the threshold of the meter. This would be achieved by replacing the gas pipeline in the meter section, with a smaller diameter pipeline - so increasing the velocity of the gas flow. The latter situation required attention from the manufacturer.

To test which of the two hypotheses given above was correct, test apparatus was designed that would force an air flow through the flow meter to check its operation. The apparatus was made in the departmental hydraulics workshop.

The first test was conducted on 29th January 1997 (frame76), with the test set up as shown in Figure 8-6 below.

Figure 8-6 Gas Flow Meter Test Setup



This test was conducted on Cell 4 only. The test was run at various rates of flow that were within the range of the flowmeters. To manually assess the rate of flow, a crude 'bin bag' flow test was performed. This involves collecting all the exhaust gas in a bin bag held tightly over the vent. The time to fill the bag is recorded, and thus an approximate flow output established.

A further set of tests was carried out on all four cells on the 5th March 1997. This time a slightly modified method was used. The flow in the electric fan was reversed, so that it blew rather than sucked. The unit was attached to the gas collection wellhead. This set up had the advantage that a potentially explosive mixture was not being passed through a source of ignition - the fan motor. It also allowed better control of flow by controlling the fan inlet air supply. Again the tests were conducted over a range of flows within that specified by the gas flow meter manufacturer.

Both sets of tests showed that there were indeed problems with the flowmeters. As a result of the tests a maintenance visit by the manufacturer was arranged. The visit was made in June 1997.

8.7 Development of a Device to Prevent Short Circuiting of Recirculated Leachate

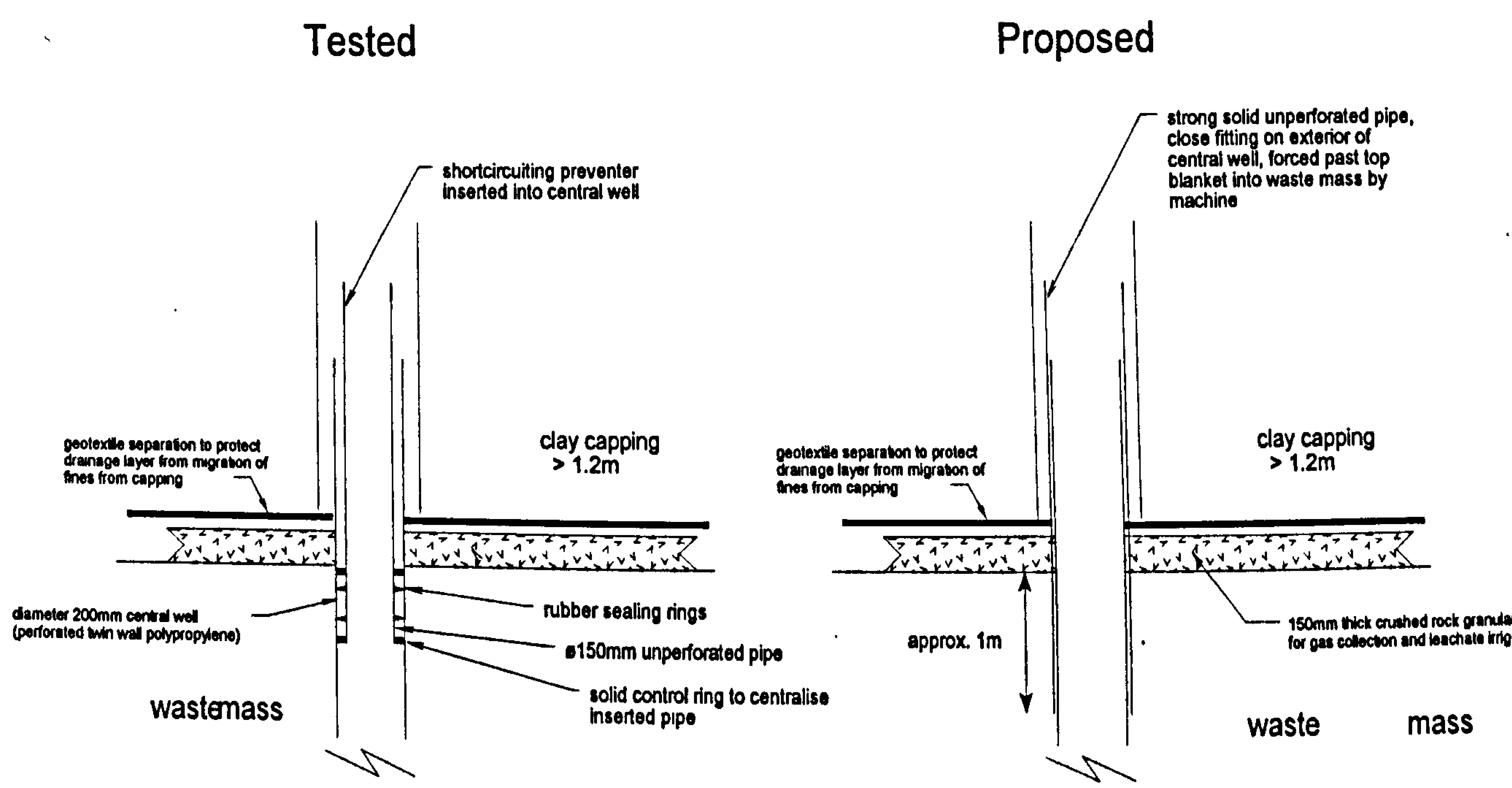
The cell design intentionally created a connection between the top blanket and the central well, as part of the gas collection system. The design failure, for which the author is responsible, was that sufficient development was not conducted to prevent the flow of leachate from the top blanket into the central well.

Soon after the leachate recirculation began in November 1996 it became clear that once about 10 m^3 of leachate had been pumped up into the top granular blanket of a cell, leachate would begin to flow from the top blanket into the central well. This leachate was 'shortcircuiting' the wastemass. Further pumping of leachate was not appropriate, as the volume of leachate passed through the wastemass was being recorded.

It was desirable to prevent shortcircuiting, so as to increase the amount of leachate that could be recirculated, and so that the whole top blanket could be surcharged with leachate, thus ensuring its good distribution. A device to prevent shortcircuiting was designed, and was fabricated in the departmental hydraulics workshop.

The device was designed to be inserted into the central well, but still allow the Ø135mm submersible pump to be installed and removed from the central well. It consisted of a unperforated tube that sealed to the interior of the perforated central well by means of sealing rings. The device is inserted down the central well until the sealing rings are below the top granular blanket. A general layout of the device is shown in the left hand half of Figure 8-7 below.

Figure 8-7 Devices for Preventing Shortcircuiting



The Mark 1 device was a rigid plastic pipe and had two sealing rings (frame74). It proved unsuccessful because the central wells tend to be distorted slightly from the vertical. This pushed the seals to one side of the well interior when the device was inserted, and so leachate could drain the other side.

The Mark 1 device was modified with a pivoting 'knuckle-joint' 1m from the base to accommodate the non-vertical central well.. The same problem was still encountered. Also the sealing rings, which were fabricated for the purpose from larger rubber rings, became unseated.

A reappraisal of the design took place and the Mark 2 device was fabricated. This used a semi-flexible pipe, Ø150mm twin wall unperforated. The flexibility of this pipe would allow for the slightly curving central well. The grooves between the ridges in the pipe exterior would provide a deeper mounting for the rubber rings. Solid plastic 'control rings' above and below the seal would keep the seal centralised in the well (frame75). Unfortunately, this device, although much more satisfactory, did not prevent the shortcircuiting.

Further Proposed Designs

A further modification was considered using an inflatable annular seal, instead of sealing rings. This would require a source of compressed gas on site, which would have to be available for several days after pumping had ceased. At the time of writing, this modification has not been taken up.

A further proposal is shown in the right hand side of the figure above. Instead of cutting off the drainage blanket on the inside of the central well, it could be cut it off on the outside. A strong solid plastic pipe would be inserted over the central well. The inside diameter of the pipe would need to be close to the outside diameter of the central well. The pipe would be forced down over the central well using the bucket of an excavator, until it had passed through the top blanket and penetrated the wastemass by approximately 1m.

8.8 Wastemass Hydraulics

The hydraulic properties of the wastemass are of crucial importance to the successful operation of the flushing bioreactor landfill. Permeability and porosity are two key factors.

Although the level of leachate in the central wells is monitored at various strategic times and the liquid inputs to a cell are known, there are insufficient data to determine permeability. A measurement of the dynamic behaviour of liquid flowing through the wastemass is required.

The rate of recharge of the central well after a leachate recirculation event was felt to be a suitable measurable parameter.

A number of constraints existed; namely that a site visit was only made once a week, and that the central well lid should not be removed for any longer than necessary, as gas flow measurements were interrupted. It was therefore clear that an automated datalogging device, that did not require the central well to be open, was required.

Orphimedes Setup

An Orphimedes[1] borehole water level recording device was used (frame77). The purchase was funded by the Department of Civil Engineering. The device was recently introduced to the UK, and some were already in use within the Department, on groundwater logging operations. It operates on the principle of displacement, measuring the pressure required to displace liquid with air, in a tube that goes to the base of the well.

A 'bubble pot' and a length of tube are submerged, the instrument remains at the top of the borehole, unsubmerged. The instrument is designed to fit down a Ø50mm monitoring well. The claimed resolution of the instrument is 1mm and the claimed accuracy 10mm.

Normally the bubble pot, which holds the submerged open end of the tube at a known elevation, is suspended from the top of the borehole. This was not appropriate in our application. The departmental hydraulics workshop fabricated a heavy brass replacement bubblepot, that would sit on the concrete base of the central well (frame78).

A schematic layout of the set up is shown in Figure 8-8 below.

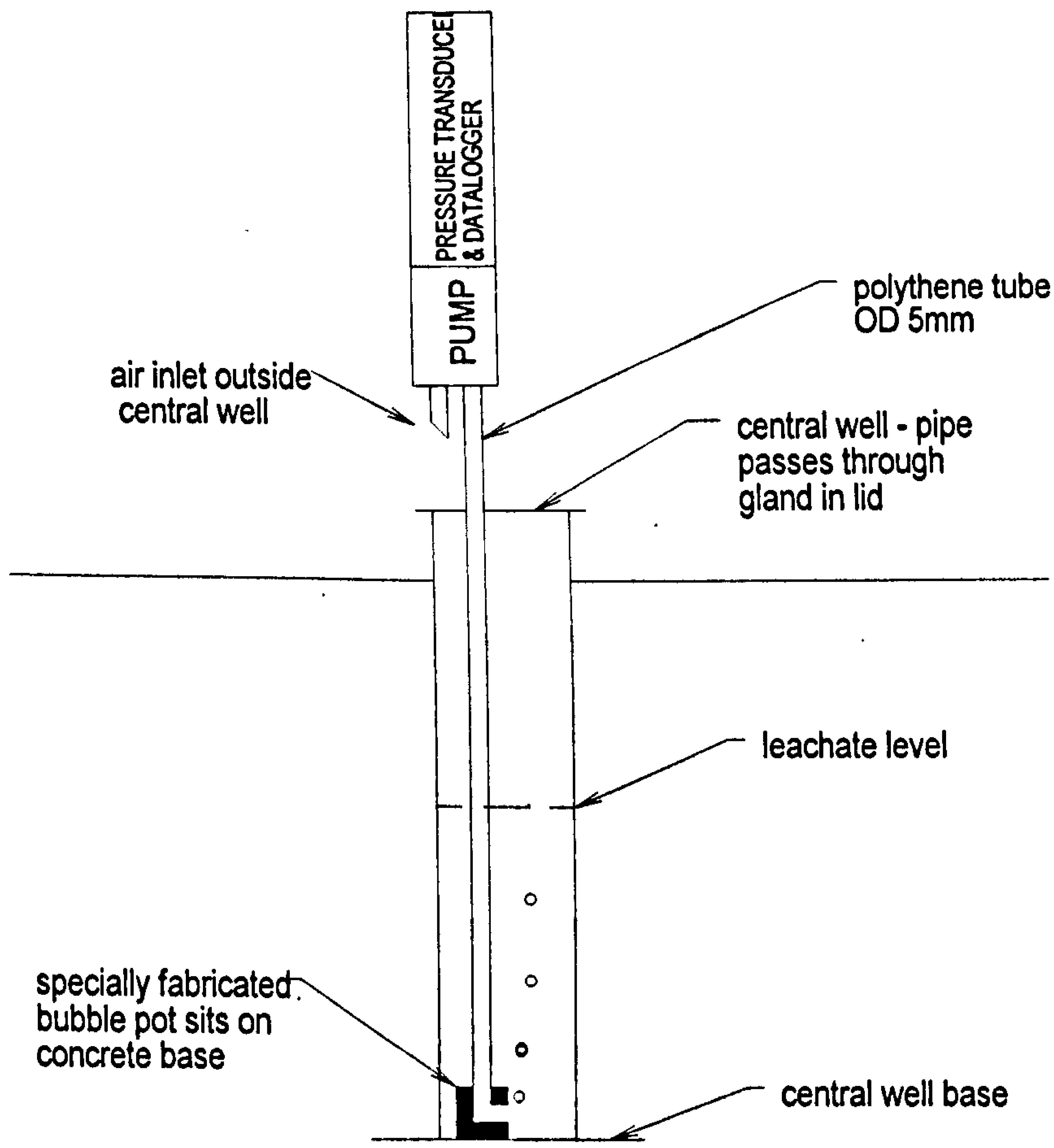
The instrument itself was not placed in the central well, as would normally be the case; this would have meant that the piston 'air' pump would have been pumping potentially corrosive landfill gas. The density of the gas may also have effected the accuracy of the readings. In addition, the integrity of the datalogger enclosure might

---

[1] UK importer: Hydrodata Services Ltd., Herts Business Centre, London Colney, AL2 1JG

have been compromised by components in the landfill gas, such as hydrogen sulphide which is able to permeate many conventional barriers.

Figure 8-8 Schematic Layout of Leachate Level Logger



For these reasons, the instrument was put in the adjacent gas flow meter chamber (frame79). The polythene pipe was run the 1 - 2m to the central well. The pipe passed through a gland in the lid, and thence to the bubblepot in the base of the well.

Measurements

Immediately after pumping for a recirculation event ceased, the submersible pump was removed from the central well. The bubble pot was then lowered to the base of the well, and a dip tone used to establish the current level of leachate. The setup and logging parameters, including the current leachate level, were entered into a laptop PC and then passed to the Orphimedes via an infrared interface. The logging rate was set to 15 minutes.

A instrument was installed on Cell 2, on a trial basis, on 22nd May 1997 for two weeks. After this, a dedicated unit was installed on Cell 1 from 31st July to 3rd September 1997, and monitored 5 recharge cycles. The unit was then moved to Cell 3 until 5th October 1997, covering another 5 cycles. However an error in the set up parameters for Cell 3 meant that only the first part of the recharge curve was recorded.

In order to collect a good dataset from Cell 3, an instrument was re-installed from 5th November to 17th December 1997. This provided only three recharge cycles, as the frequency of recirculation had been reduced to fortnightly in October 1997.

Cell Selection

Cell 1 & 3, the pulverised waste cells, are seen as the most suitable for this research. This is for the pragmatic reason that the depth of leachate is greater, and therefore a greater drawdown and recharge are experienced.

Cell 4, having no leachate recirculation, has a static leachate free surface.

Cell 2 would potentially be very interesting to compare with the pulverised waste cells, but unfortunately has a low head of leachate. This has two significant consequences. Firstly, a small range of movement, and secondly the range of movement is at a level that includes the basal drainage blanket not being fully saturated. The latter makes calculation of hydraulic parameters difficult, because both the wastemass and the drainage blanket must be considered.

Vertical and Horizontal Permeability

In the experimental set up as described above, it is hoped that data can be collected that will help to calculate wastemass permeability. The figure for permeability will be a combination of horizontal and vertical permeability, which are acknowledged to be in different orders of magnitude.

Vertical permeability will control leachate movement into the basal drainage blanket and horizontal permeability will control movement from the wastemass into the perforated central well. An experimental set up that was able to measure the isolated components would be desirable, but has not been established as yet.

9 DATA AND PRIMARY ANALYSIS

The project is data rich and it is therefore not feasible to present all raw data in hard copy. The main datasets are held in the software appendix, in Access v2.0 database format. An fuller explanation of the software appendix is given at the end of this document.

Preliminary results from this experiment have been published elsewhere (Wingfield-Hayes, Fleming and Gronow, 1997; 1998).

Table 9.1 Reminder of Treatments

Treatment	Cell 1	Cell 2	Cell 3	Cell 4
Addition of inert material	✓			
Pretreatment by wet pulverisation	✓		✓	
Recirculation of leachate; began 14 Nov 96	✓	✓	✓	

9.1 Waste Input

Pulverised waste from Cunninghame was delivered by haulage contractor, in various high capacity, articulated and rigid tippers. Untreated waste from Inverclyde was delivered in high capacity, articulated ejector vehicles, that were operated by that Council. Untreated waste from Dumbarton was delivered in the Council's waste collection vehicles.

9.1.1 Recording of Waste Consignments

Every waste consignment, that is every vehicle delivering waste to the experimental cells, was recorded, and subsequently these data were put onto a database for analysis.

Waste from both Inverclyde and Cunninghame were from multiple collection sources, mixed at the pulverisation plant/transfer station. The Dumbarton consignments were however from specific collection runs. Where this information was available it was recorded. Table 9.2 below shows the source of Dumbarton waste consignments.

The source of one third of consignments is not known. A further third is made up of waste from Helensburgh and Helensburgh shops. The balance is made up from a large number of sources, the most significant being that of the Vale of Leven at 7% by mass.

Table 9.2 Analysis of Source of Consignments for Dumbarton Waste Stream

Collection Run	no. of consign^{mt}	mass (t) by source	% mass by source
unknown	75	552.1	33.7
arrochar	6	58.1	3.5
cardross	16	64.2	3.9
clyner	1	9.7	0.6
country run	5	37.6	2.3
dumbarton	11	44.4	2.7
helensburgh	57	433.3	26.4
helensburgh shops	27	158.9	9.7
kilcreggan	5	48.4	3.0
rhu	7	63.7	3.9
roseneath	5	48.4	3.0
vale	27	115.1	7.0
vale shops	1	5.9	0.4

Weighings

A weighbridge was not operating on site at the time of the construction of the experimental cells. However it was important experimentally, to measure the mass input.

Every consignment of waste from Inverclyde and Cunninghame was weighed at source. Vehicles from Dumbarton were not all weighed, but a sample of consignments was. These weighings were conducted at local weighbridges open to the public, as the Council does operate a weighbridge.

The significance of these unweighed consignments of waste to the experiment as a whole is shown in Table 9.3 below.

Table 9.3 Significance of Unweighed Consignments

Source	% of consignments weighed	Significance of Source: Input to Experiment (t)	%
Dumbarton DC	10.7	1640	13
Inverclyde DC	100	3981	31
Cunninghame DC	100	7031	56

Note: The weighing sample rate for individual vehicles from Dumbarton was between 7.7% and 18.2%

The table shows that the Dumbarton was the smallest source of waste at 13% of the total waste input. Of this over 10% of consignments were weighed. Therefore taking the experiment as a whole over 88% of the waste input was weighed.

Mass Input

The table below shows where waste from each of the various sources was deposited.

Table 9.4 Input of Waste by Source

Source	Type of Waste	Cell 1	Cell 2	Cell 3	Cell 4
Dumbarton	untreated		816		823
Inverclyde	untreated		2168		1813
Cunninghame	pulverised	3579		3452	
Total input for each cell (t) =		3579	2984	3452	2637

The difference in total input between cells of the same waste type can be attributed to difference in volume of the cells. The larger mass input of waste in pulverised waste cells can be attributed partly to a higher density, but also to a greater mass of moisture. This is clearly shown in the following Section 9.2 Moisture Input, where comparison in carried out on a dry mass basis.

Calculation of Split Between Untreated Waste Sources

On the basis of the table above, the split of the untreated waste streams to Cells 2 and 4 was calculated.

Table 9.5 Untreated Stream - Split Between Sources

	Cell 2	Cell 4	Both
Dumbarton	27.4%	31.2%	29.2%
Inverclyde	72.6%	68.8%	70.8%

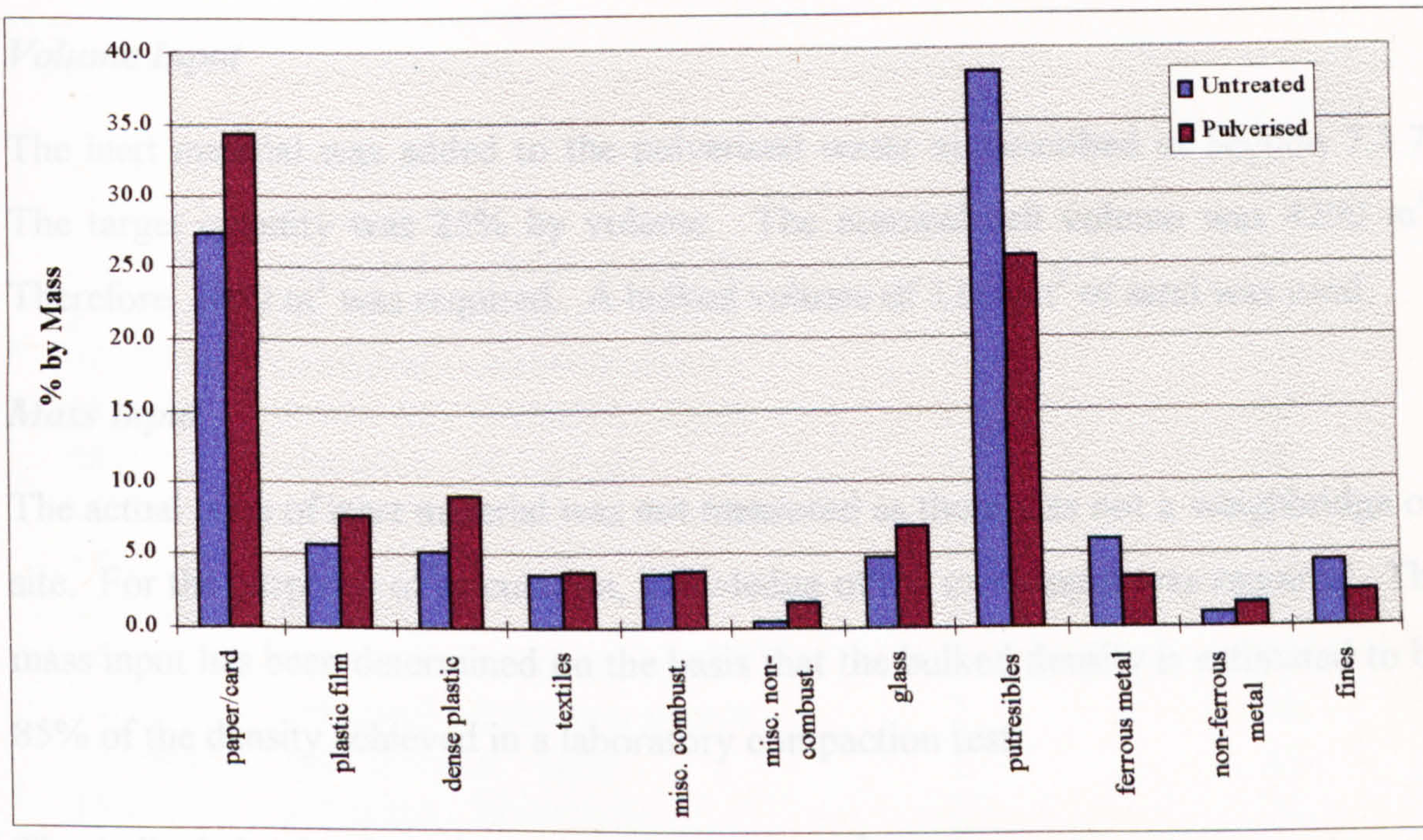
The figures show that the split between the two sources of untreated waste was fairly close. In terms of mass, as shown in Table 9.4, the split of Dumbarton waste was almost exactly to the tonne, however the larger cell meant more Inverclyde waste was required to fill it. At the filling stage, the volumes had not been calculated in the MOSS digital terrain model.

9.1.2 Weighted Characterisation Analysis

Characterisation of each of the three waste streams is described in Section 6.7. After filling was complete, data were available to calculate the appropriate weightings for a comparison of untreated and pulverised waste streams. The weightings are calculated on the basis of the split as shown in the figure for both cells in Table 9.5.

During the pulverisation process an overdrum magnet recovers ferrous metal from the output conveyor. The plant manager, estimates that the removal efficiency is around 60%. Therefore the characterisation shown below reflects this, and the quantity of ferrous metal is 40% of the mass recorded in the characterisation.

Figure 9-1 Comparison of Untreated and Pulverised Waste Streams



The graph shows the characterisation of the raw waste streams in the proportions that they were received at site. The untreated waste stream has a significantly greater mass of putrescible fraction. This was to be expected from the results shown in Section 6.7. The untreated waste also contains a greater quantity of fines, and ferrous metal. The increased putresible, ferrous metal and fines fractions in the untreated waste is offset by larger paper, plastics, glass and ferrous metal fraction in the pulverised waste streams.

It should be stressed here that the comparison in being made between the untreated waste stream and the pulverised waste stream **prior to pulverisation**. The comparison is for the purposes of determining equality of feedstock for microbial degradation in the landfill. It is conducted prior to pulverisation, as after pulverisation, the same material is present, but in a mainly unrecognisable state.

9.1.3 Inert Material

Volume Input

The inert material was added to the pulverised waste as described in Section 7.3.7. The target quantity was 25% by volume. The nominal cell volume was 4200 m^3. Therefore, 1050 m^3 was required. A bulked volume of 1134 m^3 of sand was used.

Mass Input

The actual mass of inert material was not measured as there was not a weighbridge on site. For the purposes of calculation, knowledge of the mass input was required. The mass input has been determined on the basis that the bulked density is estimated to be 85% of the density achieved in a laboratory compaction test[1].

The bulked density is estimated to be 1.50 t/m^3, and therefore the mass input is calculated as 1696 tonnes.

9.2 Moisture Input

9.2.1 Moisture Content of Waste Stream

Sampling and Testing

Bulk samples of waste were taken from consignments immediately after they were deposited in the cells. The moisture content was determined, using a method of oven drying at 105°C. The method used is based on BS 1377: Part 2: 1990, Method 3. This is a soils test specification. The oven temperature would be better a little lower, as plastic in the waste tends to partially melt, particularly that in contact with the metal sample container. The author is not aware of any established test methods specifically for waste samples.

[1] 1 litre mould using 2.5kg rammer, as described in Section 6.7.5.

Table 9.6 Moisture Content Analysis on Incoming Waste Streams

Sample Date	Type of Waste	Destination Cell	Moisture Content (% dry mass)
31/08/95	pulverised	3	48
31/08/95	pulverised	3	79
31/08/95	untreated - unknown source	4	38
31/08/95	untreated - unknown source	4	44
08/09/95	untreated - unknown source	4	66
08/09/95	untreated - unknown source	2	32
08/09/95	untreated - Inverclyde	2	28
08/09/95	untreated - unknown source	4	63
14/09/95	pulverised	1	80
14/09/95	pulverised	1	54
14/09/95	untreated - unknown source	2	33
14/09/95	untreated - unknown source	2	48
18/09/95	inert material - sand	1	13
18/09/95	untreated - Inverclyde	2	31
18/09/95	untreated - Inverclyde	2	34
18/09/95	untreated - Dumbarton	4	111
22/09/95	pulverised	1	75
22/09/95	untreated - Dumbarton	2	13
22/09/95	untreated - bag of kitchen waste	2	108
stored sample	inert material - sand	1	13
stored sample	inert material - sand	1	14

Obtaining a representative sample of material as diverse as waste is not easy. It is easier in the pulverised waste than the untreated waste. Sample size varied. Normally one large bulk sample, amounting to about 6kg dry mass, was taken. This was augmented by a number of smaller samples of around 2kg dry mass. The main reason for only one large sample being taken was the limitation of oven space.

The one intentionally unrepresentative sample, a plastic carrier bag of kitchen waste shows that there is a great heterogeneity of moisture content between elements of the waste stream. In retrospect, it would have been useful to have carried out moisture content analysis on individual categories of waste as part of the characterisation process.

Analysis of Moisture Content Data

Table 9.7 Summary of Moisture Content Analysis

	Untreated waste				Pulverised waste	Sand
	dumbarton	inverclyde	unknown	all untreated	cunninghame	(inert)
moisture content	62	31	46	45	67	13
no. of determ.	2	3	7	12	5	3
range	98.0	6.8	33.9	98.0	31.7	1.6
standard dev.	69.3	3.4	13.7	25.5	15.0	0.92

Figures for the Sand are included in the table for completeness, as it is part of the waste input for Cell 1. The statistics show what we may expect for a homogeneous material.

As far as the waste streams are concerned, surprisingly the samples of Inverclyde waste show a smaller range and standard deviation, than the pulverised waste, which one would expect to be homogenised to a greater extent. This is on the basis of only three Inverclyde samples so the small range may be a coincidence. Likewise the very large range of the two Dumbarton samples.

The high range and standard deviation of the Dumbarton samples, increases both the range and standard deviation of the 'all untreated' figure. The other figures that contribute to the 'all untreated' figures are fairly similar to those for pulverised waste. Therefore, but for the Dumbarton figures, which may be statistical outliers, the statistical distribution of data from both pulverised and untreated streams is similar.

The statistical calculations to achieve the figures for 'all untreated', are not weighted for the uneven split between mass input from Dumbarton and Inverclyde.

The key data that emerges are that average moisture contents (dry mass basis) for :

pulverised waste = **67%**

untreated waste = **45%**

The elevated moisture content of the pulverised waste is to be expected. In fact the elevation is a little less than calculations predict:

1. During pulverisation, around 225 litres of water are added per tonne of waste.
2. Assumption: the incoming untreated waste at Cunninghame has a moisture content of 45%
3. Consider 1000kg of untreated waste. At 45% moisture content, the waste comprises 310kg of moisture, and 690kg of dry matter. If 225kg of water is added, there is a total of 535kg of moisture.
4. Therefore the predicted moisture content is **78%**

There are a number of reasons that the actual moisture content is lower than that predicted. Evaporation is perhaps the main reason. During the process, the tumbling action exposes a large surface area of the waste to air. Again during storage (up to 2-3 days in late summer) and transit (netted tipper), further opportunities for evaporation exist. Moisture loss by evaporation is probably enhanced in pulverised waste that is stored for any more than a few hours, because aerobic microbial activity becomes established fast, resulting in temperature elevation.

The other reason is that the Cunninghame untreated waste stream probably has a lower initial moisture content. This prognosis is supported by the characterisation data[1], which show that the Cunninghame waste stream has a smaller putrescible fraction (high moisture content), and a larger paper/card fraction (lower m.c.).

[1] see Section 6.7

9.2.2 Additional Water Input Prior to Capping

There are several other sources of moisture input to the experimental cells apart from the waste stream. Precipitation is the main one. The weather conditions during the time between excavating a cell and beginning to fill a cell were sufficiently good that there was no standing water in any of them. When cell filling began, a layer of waste was put in the base of the cell as quickly as possible so that any precipitation would have an opportunity to be absorbed, rather than just sit in the basal drainage blanket.

Pre-construction water balance calculations[1] had shown that there would be no free leachate generated. While experienced showed that free leachate is nearly always generated, there was concern that the quantity would be insufficient to provide a significant reservoir for recirculation. To ameliorate this situation, water was pumped from an adjacent burn onto the top of the waste, prior to capping.

The situation at the time of capping is given in the table below.

Table 9.8 Additional Moisture to Each Cell

	Cell 1	Cell 2	Cell 3	Cell 4	Comments
Filling Commence Date	01/08/95	07/08/95	09/08/95	23/08/95	
Capping Date	17/10/95	19/10/95	13/10/95	08/11/95	
Total Precipitation (mm)	271	270	230	365	
Evaporation (mm)	0	0	0	0	assumpt.
'Additive Precip.' (mm)	271	270	230	365	
Cell Plan Area (m2)	899	899	899	899	nom.29x31m
Addit. Precip. Input (m3)	243	243	206	328	
Water pumped on cell (m3)	21	76	24	0	
Total Add. Moisture (m3)	264	319	230	328	

Note: The term 'additive precipitation' is used to mean the total precipitation minus evaporation losses. It is the amount of precipitation available for infiltration into the wastemass.

[1] as per Waste Management Paper 26D (Great Britain. DoE, 1996), process described in Section 6.5.5

Evaporation

Evaporation has been assumed to be zero while the cell were open, with the implication that all precipitation was available for infiltration. It had been hoped that a calculation of potential evaporation could have been made using weather station data. Delays in delivery and commissioning of the automatic weather station (AWS) meant that this data are not available.

Factors that support the use of a zero evaporation figure:

- Subsequent AWS data have shown the site experiences high relative humidities.
- Infiltration of rainfall is fairly rapid on the open waste surface, and percolation down through the waste profile will move water away from the location of evaporation quickly.
- Once the MSW has been bladed out, and the bin bags opened, the albedo of the open waste surface is quite high.
- The plastic waste tends to be orientated horizontally by the blading action. This has the effect of covering a significant proportion of the surface with an impermeable layer.
- The length of time between starting to fill the cells and capping was relatively short.

Factors that deny the use of a zero evaporation figure:

- The top of wastemass is subject to aerobic degradation, which being exothermic will increase the temperature of that part of the waste and therefore increase the evaporation.
- The site is quite windy.
- The late summer of 1995 was unusually dry and sunny.
- Permeable elements of the wastemass, such as paper, may 'transpire' moisture[1].

Quantification of these factors and their effects is not straightforward and has not been carried out to date. It would be interesting in terms of further research, to develop a relationship between evaporation from the waste surface and climatological parameter, and thus calibrate for instance, one of the Penman models. However, this

[1] This concept developed in Section 5.3.4

is outwith the scope of this project. For the purposes of this project 'engineering judgement' has been used to make the assumption that evaporation is not significant in terms of the total amount of moisture in a cell.

Surface Runoff

There was no surface runoff outwith the cells. Site observations show that the infiltration rate was not exceeded by the precipitation rate. Had runoff occurred it would have been contained by the cell wall.

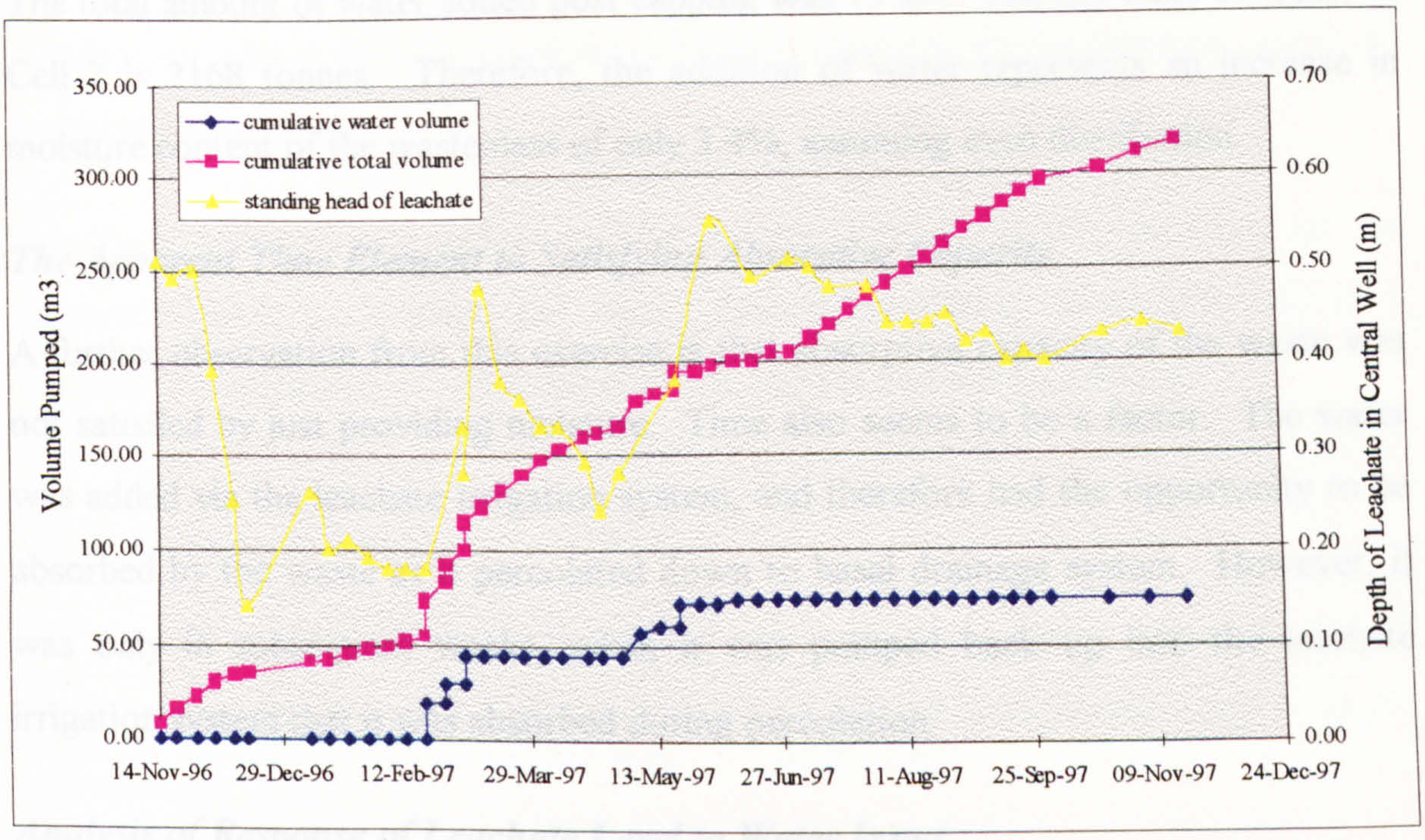
Water Pumped onto Cells

Cell 2 had the largest quantity of water pumped onto it, as there was most concern about this cell, Cell 1 & 3 having higher moisture content pulverised waste. Cell 4 was capped a little later and required no additional pumped water, as further precipitation had made up for any shortfall.

9.2.3 Water Addition Post Capping

Soon after leachate recirculation began in November 1995, it became clear that there was insufficient free leachate in Cell 2 to continue recirculation. The deficit in leachate was being caused because the absorptive capacity of the untreated waste was not satisfied. It was decided to add water to the cell on an ad-hoc basis until the absorptive capacity was satisfied, and there was sufficient free leachate to continue recirculation as normal. Water was pumped from an adjacent burn into the leachate recirculation system.

Figure 9-2 Effect of Water Addition and Leachate Recirculation on Standing Leachate Head in Cell 2



From the graph above, it can be seen that at commencement of leachate recirculation, the standing leachate level was 0.5m, as depicted by the yellow line. Soon after this the level fell dramatically to a pessimum in the middle of December 1996. The rate of recirculation was moderated, as shown by a lower gradient in the cumulative total volume (the magenta line), and the level then recovered a little, before dropping again.

The first batch of water addition , at the end of February and beginning of March 1997 (shown by the first steps in the blue line), increased the level to just below 0.5m. The rate of recirculation was stepped back up again to around 7m^3 per weekly event. This resulted in a fall in level again to 0.25m at the end of April 1997. A further batch of water addition was undertaken, which increased the standing level to 0.55m. With subsequent recirculation, the standing head fell a little but has stabilised at around 0.45m, the absorptive capacity of the waste apparently satisfied.

Increase in Moisture Content

The total amount of water added post capping was 73 m^3. The dry mass of waste in Cell 2 is 2168 tonnes. Therefore, the addition of water represents an increase in moisture content of the wastemass of only 3.4%, assuming even distribution.

The Apparent Time Element to Satisfying Absorptive Capacity

A further observation from this exercise is that absorptive capacity of the waste was not satisfied by just providing moisture. Time also seems to be a factor. The water was added via the leachate irrigation system, and therefore had the opportunity to be absorbed by the waste as it percolated down to basal drainage system. However, it was only in subsequent weeks, when it was pumped back up into the leachate irrigation system that it was absorbed during percolation.

Analysis of Response of Leachate Level to Water Input

Analysis of the response of leachate level to water input could potentially provide information on permeability and porosity of the wastemass. Unfortunately, an automated level logging device was not available at that time, and the frequency of information collection was not sufficient to provide enough data to calculate permeability.

However, the real impediment to meaningful analysis of the Cell 2 leachate level / input relationship is that the standing level of leachate is sufficiently low that the basal drainage blanket is not completely saturated. This has been established by looking at data in the MOSS digital terrain model, and relating it to the Reduced Level of the leachate surface. The problem with the basal drainage layer not being completely saturated with leachate is:

1. The hydraulic characteristics (permeability and porosity) of the granular drainage blanket and the wastemass are quite different; both parameters probably by orders of magnitude.

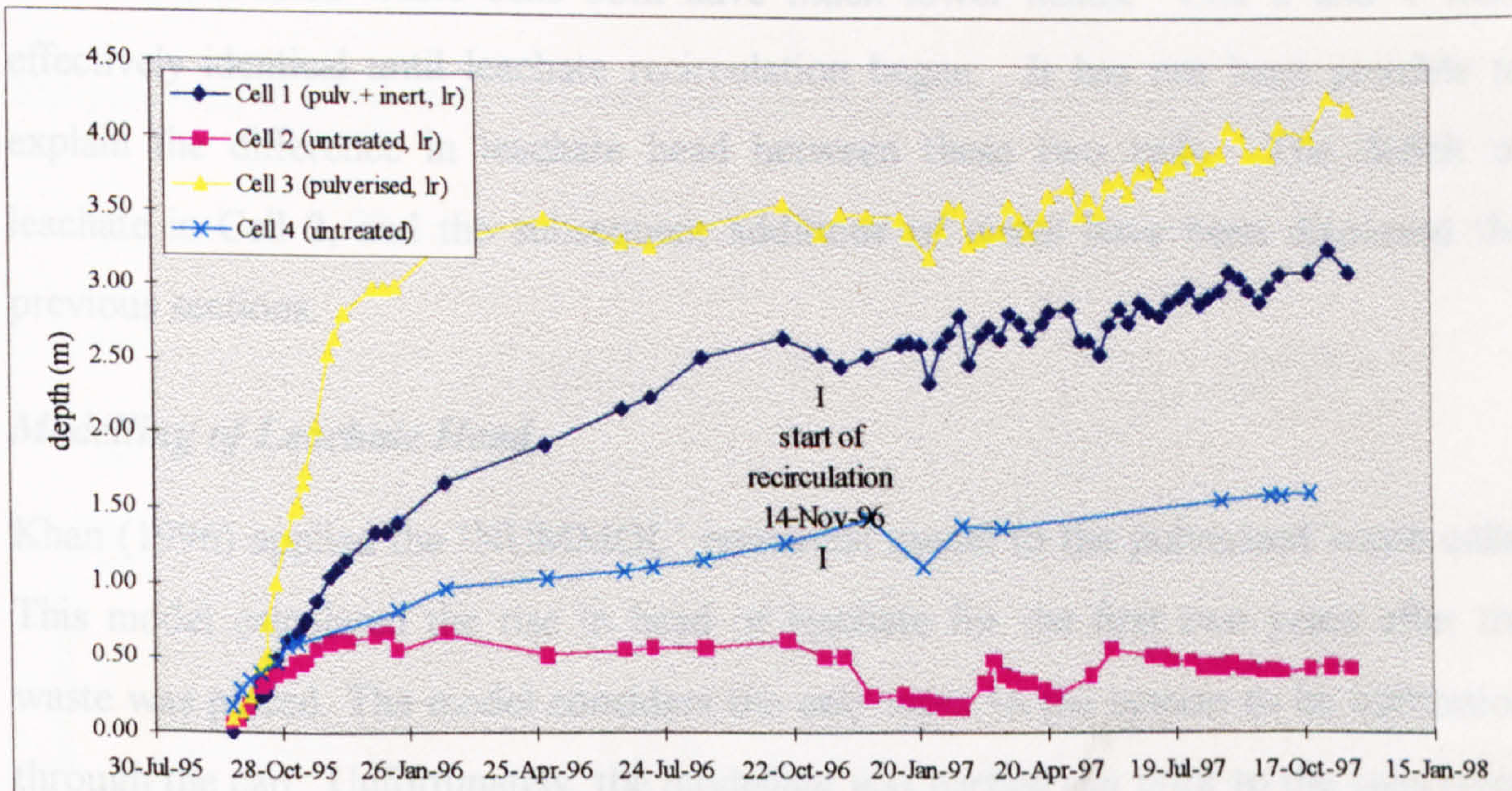
2. The interface between the wastemass and the drainage blanket is sloping, at a fall parallel to the base of the cell. The location of the interface was established in a relatively coarse fashion (compared to the thickness of the blanket), prior to placement of waste.

Therefore, without information on the precise location of the interface of the unsaturated drainage blanket, the results from a calculation of porosity will be a combination of the properties of the drainage blanket and the wastemass.

9.2.4 Leachate Level

The standing level of leachate in the central well is shown in Figure 9-3 below. There are fewer determinations for Cell 4, because the wellhead is not opened each week for recirculation.

Figure 9-3 Leachate level in Central Well



Note: 1. Prior to start of recircualtion, pumping trial on Cells 1 & 3 on 11-13 Sept 96
2. Water addition to Cell 2 in February and April 97

The extent of the saturated zone in the two pulverised cells is great. It was expected that after an initial rise the level would stabilise, free leachate having drained from the wastemass. This appeared to have occurred around July/August'96. However later in the year towards winter, and after leachate recirculation had begun, the head began a further steady increase.

The reasons why the head is still increasing could be:

- drainage from the wastemass still occurring, due to low permeability
- consolidation from overburden, reducing porosity
- ingress of groundwater

Groundwater ingress is not implicated on any significant scale because the level of leachate is at or above the level of surrounding groundwater, although the latter is not monitored. Secondly, the concentration of chloride in the leachate is constant. This indicates that dilution of the leachate is not occurring. A combination of the first two points is probably the cause, although the small amount of recorded settlement indicates that consolidation is not great.

The two untreated waste cells both have much lower heads. Cell 2 and 4 were effectively identical until leachate recirculation began. It has not been possible to explain the difference in leachate head between these two cells. The deficit of leachate in Cell 2, and the subsequent additions of water have been discussed the previous sections.

Modelling of Leachate Head

Khan (1996) applied the 'NUMMOL' numerical model to the pulverised waste cells. This model calculated the rise in head of leachate for the first two years after the waste was placed. The model considers the only input to the system to be infiltration through the cap. Unfortunately, the modelling was carried out prior to the cells being constructed, so many of the meteorological and waste parameters had to be estimated. In particular the density of waste was underestimated. The results indicate that after two years, a rise in leachate head of around 0.2m should have been expected from infiltration.

9.3 Leachate Recirculation

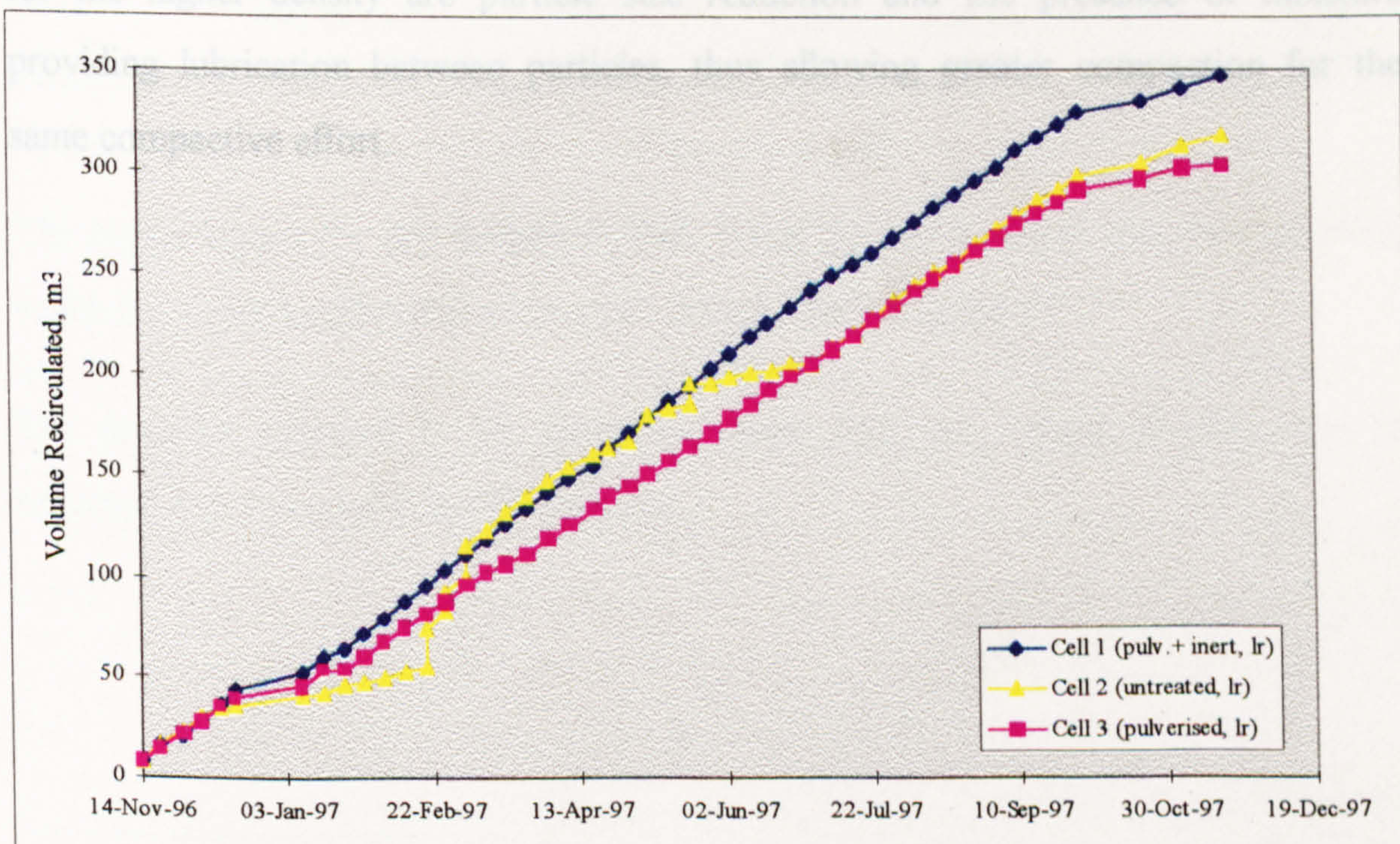
Leachate recirculation began on 14th November 1996. Each pumping event has been individually calculated. The actual pumped volume of an event has been modified by setting a ceiling value, so that overpumping which results in shortcircuiting down the central well is not counted as recirculation of leachate through the wastemass. The ceiling values for each cell have been set by assessing the values which result in shortcircuiting - the occurrence of which is a parameter that is recorded on site.

Table 9.9 Corrected Total Recirculation Values to end of November'97

	Cell 1	Cell 2	Cell 3
Ceiling Recirc. Volume per event, m^3	8	8	7
Total Leachate Recirculated, m^3	346	243	307
Water added post capping, m^3	0	73	0
Total Volume, m^3	346	316	307

The progression of leachate recirculation is shown in the following graph

Figure 9-4 Cumulative Recirculated Volume



Both Cells 1 & 3 show a fairly steady rise. Cell 2 is more variable, due to the deficit of leachate and the subsequent additions of water.

9.4 Waste Density

Density of the wastemass was measured on a whole cell basis and by in situ density tests.

9.4.1 Whole Cell Density

The total wet mass was determined from waste input data as given in Section 9.1. The mass of moisture and dry mass of waste was calculated using moisture content data, given in Table 9.7. The volume of the cells was calculated using MOSS digital modelling as described in Section 7.5. Table 9.10 below shows how the whole cell density was calculated.

As would be expected the pulverised waste cells have a higher wet density. However, they also have a higher dry density, which indicates that the elevated wet density cannot be attributed just to a greater mass of moisture. The most plausible reasons for the higher density are particle size reduction and the presence of moisture providing lubrication between particles, thus allowing greater compaction for the same compactive effort.

Table 9.10 Whole Cell Waste Density Calculation

source		Cell 1 pulv + inert	Cell 2 untreated	Cell 3 pulv	Cell 4 untreated
dumbarton	wet mass t		816		823
	mcd %		62		62
	dry mass t		503		507
	mass of moisture t		313		316
inverclyde	wet mass t		2168		1813
	mcd %		31		31
	dry mass t		1655		1384
	mass of moisture t		513		429
cunninghame	wet mass t	3579		3452	
	mcd %	67		67	
	dry mass t	2140		2064	
	mass of moisture t	1439		1388	
sand	wet mass t	1696			
	mcd %	13			
	dry mass t	1501			
	mass of moisture t	195			
	total dry mass t	3642	2158	2064	1892
	mass of moisture t	1634	827	1388	745
	volume of cell m3	4440	4022	3357	3633
	wet density t/m3	**1.19**	**0.74**	**1.03**	**0.73**
	dry density t/m3	**0.82**	**0.54**	**0.61**	**0.52**

The higher figure for dry density in Cell 1 can be attributed to the inert material, which has a dry density of in excess of 1.5 t/m^3 when compacted[1].

The densities achieved in the untreated waste cells are typical of what may be expected in conventional landfill practice.

[1] see Section 6.7.5

9.4.2 In Situ Density Tests

In situ density tests were conducted in the top of the final lift of waste in each cell. Moisture content determinations were not carried out on the waste excavated, and therefore the whole cell average moisture content has been used in calculations.

Table 9.11 Waste In Situ Density Tests

	Cell 1 pulv + inert	Cell 2 untreated	Cell 3 pulv	Cell 4 untreated
mass of waste removed, kg	1059	776	1185	735
mass of water to fill void, kg	1109	1175	1027	1285
volume of void, m^3	1.109	1.175	1.027	1.285
wet density, t/m^3	**0.95**	**0.66**	**1.15**	**0.57**
assumed moisture content[1], %	67	45	67	45
dry mass of waste removed, kg	634	535	710	507
dry density , t/m^3	**0.57**	**0.46**	**0.69**	**0.39**

The in situ density tests show the same trend of greater density in the pulverised cells. However, Cell 3 has a higher density than Cell 1, which was not expected. There is no obvious reason to explain this difference, and it may be rogue value, given that the density is higher than the whole cell value. It is perhaps an indication that a single test of each cell is insufficient to gain a reliable value. This was realised prior to the tests being conducted, and it would have been desirable to have conducted at least three tests on each cell. However, in the one day allocated to the exercise, it was possible for the five personnel and three machines to carry out only a single test on each of the four cells. In addition, difficulty was experienced while conducting the test in excavating a discrete hole in the waste, and this inevitably led to some experimental error.

[1] from Table 9.7

9.4.3 Comparison of Density Measurements

The key fact that may be drawn from comparing the two measurements of density on each cell, is that the density of the upper part of the wastemass is significantly less than the cell average. The implication of this is that the density of the lower part of the wastemass is significantly greater than the average. This would be expected due to the effect of overburden on the base of the wastemass. However, higher densities than the values established for the pulverised waste cells in whole cell tests, will have significant negative implications for permeability.

9.5 Wastemass Temperature

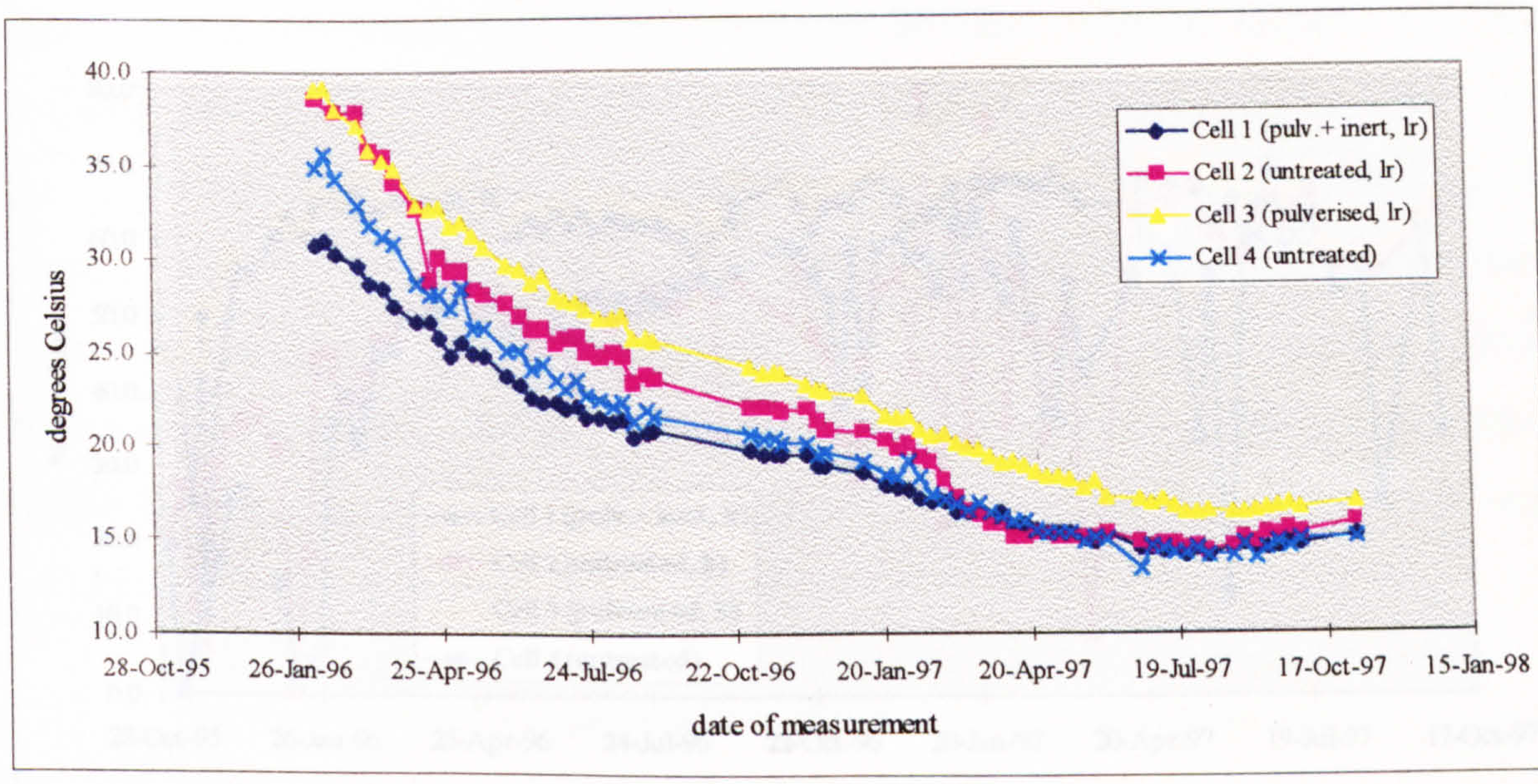
Wastemass temperatures reveal that the general trend of temperature is downwards, but levelling out, as shown in the figure below. One or two readings are out of trend. These should be ignored. A low battery in the reading device appears to adversely affect accuracy.

The probes are at nominal depths of 3.35m, 4.40m, and 5.75m below the topsoiled surface of the cell. The data presented are for the middle thermocouple of the centre temperature probe. This is likely to be the hottest area in the wastemass, which is confirmed by the thermocouple readings.

All four cells are broadly the same temperature, and have fallen to a plateau just above ambient. This indicates that ambient conditions dictate temperature in this shallow wastemass rather than any of the manipulations applied.

Cell 1 appears to be the coolest of all the cells; it was filled first and had the bottom 2m turned over to mix in the inert material soon after the waste was placed. This may have led to some heat loss, but as more air would have been introduced it may be expected that the exothermic consumption of the trapped air would have offset this. Cell 3 is shown to be the warmest marginally. Cell 2 shows a temperature drop in February'97 which could be associated with the addition of water, whose temperature was around 5°C.

Figure 9-5 Temperature - Centre of Wastemass



There was initially a considerable spread in the three temperatures on each probe. The temperatures of the three thermocouples on a probe have now converged to the point where the spread is negligible.

For all cells, the outer probe tends to be 2 - 3°C lower than the inner probe.

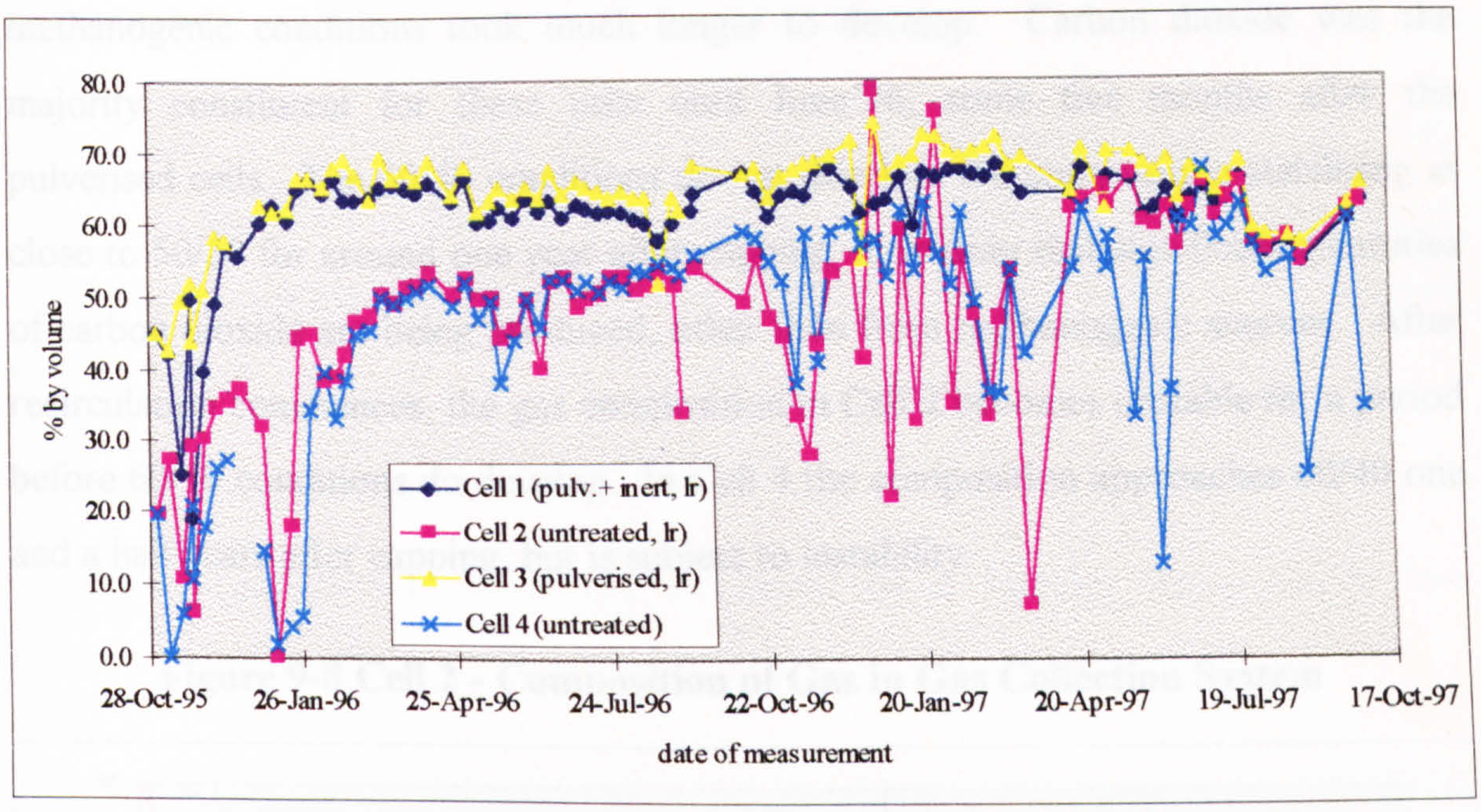
Of the three thermocouples on each probe, the top one is the coolest in all cells. There appears to be a tendency for the bottom thermocouple to be warmest on the outer probe, with the middle thermocouple being warmest on the inner probe.

9.6 Gas Composition

9.6.1 Weekly Measurements

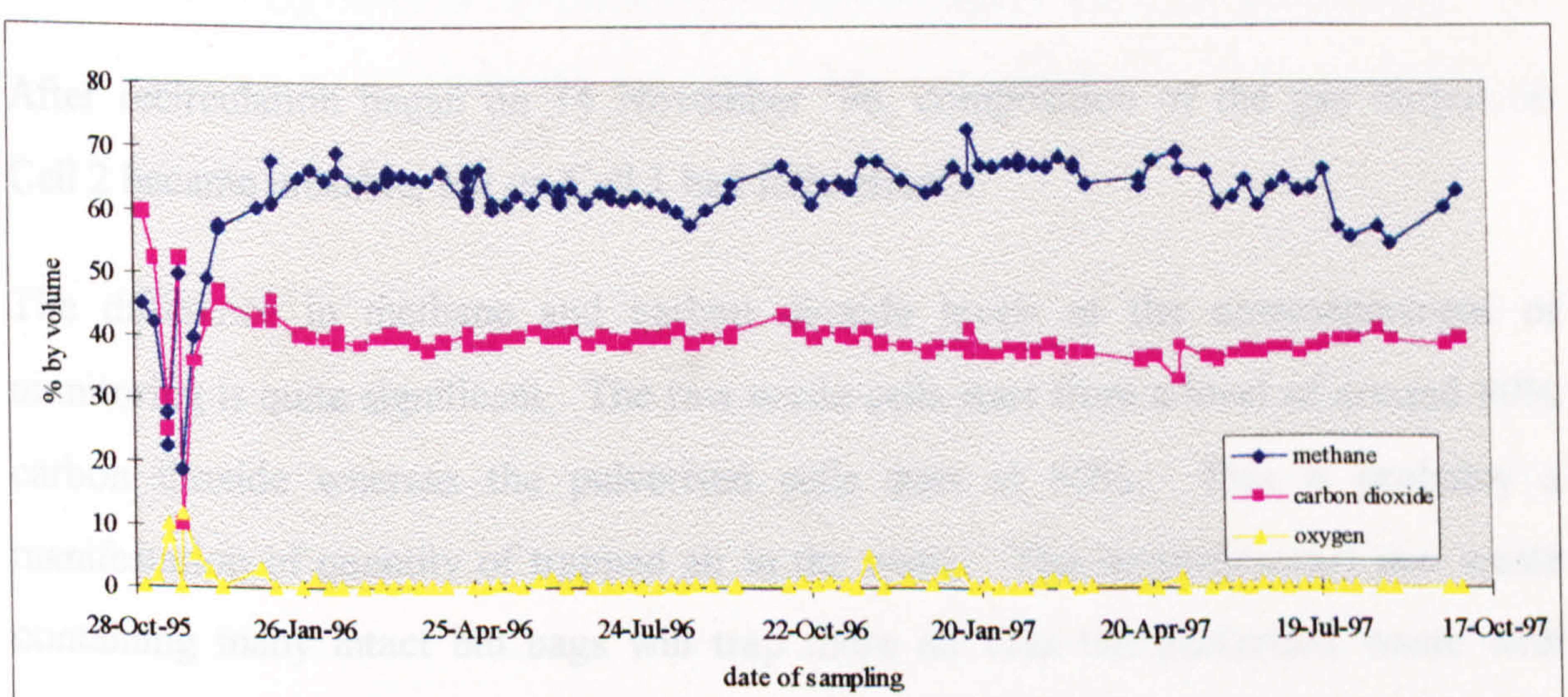
The methane concentration for all four cells is shown in the figure below. The two pulverised waste cells establish a high and steady level of methane output in a matter of weeks, whereas the two untreated cells progress much more slowly. The stability of gas composition is also shown to be poorer in the untreated cells.

Figure 9-6 Methane Concentration in Gas Collection System



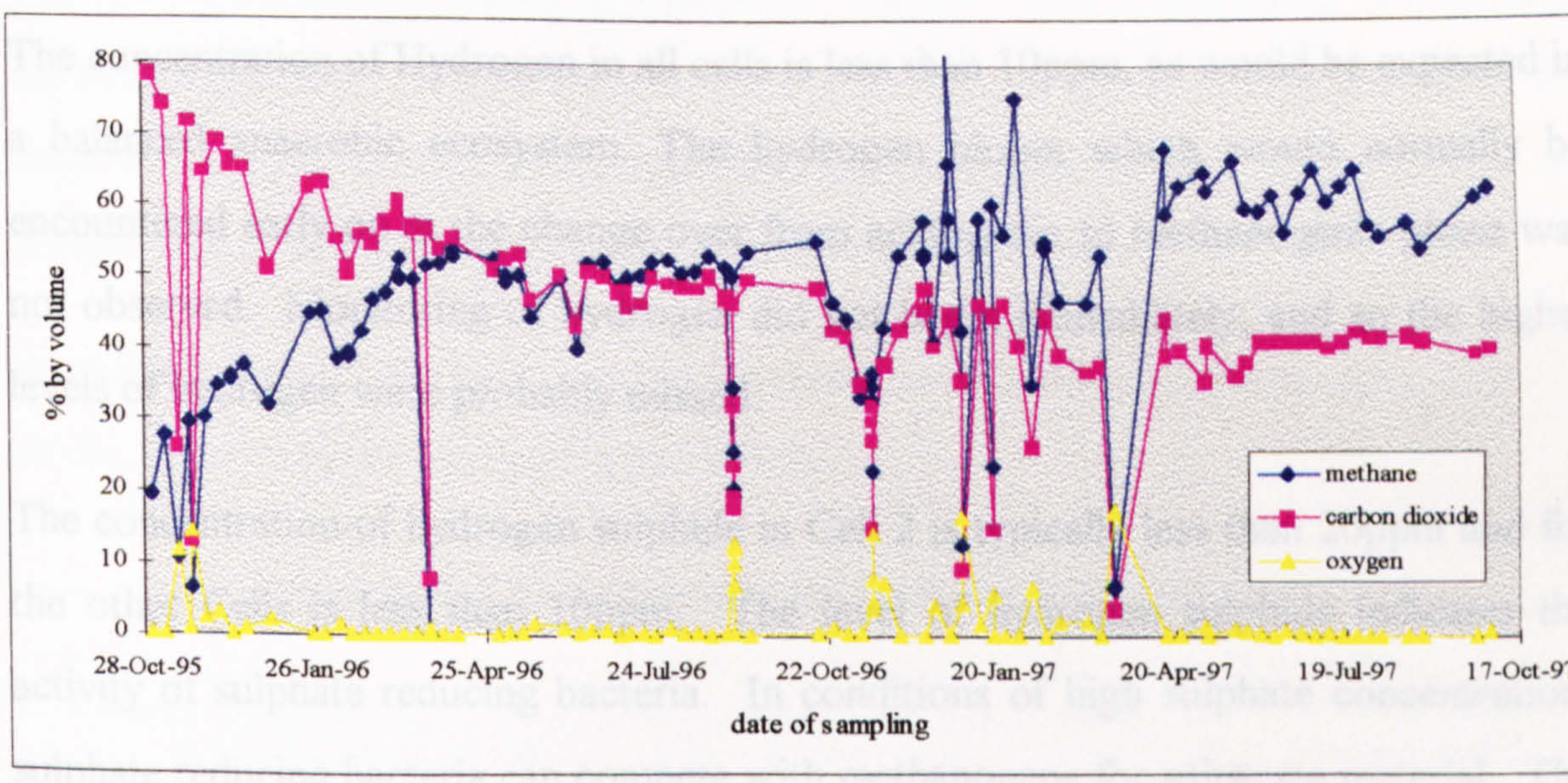
The pulverised cells, exemplified by Cell 1 in Figure 9-7 below, shows that they became methanogenic rapidly changing over from a majority of carbon dioxide to a majority of methane around the end of November'95, only a few weeks after capping. They continue to develop to what is taken to be full methanogenic conditions of around 60% methane and 40% carbon dioxide. This remains steady from January'96 onwards.

Figure 9-7 Cell 1 - Composition of Gas in Gas Collection System



The untreated waste cells, exemplified by Cell 2 in Figure 9-8 below, show that methanogenic conditions took much longer to develop. Carbon dioxide was the majority constituent for these cells until June'96, some five months after the pulverised cells. The 60/40 conditions do not develop, the composition stabilising at close to 50/50 for around one year after capping, indicating that significant quantities of carbon dioxide are being produced, other than from methanogenic sources. After recirculation commences, the gas composition in Cell 2 becomes unstable for a period before 60/40 conditions do develop. In Cell 4 the composition approaches 60/40 one and a half years after capping, but is subject to instability.

Figure 9-8 Cell 2 - Composition of Gas in Gas Collection System



After recirculation began on 14 November '96, composition of the gas output on Cell 2 became unstable, but on Cell 1 had little effect.

The difference in methane and carbon dioxide levels at the commencement of monitoring is quite significant. The raw waste cells start from a level of around 80% carbon dioxide whereas the pulverised cells start at 60%. This is probably a manifestation of quantity of trapped air in the waste. The heterogeneous raw waste containing many intact bin bags will trap more air than the pulverised waste with smaller bulk particle size, and in which voids in porous media are likely to have air displaced by water. The trapped air is used in the aerobic hydrolysis of biopolymers, and needs to be consumed entirely before methanogenic bacteria can colonise the waste.

Occasionally a weekly results shows no methane and carbon dioxide, and 20% oxygen. If this is out of trend it can be ignored. Atmospheric gases can enter the gas vents during certain climatic conditions and especially if the cell is not gassing strongly.

Hydrogen and Hydrogen Sulphide

Both these parameters, which are monitored on a monthly basis, are in low concentrations in all cells.

The concentration of Hydrogen in all cells is less than 10ppm, as would be expected in a balanced anaerobic ecosystem. The hydrogen bloom which would normally be encountered early on at the change over from acidogenic to methanogenic phase was not observed. Monitoring of hydrogen did not begin immediately, and so the higher levels of hydrogen were probably missed.

The concentration of hydrogen sulphide in Cell 2 is typically less than 20ppm and for the other Cells is less than 10ppm. The level of hydrogen sulphide indicates the activity of sulphate reducing bacteria. In conditions of high sulphate concentration, sulphate reducing bacteria can compete with methanogens for substrate material. The levels of hydrogen sulphide are not high. The sulphate levels in the leachate are commensurately low.

Gas Micro-constituents

The micro-constituents of the landfill gas were measured over a period of a three weeks during the summer of 1997 (Mirza,A 1997). Samples were analysed by GC-MS to assess the concentration of a suite of 29 volatile organic compounds. 23 of the 29 VOCs were detected in one or more of the cells. The concentrations observed rarely exceeded occupation exposure limits.

Four were being consistently emitted: Ethylbenzene, Benzene, Toluene, and Trichlorofluoromethane. The latter is a refrigerant gas, however it was found to be present in Cell 1 and to a lesser extent in Cell 3. These two cells received the pulverised waste stream, which did not contain redundant white goods, such as refrigerators.

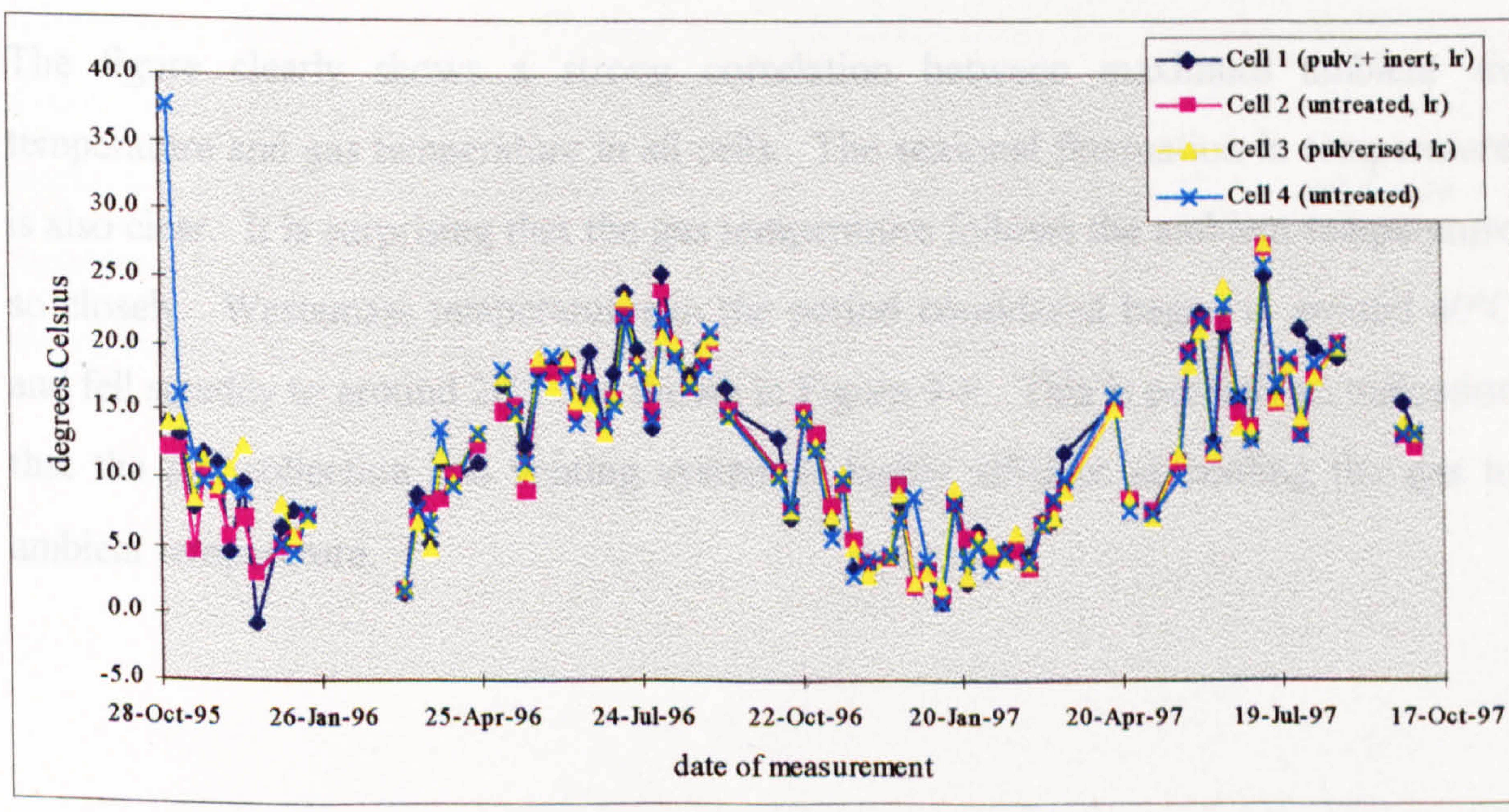
The pattern of emissions from the cells did not provide any clear evidence that, the waste manipulation techniques employed in this experiment, affected VOC output.

9.7 Gas Temperature

The gas temperature is shown in Figure 9-9, below. There appears to be a distinct seasonal fluctuation. The temperature of the wastemass and of the leachate does not fluctuate to this extent, indicating that ambient conditions strongly affect the temperature of gas in the gas collection and venting system.

In addition readings are taken around the middle of the day, and therefore are likely to be the higher temperatures of the gas stream.

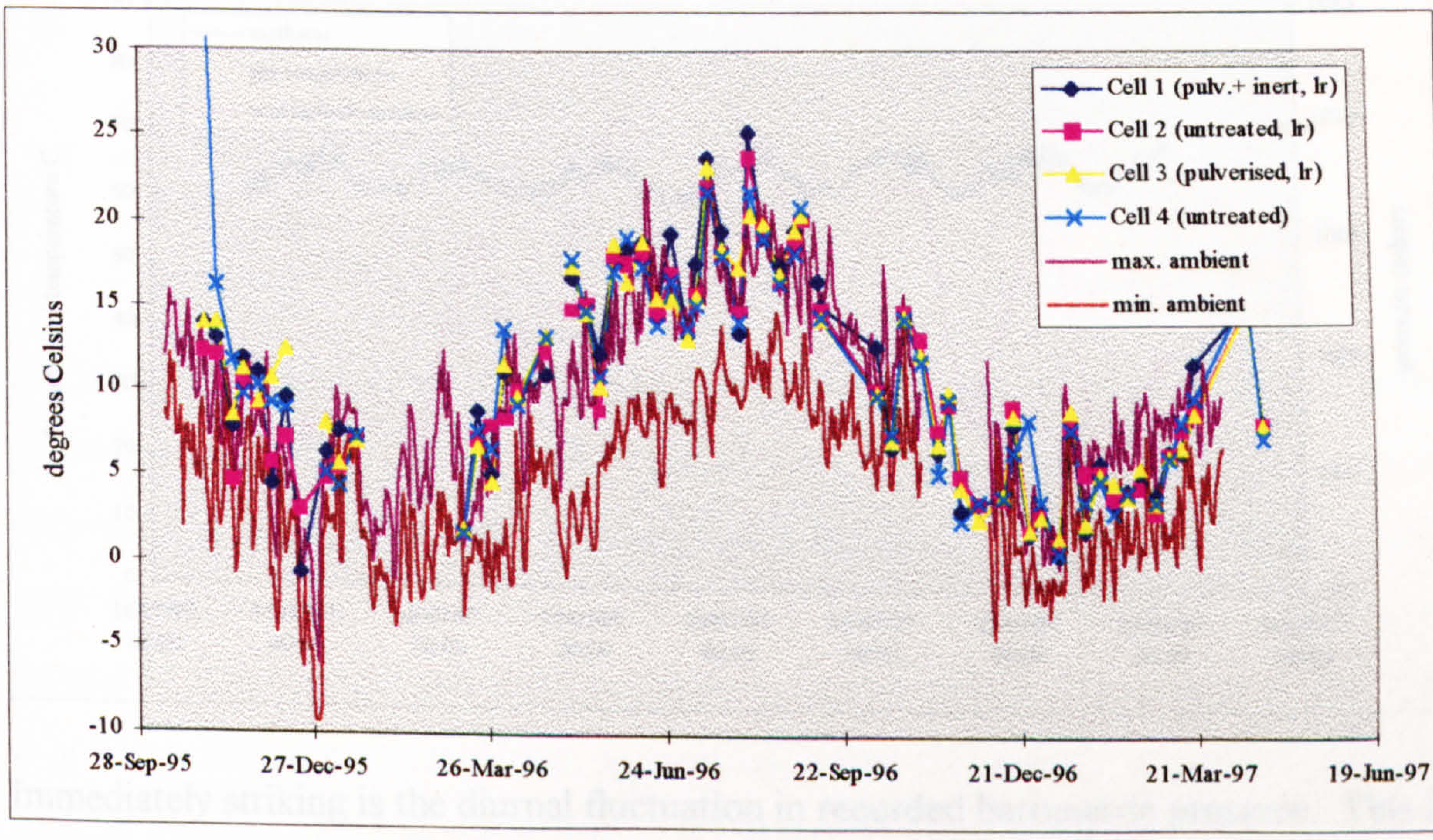
Figure 9-9 Temperature of Gas from Sampling Port



9.7.1 Correlation of Gas Temperature And Ambient Temperature

In the figure below, landfill gas temperature at the sampling port is shown together with maximum and minimum ambient air temperatures. The gas temperatures are measured on a weekly basis and the air temperature is shown on a daily basis. The air temperature data is taken from the automatic weather station.

Figure 9-10 Gas Composition and Ambient Temperature

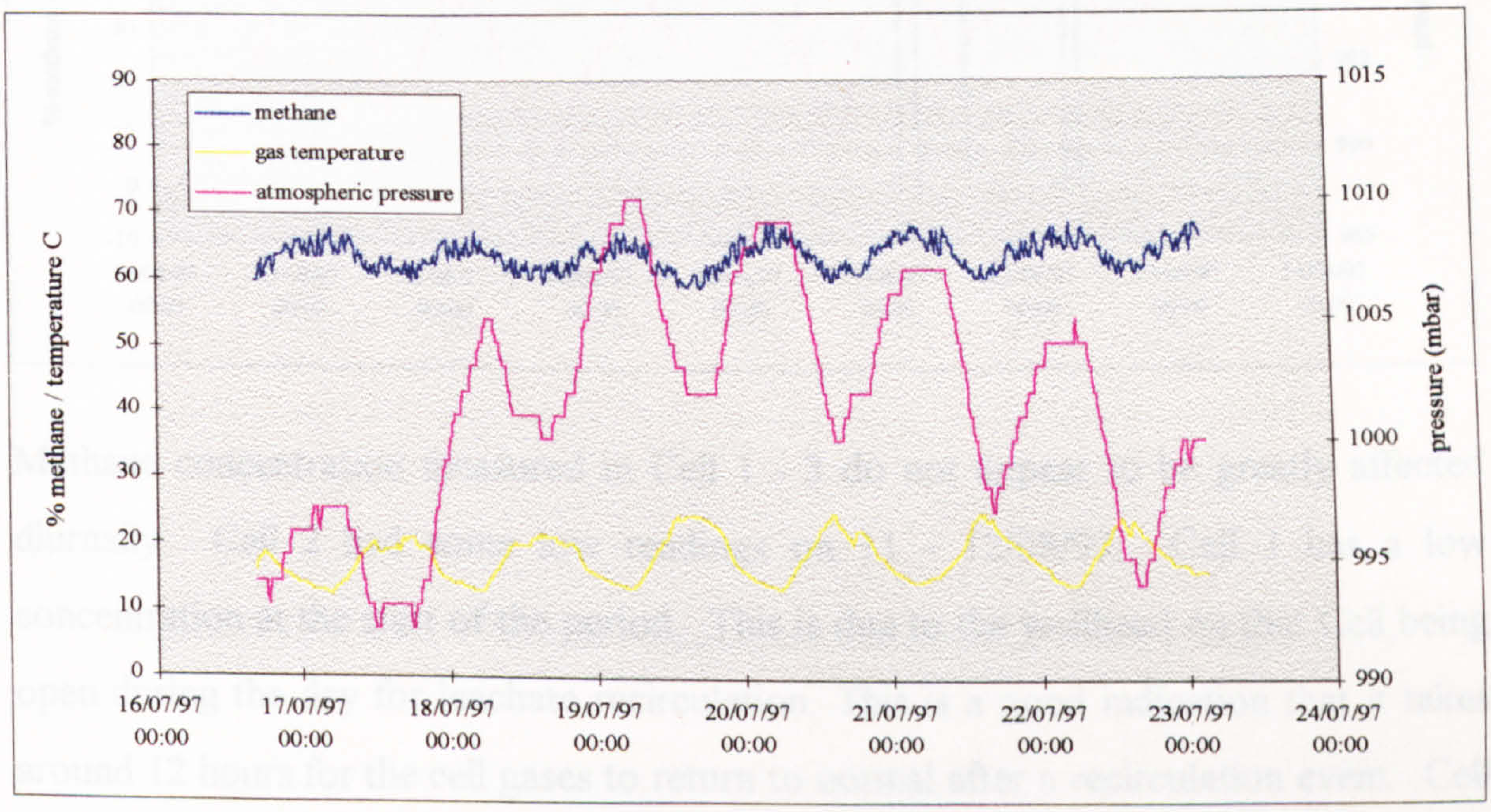


The figure clearly shows a strong correlation between maximum ambient air temperature and gas temperature in all cells. The seasonal fluctuation in temperature is also clear. It is surprising that the gas temperature follows the ambient temperature so closely. Wastemass temperatures in the period considered began at around 40°C and fell steadily to around 20°C, as shown in Figure 9-9. This is perhaps an indication that the gas collection and venting system is highly efficient at cooling the gas to ambient temperature.

9.7.2 Diurnal Fluctuations in Gas Temperature and Composition

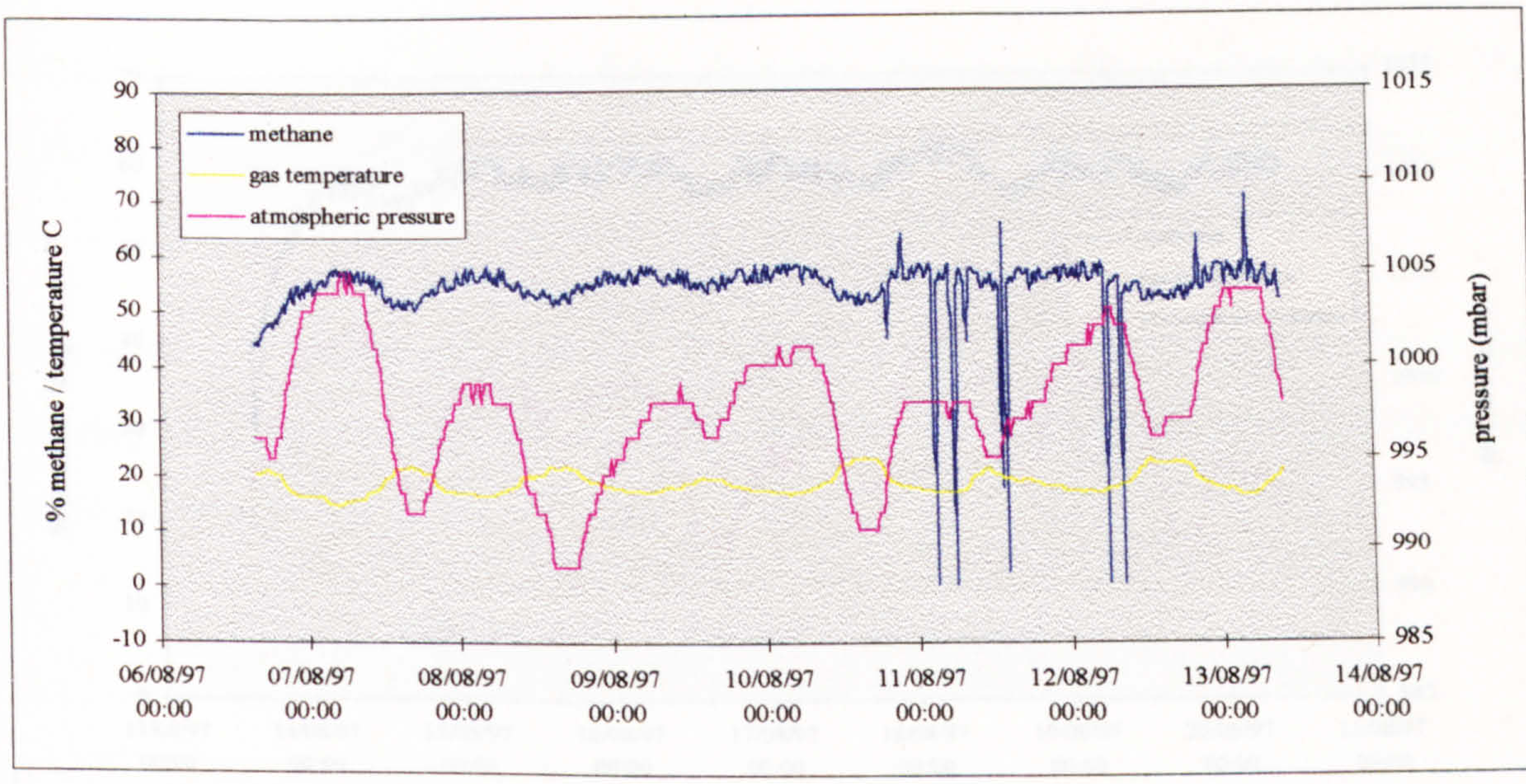
Diurnal fluctuations were measured to assess how representative the 'middle of the day' spot measurements were. A 20 minute log interval was used, and each cell was monitored in turn, for a week.

Figure 9-11 Cell 1 - 20 min Logging of Temperature and Composition



Immediately striking is the diurnal fluctuation in recorded barometric pressure. This is recorded by the gas analyser. Being a portable instrument, the pressure sensor is not likely to be extremely accurate. It was initially thought that the diurnal fluctuation might be a temperature induced sensor drift. However, barometric pressure as measured by the automatic weather station, was compared with the period in the above figure. It showed that there *was* a nocturnal increase in pressure.

Figure 9-12 Cell 2 - 20 min Logging of Temperature and Composition



Methane concentration measured in Cell 1 - 3 do not appear to be greatly affected diurnally. Cell 2 had some low readings on 11 - 12/08/97. Cell 3 has a low concentration at the start of the period. This is due to the wellhead on that Cell being open during the day for leachate recirculation. This is a good indication that it takes around 12 hours for the cell gases to return to normal after a recirculation event. Cell 4 is highly variable although this appears not to be particularly associated with the time of the day. During the 01/08/97 the methane concentration becomes very low for around 20 hours. This is may be associated with the rising barometric pressure over the same period. It is a good illustration of how a weekly spot sample from this cell could be misleading. This perhaps explains some of the variability in the measured long term methane concentration that is shown in the above Section 9.6 .

Figure 9-13 Cell 3 - 20 min Logging of Temperature and Composition

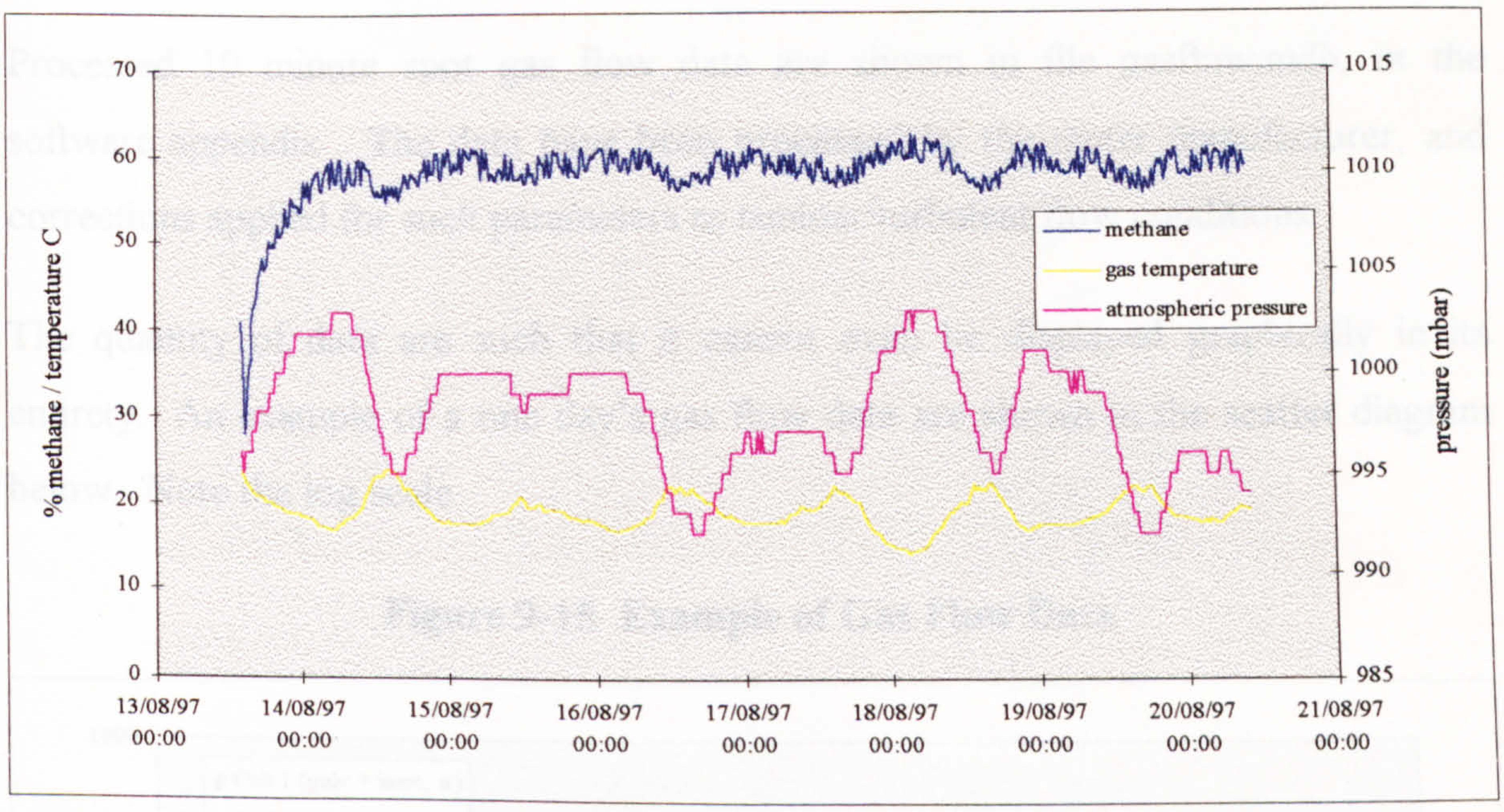
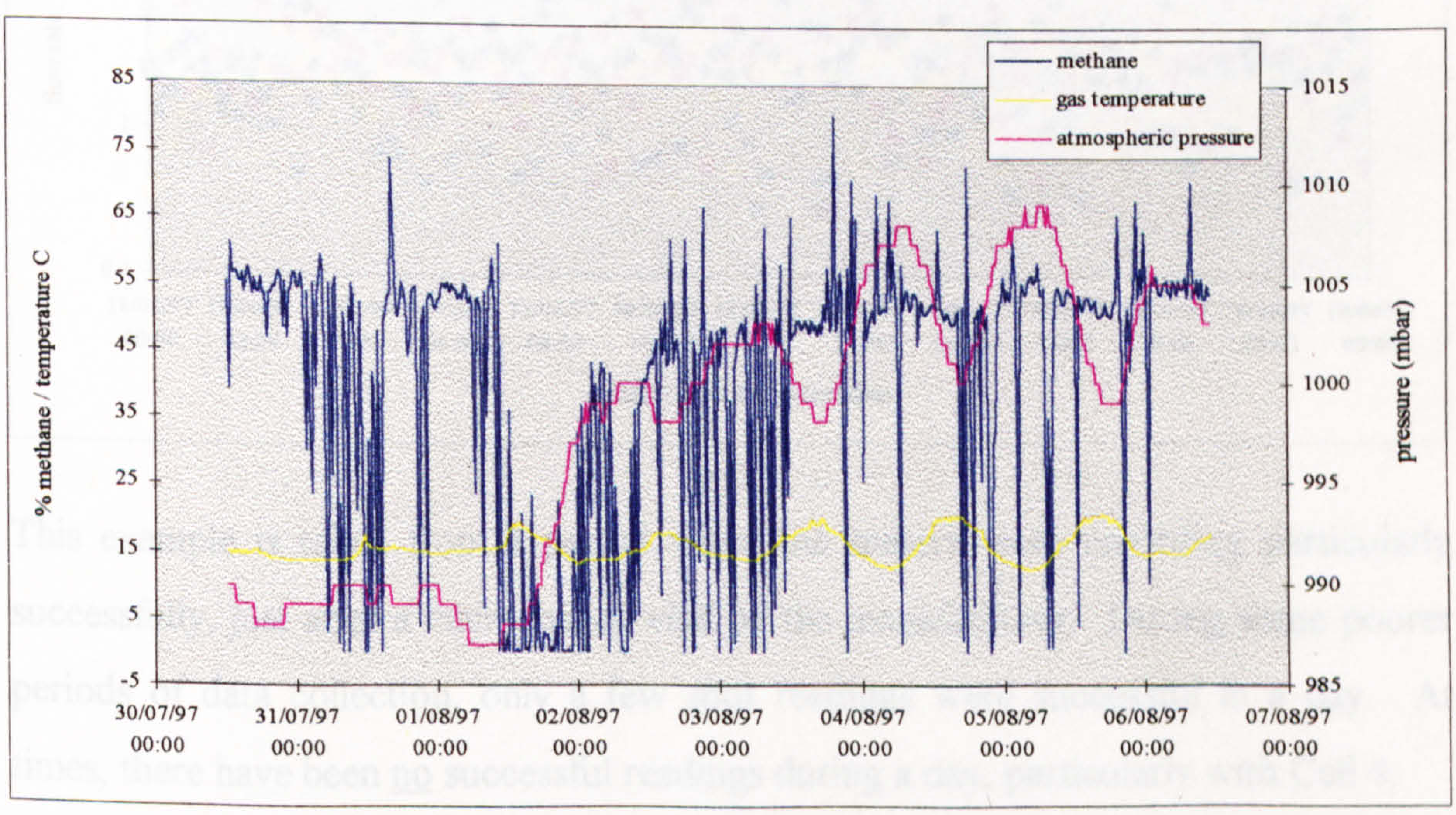


Figure 9-14 Cell 4 - 20 min Logging of Temperature and Composition



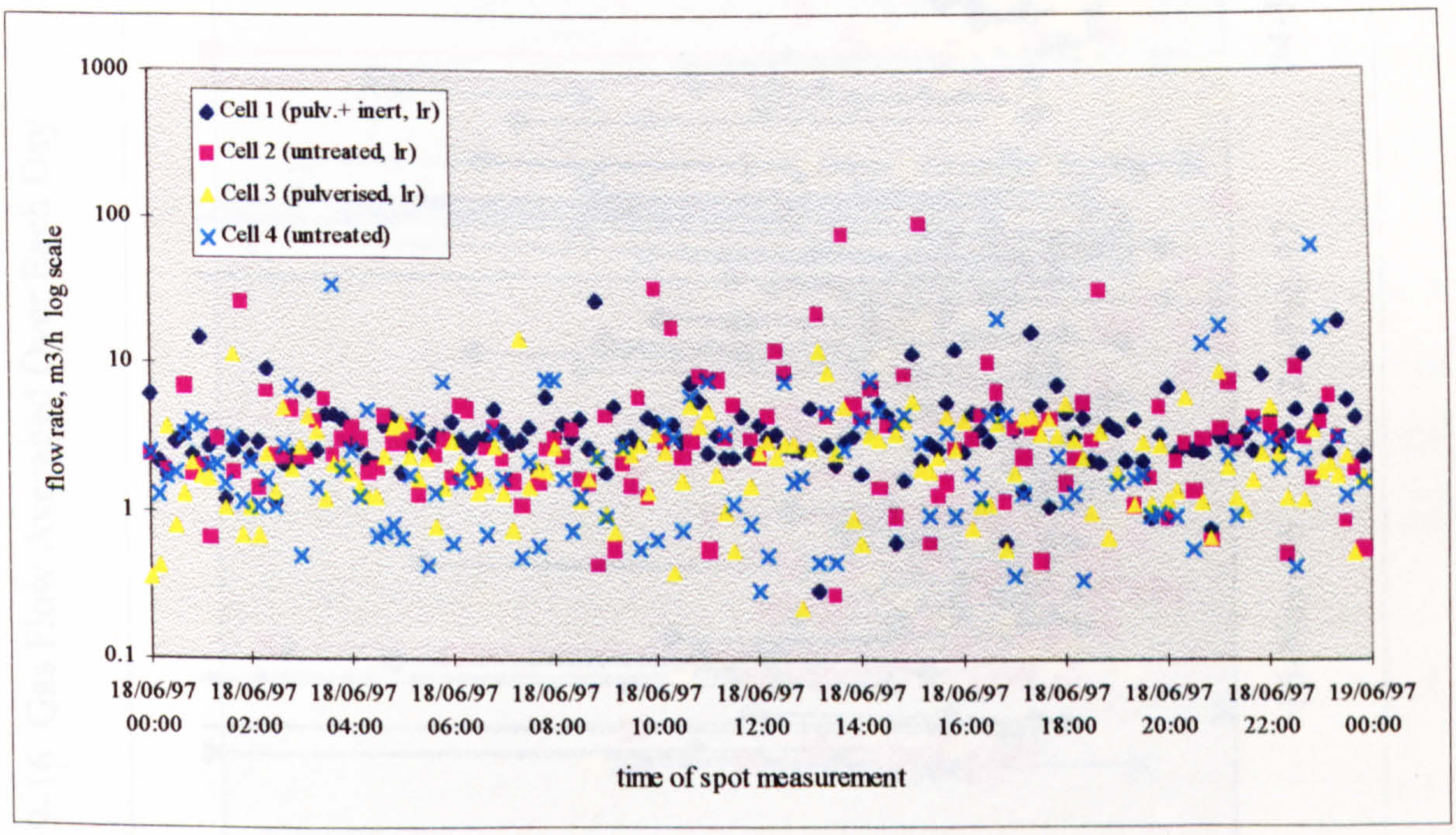
Gas temperature appears to be affected by around a 10°C diurnal fluctuation in all cells.

9.8 Gas Flow

Processed 10 minute spot gas flow data are shown in file gasflow.mdb, in the software appendix. The data have been processed by the meter manufacturer, and corrections applied for such parameters as laminar/turbulent flow conditions.

The quantity of data are such that it cannot even be displayed graphically in its entirety. An example of a one day's gas flow data are shown in the scatter diagram below. Note the log scale.

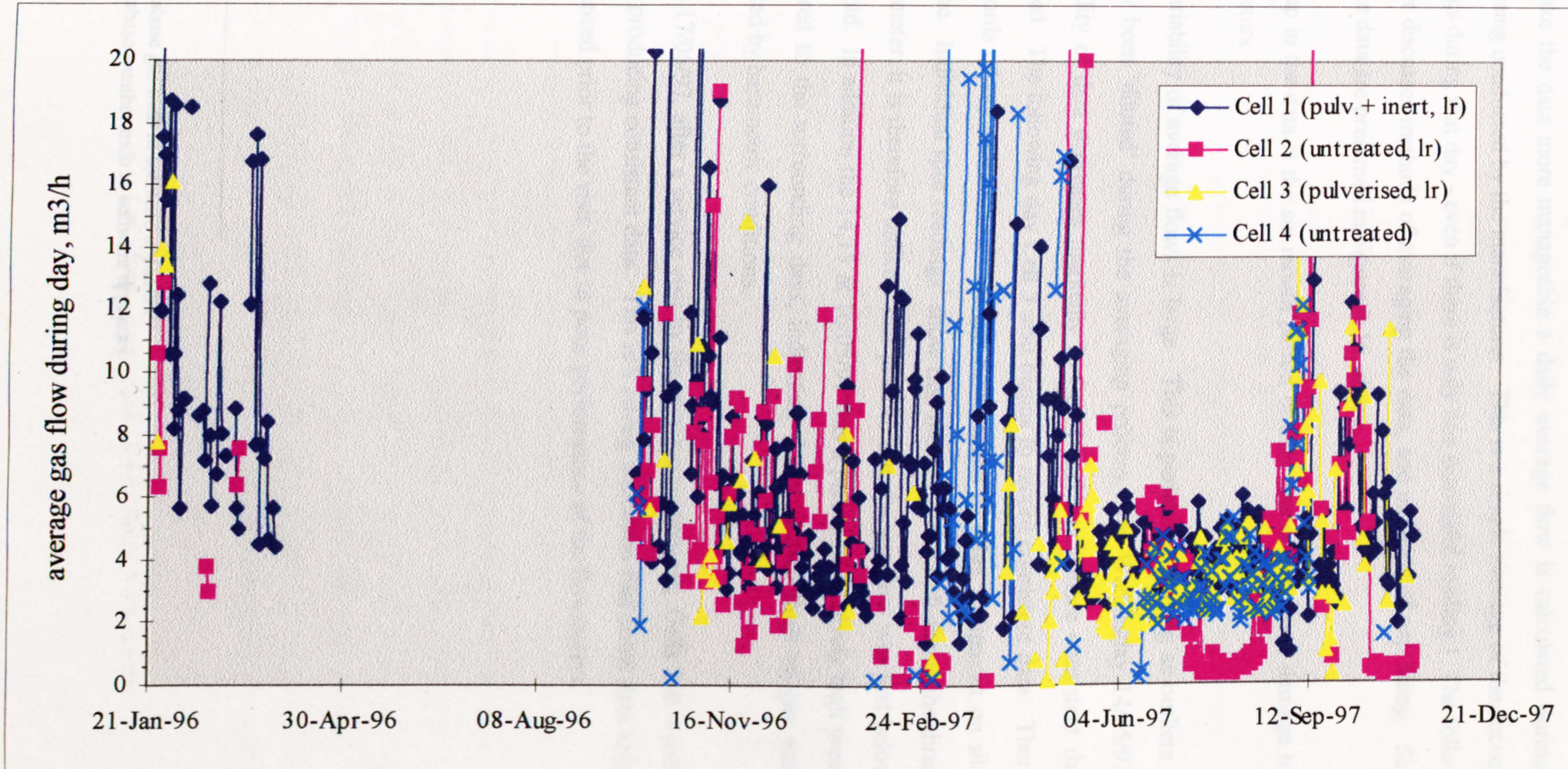
Figure 9-15 Example of Gas Flow Data



This example is taken from a period when the meters were recording particularly successfully, just after a maintenance visit by the manufacturer. During some poorer periods of data collection, only a few spot readings were successful in a day. At times, there have been no successful readings during a day, particularly with Cell 4.

The variability of the data is particularly noticeable, with the two untreated cells appearing to have the most outliers. Some values are in excess of 100 m^3/h. Statistical analysis of the data are presented in the following chapter.

Figure 9-16 Gas Flow Averaged Over Each Day



To make the data more manageable a daily average flow is calculated during the processing conducted by the manufacturer. This is a simple average of the successful readings during that day - even if there is only one successful reading ! The following chapter discusses methods of averaging the data, and methods of gap filling. Simple average data are presented in Figure 9-16, above.

The gap in the data is the six month period of data loss due to flood damage to the flowmeters.

The variability of average flows is large. This is perhaps surprising as outliers have already been 'diluted' during the averaging process. On Wednesday 14/05/97 the variability of data decreases markedly in Cell 1 and much more consistent data is recorded. The following day Cell 3 also begins to record consistent data. There are no records of any alterations to the gas flow meters or other equipment on site, on this date. Individual spot readings[1] show that the values are well above the threshold of the meter; it is therefore unlikely that prior to this the gas flow was just below the threshold. In addition the 14,15 & 16/05/97 was a period of relatively high pressure[2] compared to the surrounding days, indicating that a sudden flush of gas was not produced by barometric conditions.

On the 17/06/97, after a service visit by the meter manufacturer, Cells 2 & 4 joined 1 & 3 in producing consistent data. This is a strong indication that some data loss was experienced prior to the visit, due to poor performance of the flowmeters.

---

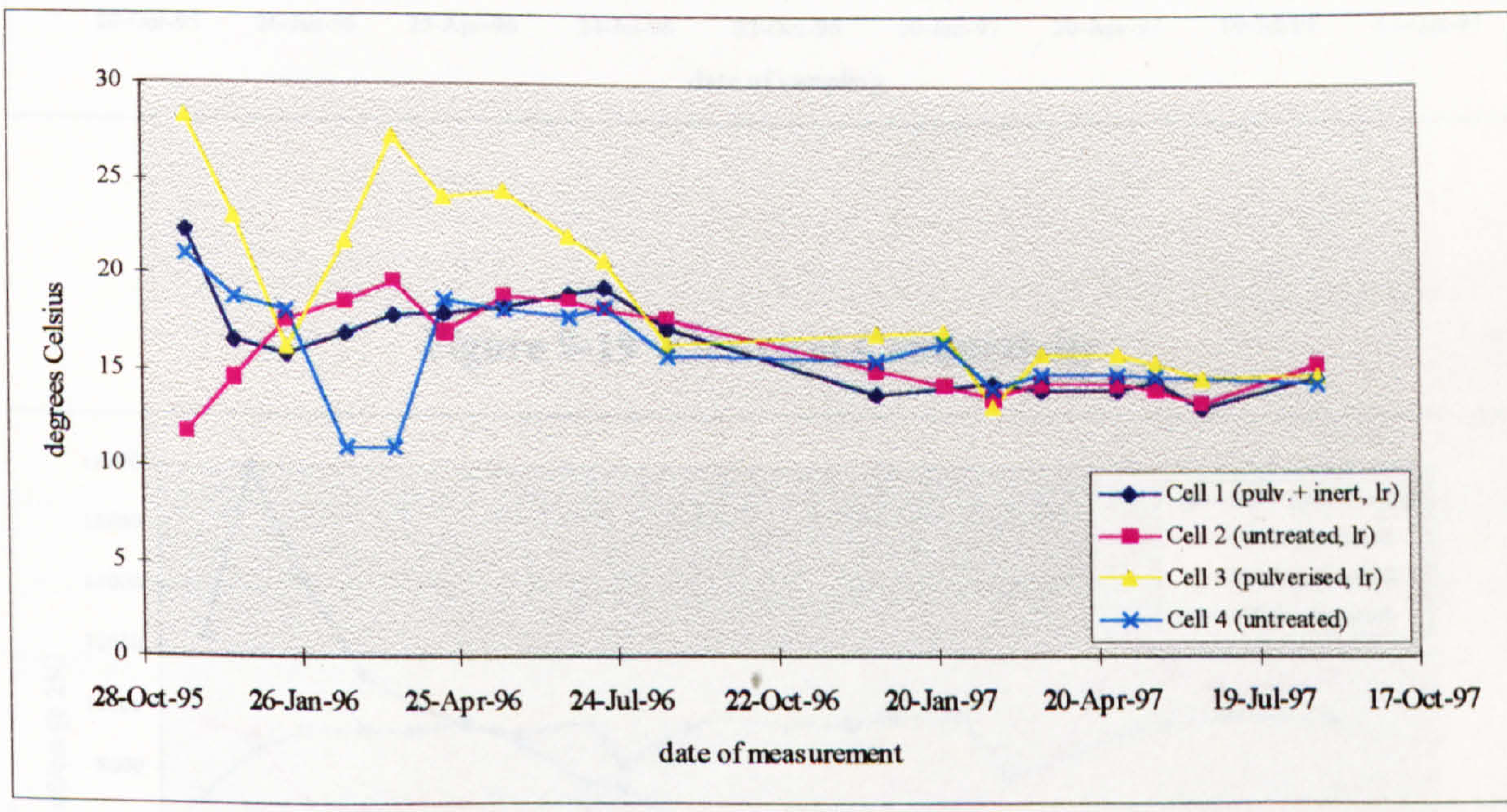
[1] see database gas.mdb in software appendix
[2] see database weather.mdb in software appendix

9.9 Leachate Composition

All results of analysis of leachate composition pertain to leachate sampled from the central well.

The **temperature** of leachate at sampling is shown is below. Cells 1 & 2 have steady temperatures in the high teens coming from an initial 21-22°C. Cell 3 shows a variable but generally higher temperature. Cell 4 is similar to Cells 1 & 2 with the exception of February and March 96, during which a significant dip in temperature was recorded. The reason for this is not known, but a measurement error is not ruled out. The leachate temperature in all cells appears to be steady at around 15°C.

Figure 9-17 Leachate temperature at sampling



Methanogens are sensitive to **pH**. As discussed in the Chapter 5 , they are most active in the range 6.8 - 7.4 , and are able to control the pH of their ecosystem by the consumption of acetate. Cells 1 - 3 have settled down within this range fairly quickly hailing an end to the acidogenic stage. Cell 4 however remained acidic until April'96, evidence of an acid souring event. At this stage, prior to recirculation beginning, Cell 2 and 4 were experimentally identical. The reason for the difference is not explained.

Further evidence for acid souring is discussed later. After April'96 Cell 4 came to neutral.

Figure 9-18 pH

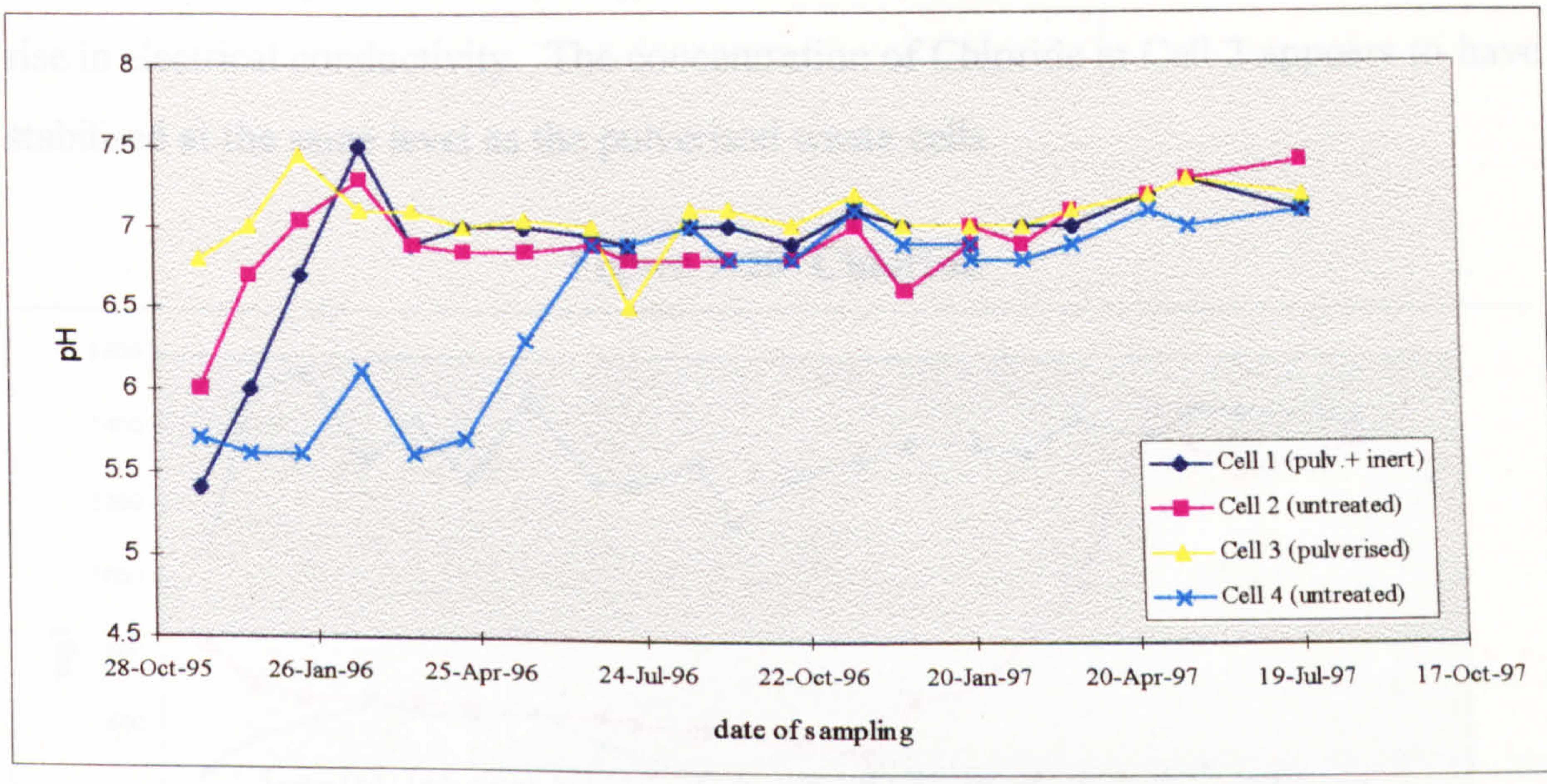
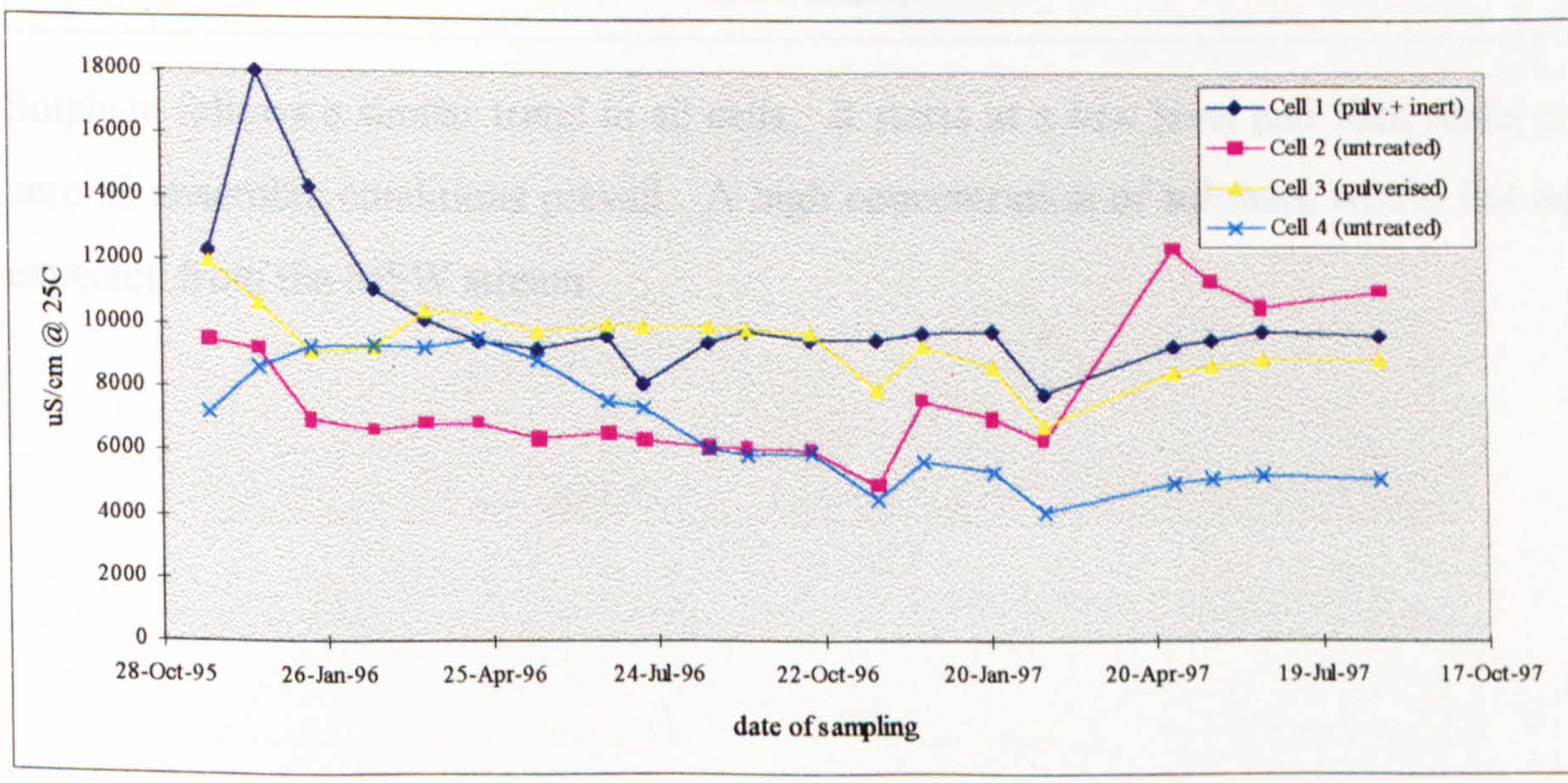
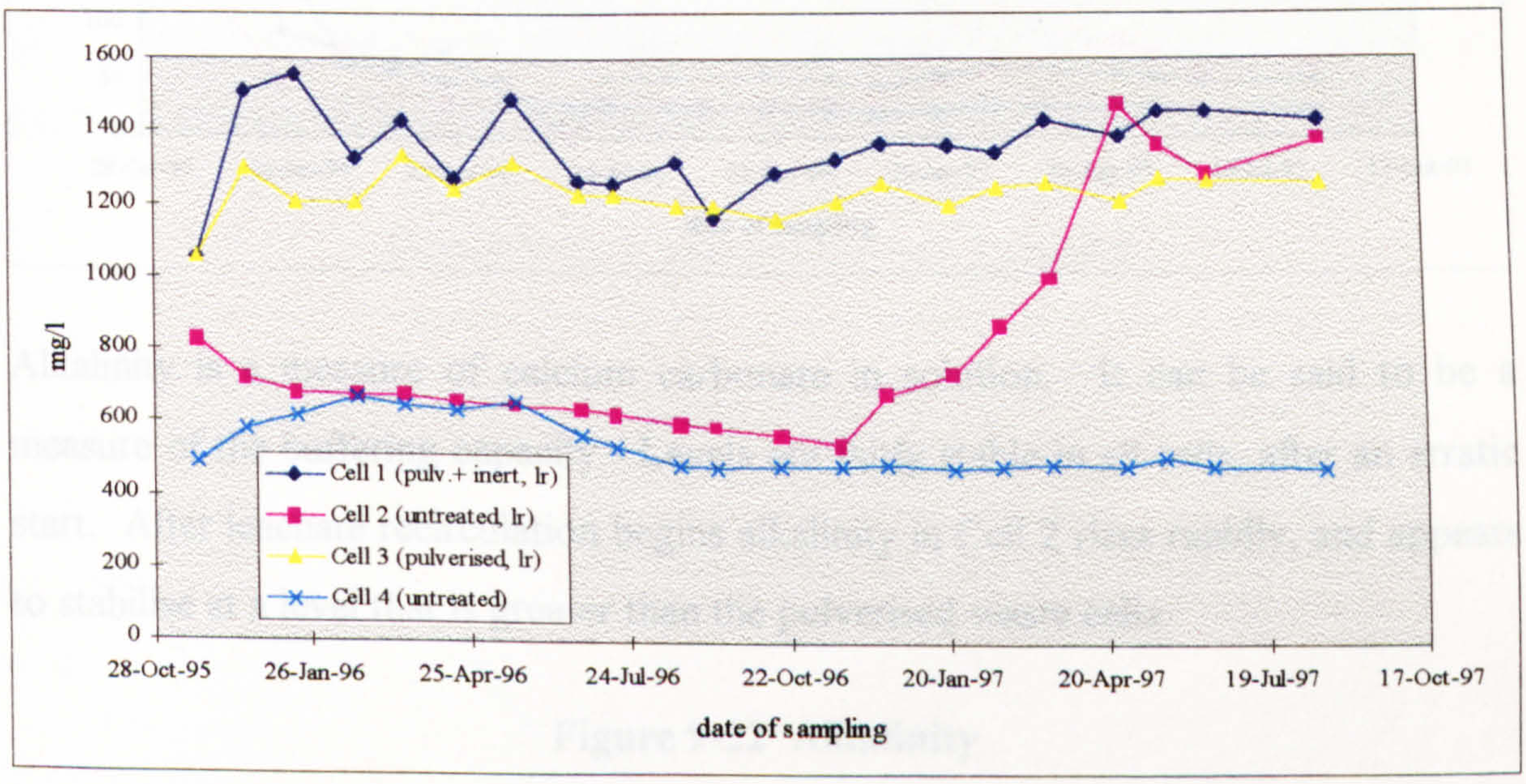


Figure 9-19 Electrical Conductivity



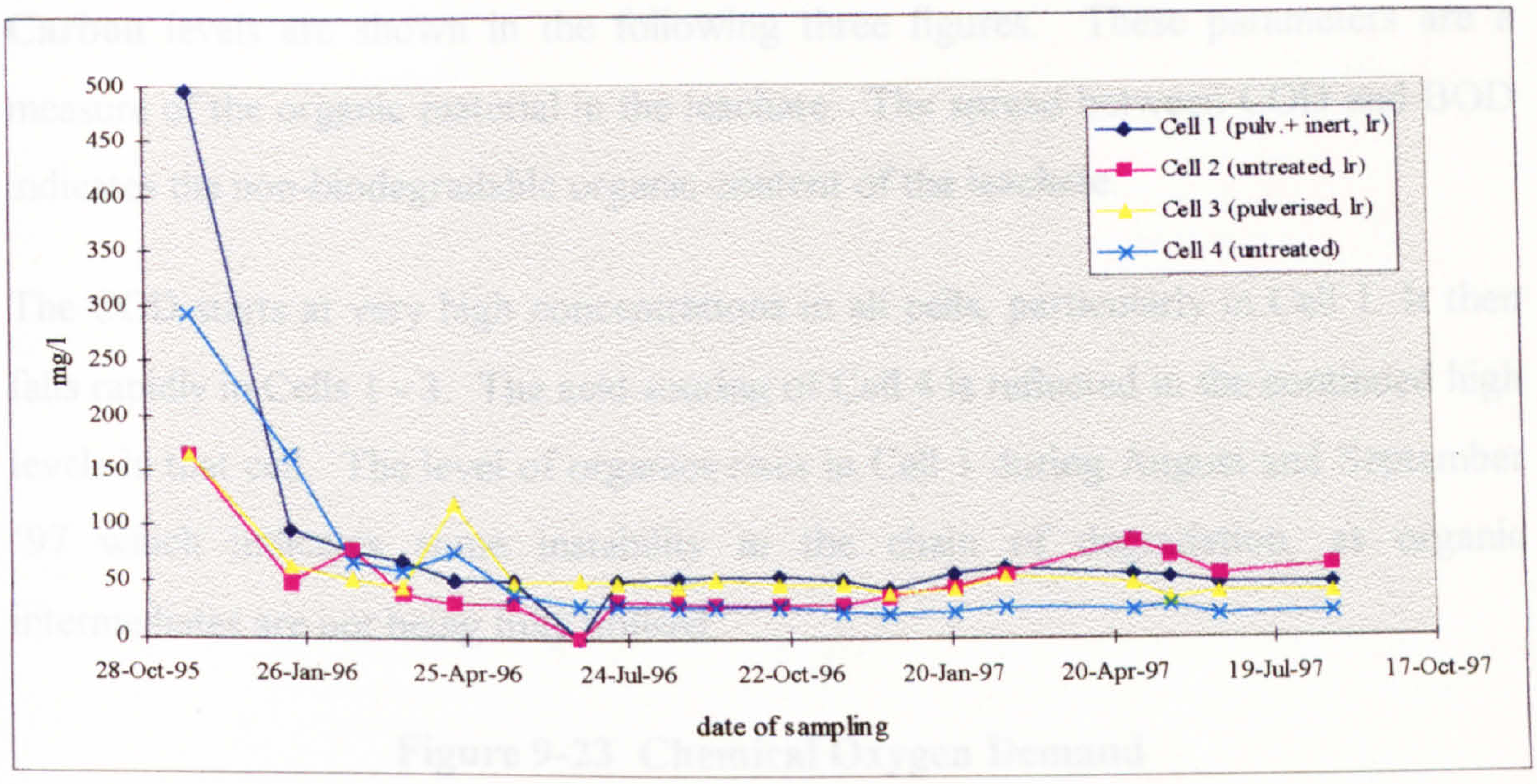
Electrical conductivity (EC) is shown in Figure 9-19. EC is a measure of the ions in solution. As would be expected the pulverised cells with a greater chloride content (Figure 9-20 below) exhibit a greater conductivity. Cells 1 - 3 show a falling and then stabilising EC, whereas Cell 4 has a period of stability at the higher level before falling in April 96. It now appears to have stabilised. This is probably associated with the acid souring state. After leachate recirculation began in November'96 the chloride concentration in Cell 2 leachate rose sharply indicating a flushing out of soluble salts, which had already occurred in the pulverised waste cells. There was a commensurate rise in electrical conductivity. The concentration of Chloride in Cell 2 appears to have stabilised at the same level as the pulverised waste cells.

Figure 9-20 Chloride



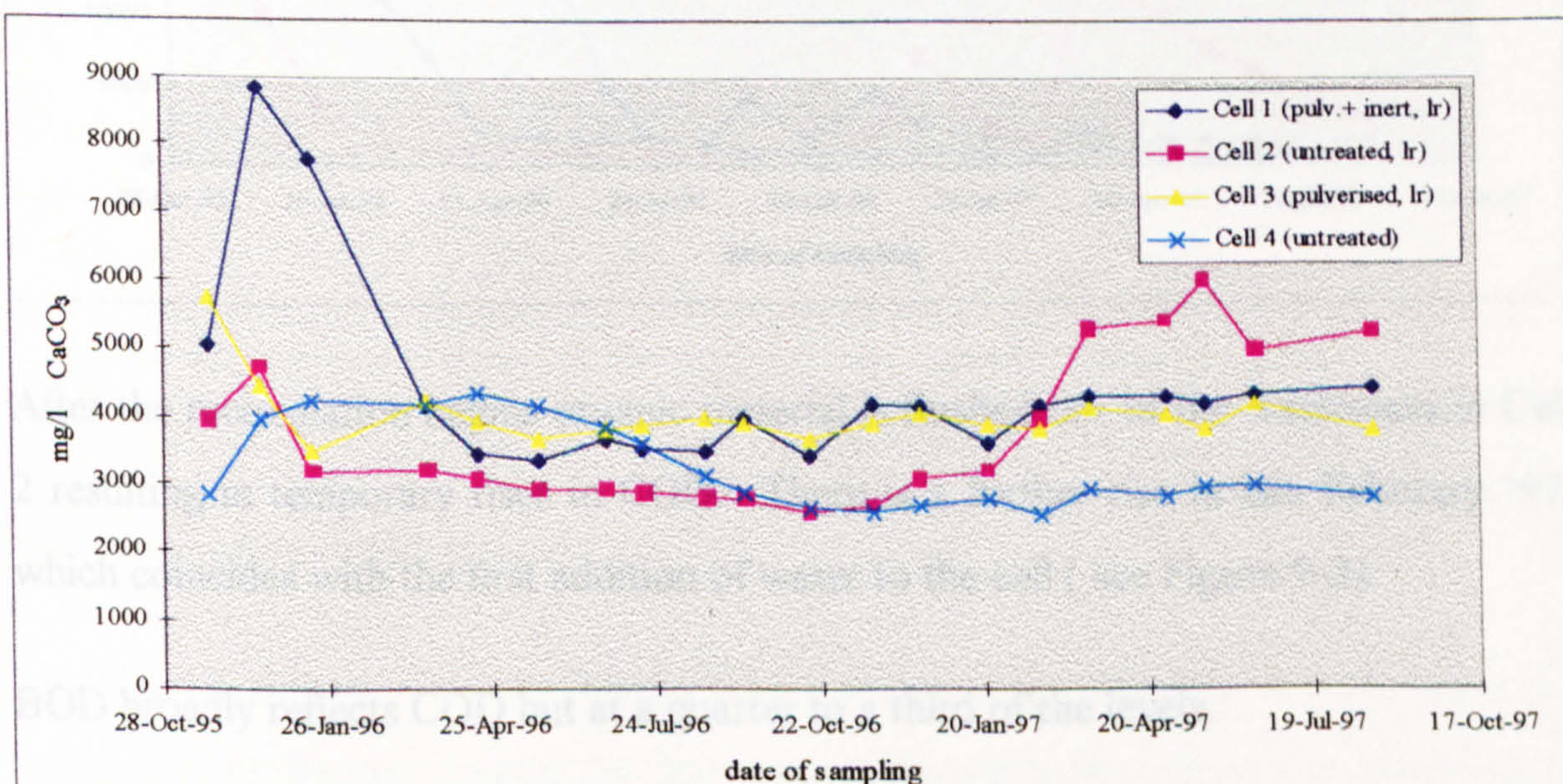
Sulphate follows a similar trend in all cells. It starts at a low level and then tends to zero as anaerobic conditions prevail. A high concentration of sulphate would not be expected from the MSW stream.

Figure 9-21 Sulphate



Alkalinity is a measure of calcium carbonate in solution. It can be said to be a measure of the buffering capacity. Levels are fairly stable in all cells, after an erratic start. After leachate recirculation begins alkalinity in Cell 2 rises rapidly, and appears to stabilise at a level that is greater than the pulverised waste cells.

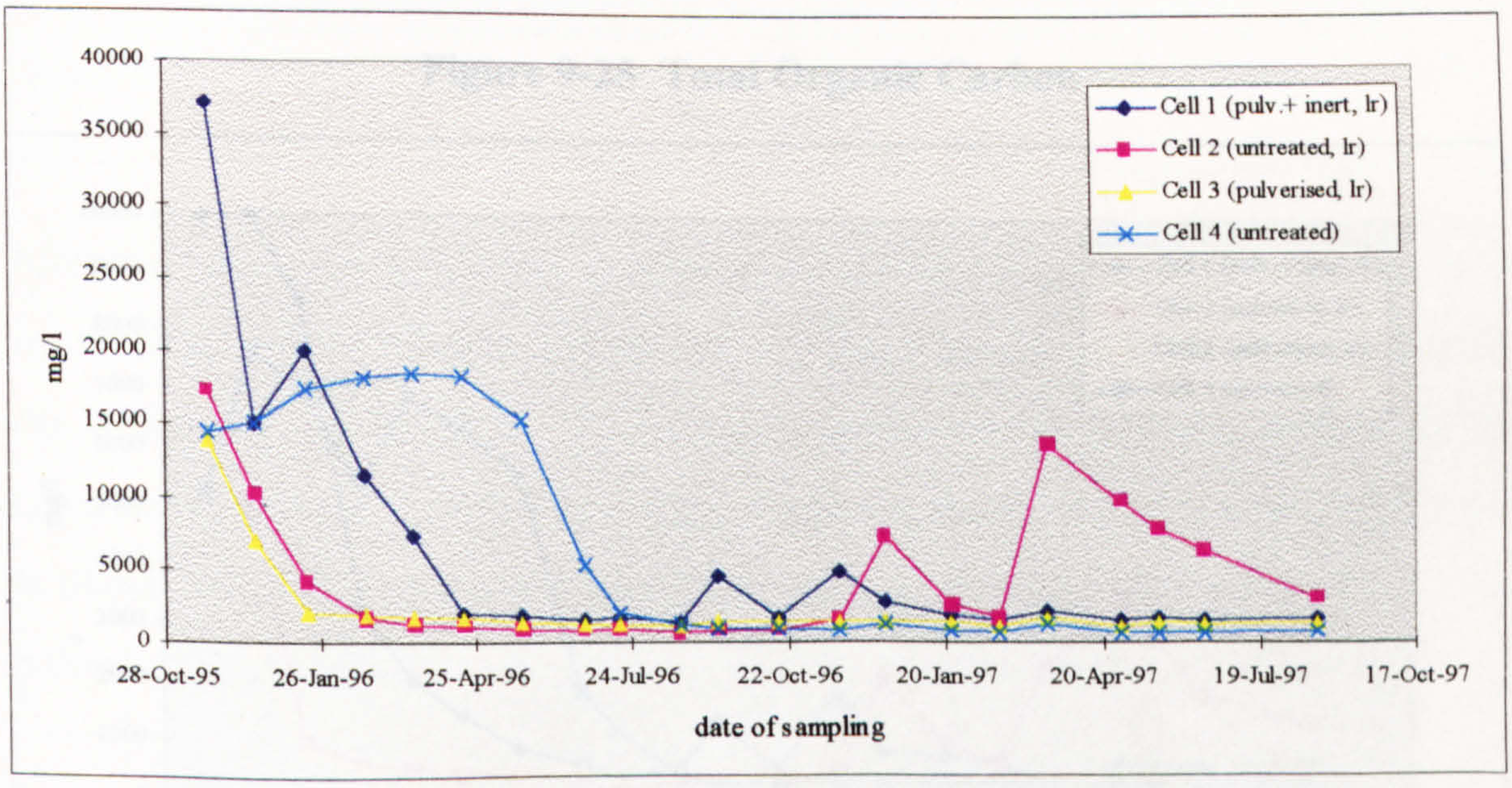
Figure 9-22 Alkalinity



Chemical Oxygen Demand, Biochemical Oxygen Demand and Total Organic Carbon levels are shown in the following three figures. These parameters are a measure of the organic material in the leachate. The spread between COD and BOD indicates the non-biodegradable organic content of the leachate.

The COD starts at very high concentrations in all cells, particularly in Cell 1. It then falls rapidly in Cells 1 - 3. The acid souring of Cell 4 is reflected in the continued high levels in that cell. The level of organics rises in Cell 1 during August and September '97 which indicates some instability in the chain of degradation, as organic intermediates are not being fully utilised.

Figure 9-23 Chemical Oxygen Demand



After the recirculation begins organic material is flushed out of the wastemass in Cell 2 resulting in temporary rises in COD. There is a further rise in late February '97, which coincides with the first addition of water to the cell (see Figure 9-2).

BOD broadly reflects COD but at a quarter to a third of the levels.

Figure 9-24 Biochemical Oxygen Demand

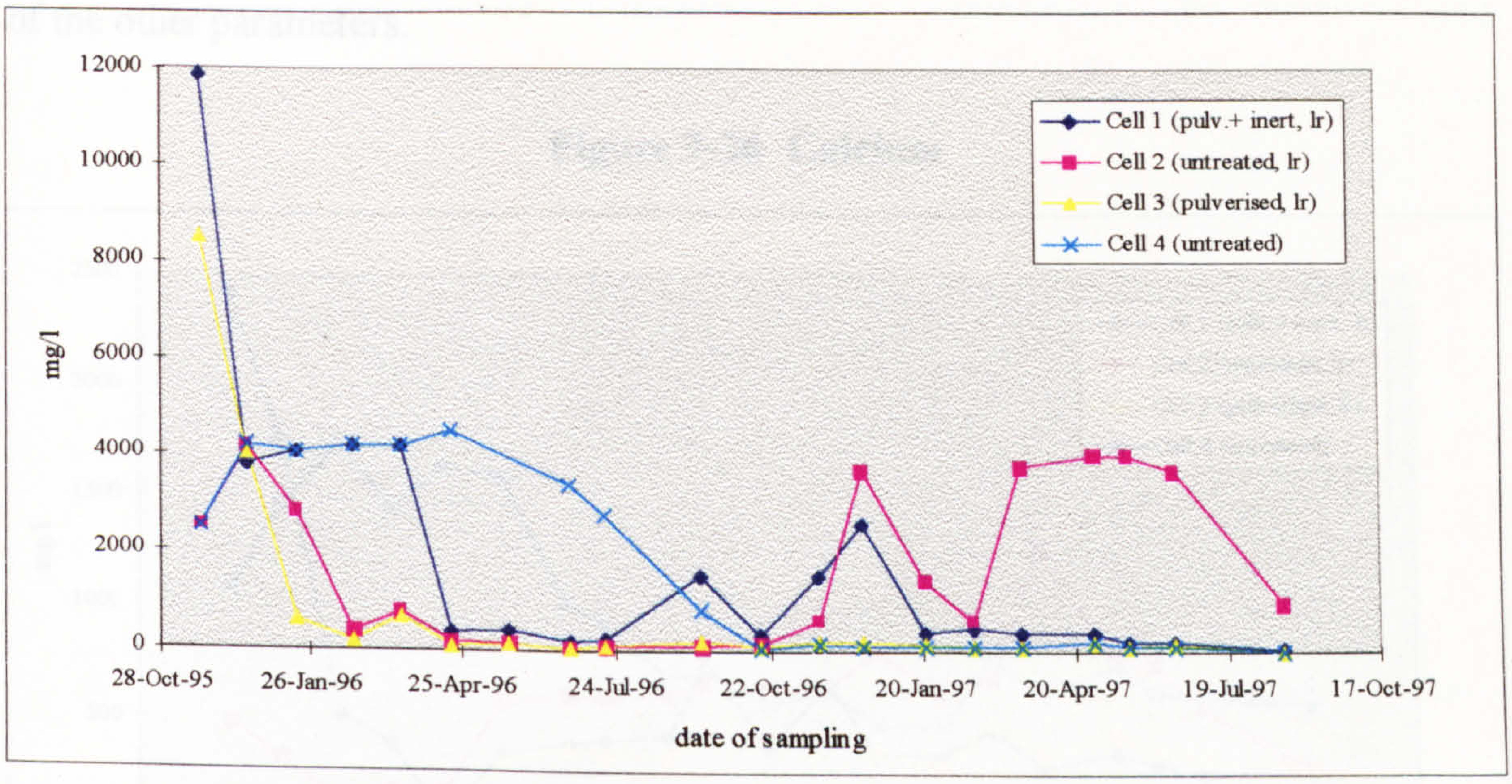
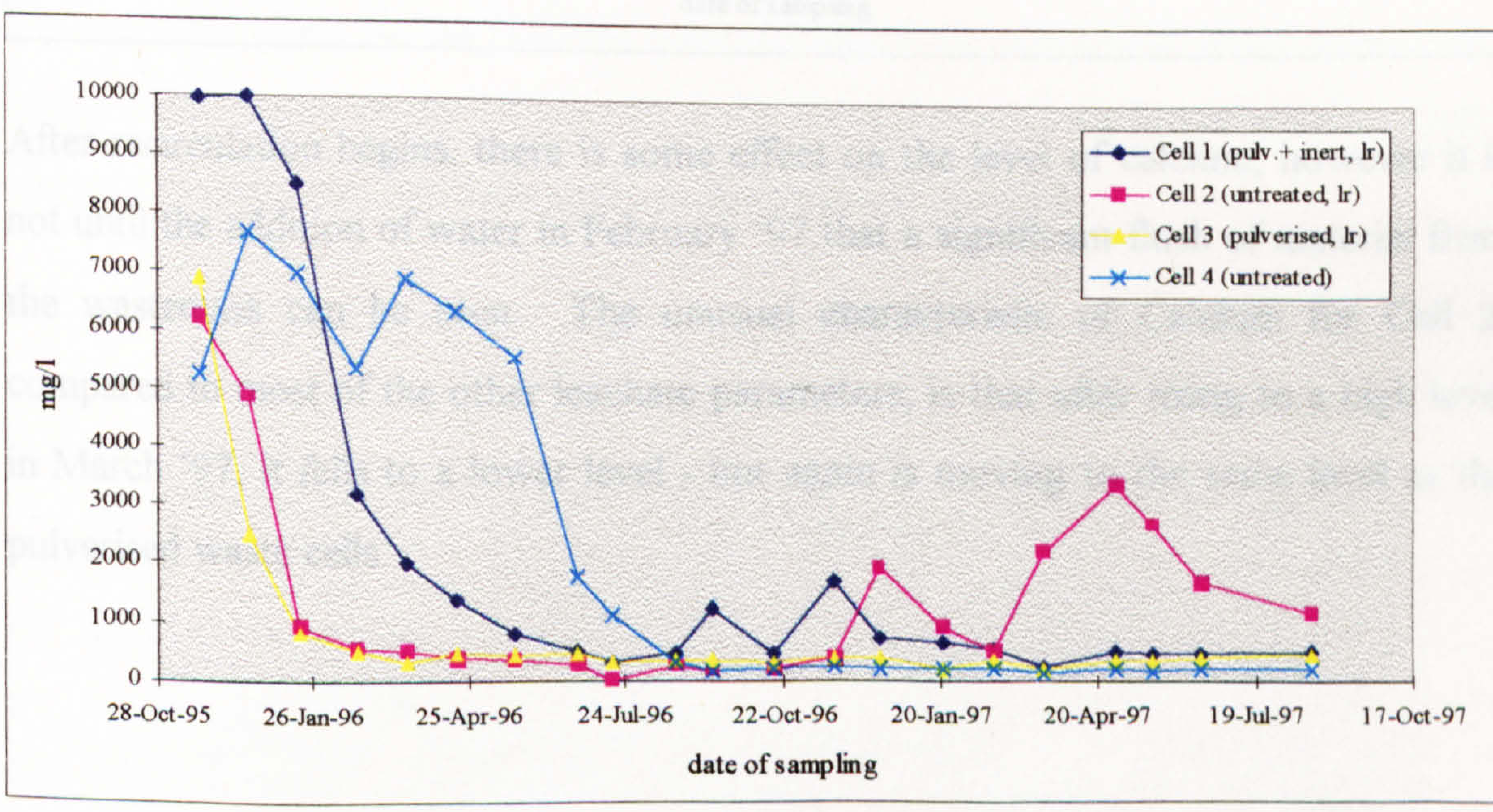


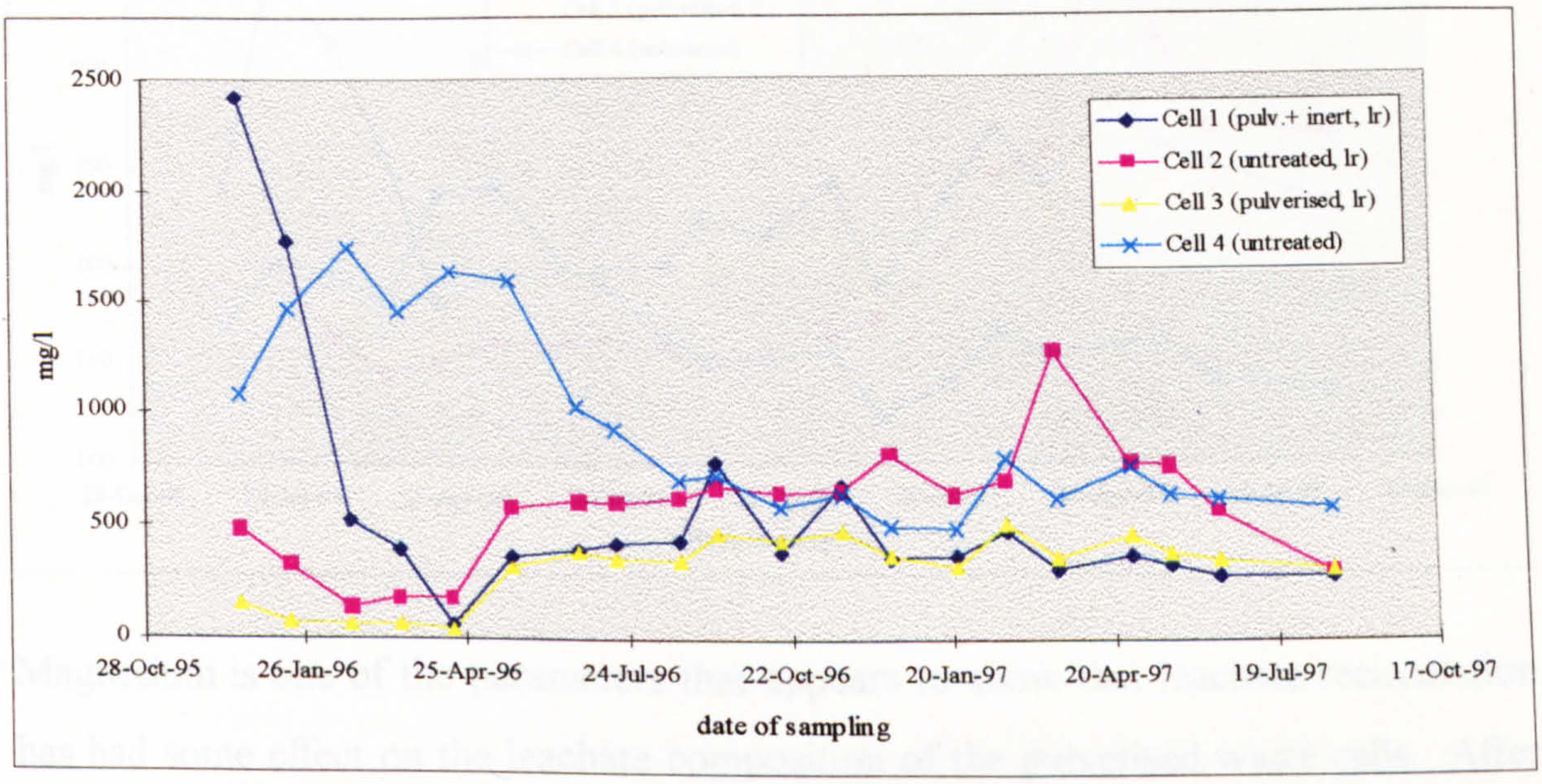
Figure 9-25 Total Organic Carbon



TOC also reflects COD trends.

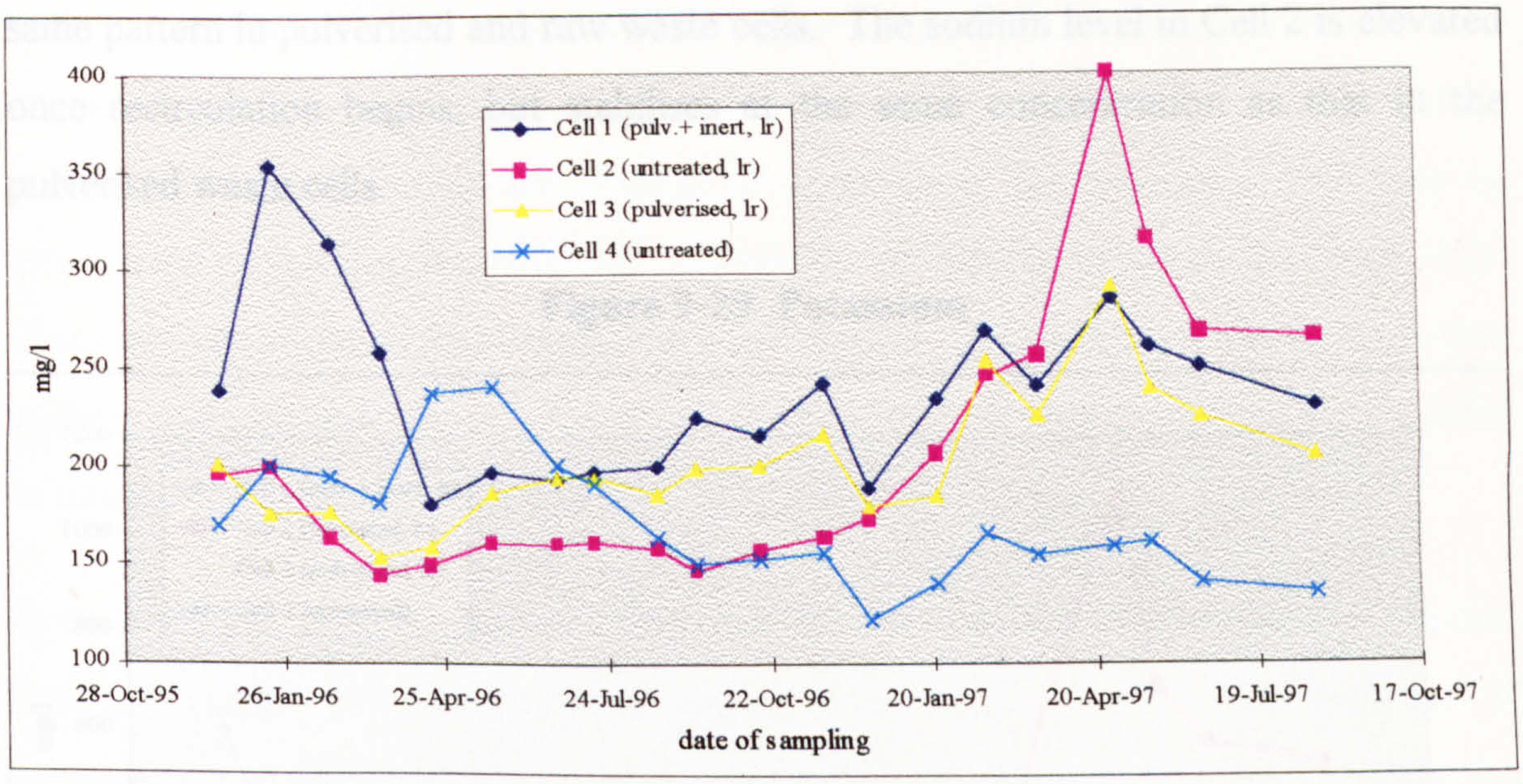
The **soluble metals**, Calcium, Magnesium Sodium, and Potassium, are shown in the following four figures. During the first year, calcium broadly follows the reciprocal of pH. This perhaps not surprising as Calcium Carbonate will be coming in and out of solution as the pH changes. However, the concentration of calcium in the untreated waste cells is higher than in the pulverised waste cells. The reverse is true with most of the other parameters.

Figure 9-26 Calcium



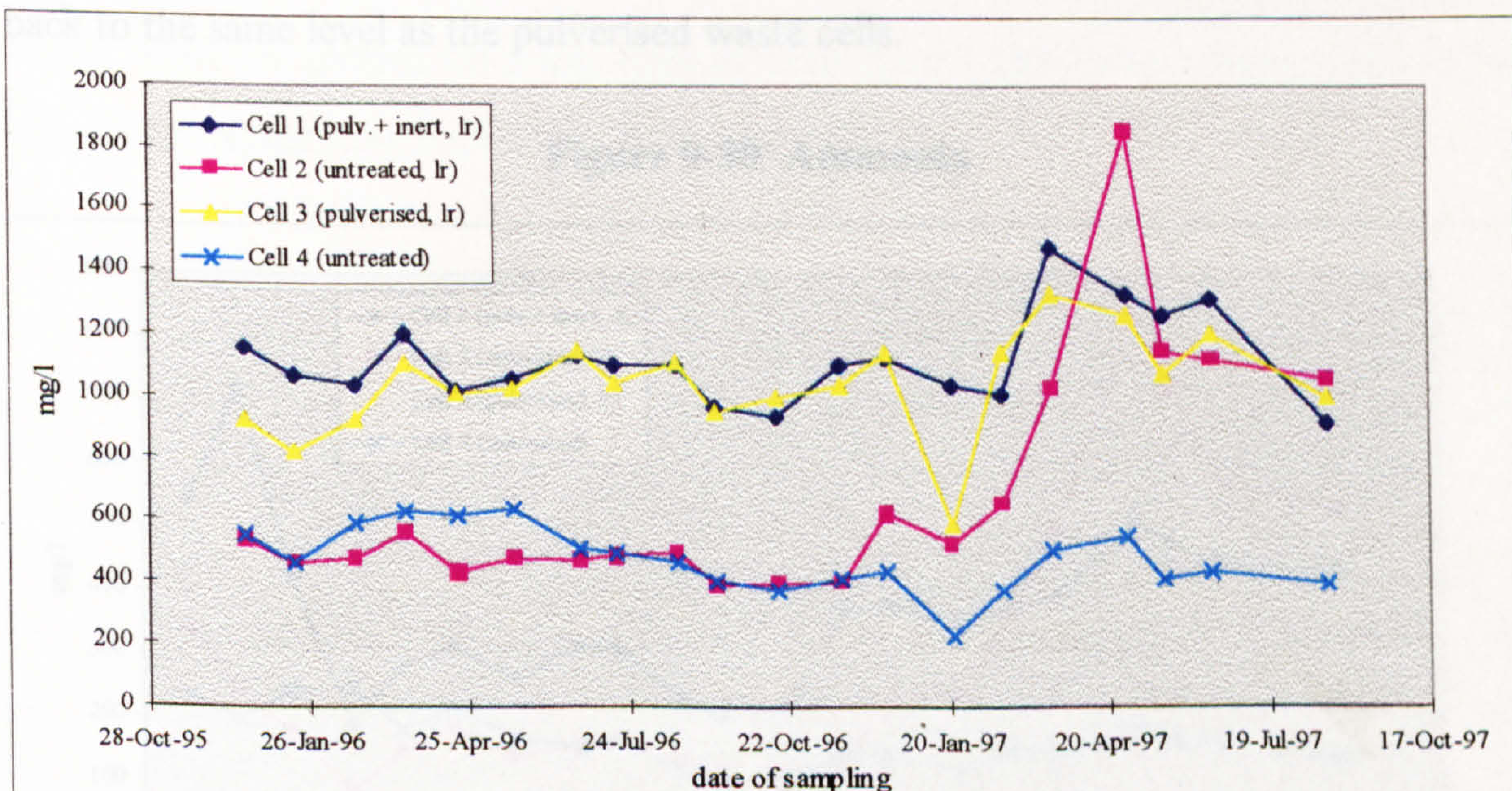
After recirculation begins, there is some effect on the level of calcium, however it is not until the addition of water in February '97 that a significant flush of material from the wastemass can be seen. The unusual characteristic of Calcium for Cell 2, compared to most of the other leachate parameters, is that after rising to a high level in March '97, it falls to a lower level - but again is moving to the same level as the pulverised waste cells.

Figure 9-27 Magnesium



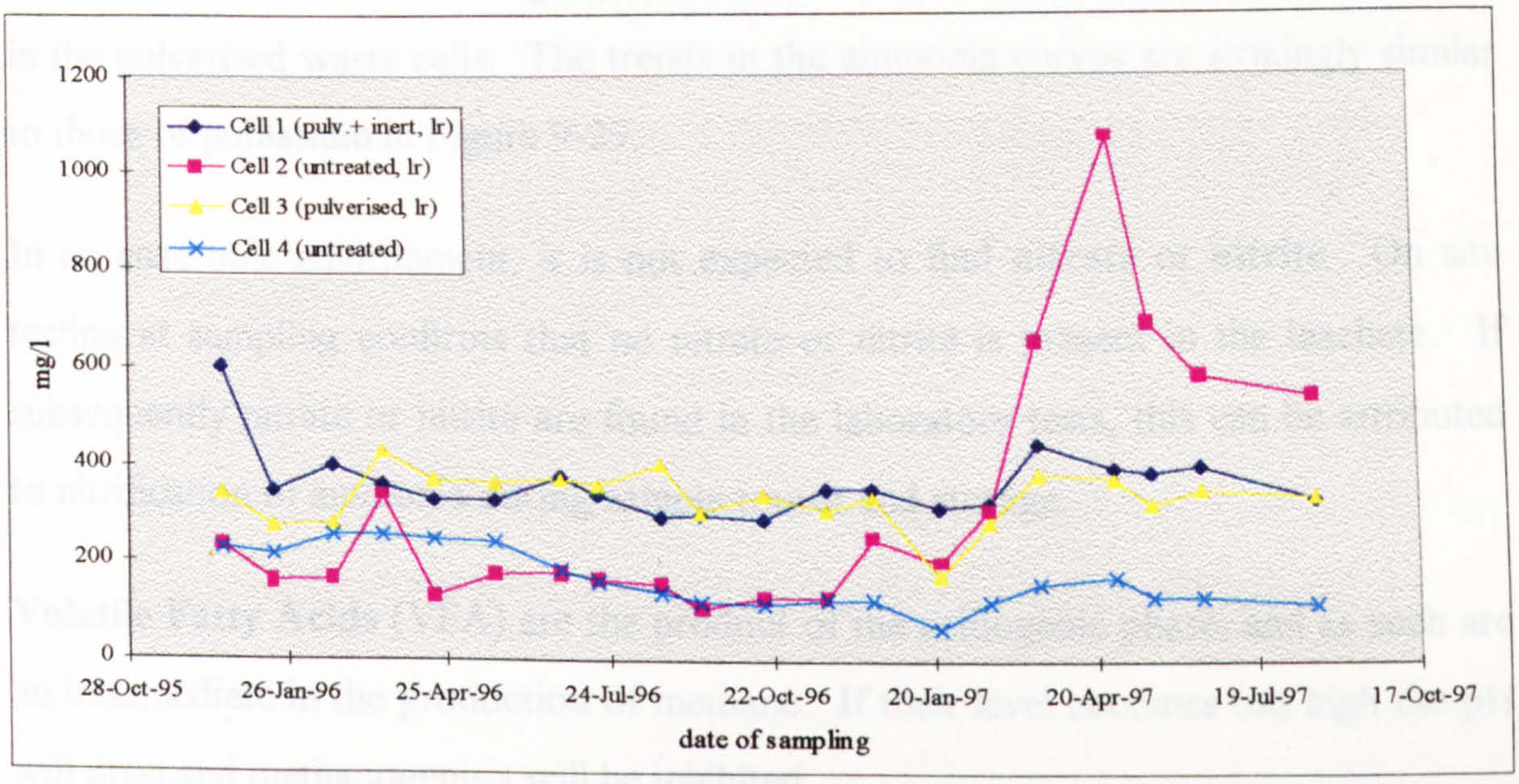
Magnesium is one of the parameters that appears to show that leachate recirculation has had some effect on the leachate composition of the pulverised waste cells. After recirculation begins on the 14 Nov 96, Cells 1 and 3 rise slowly but erratically. Cell 2 shows a stronger rise, but falls again as recirculation proceeds.

Figure 9-28 Sodium



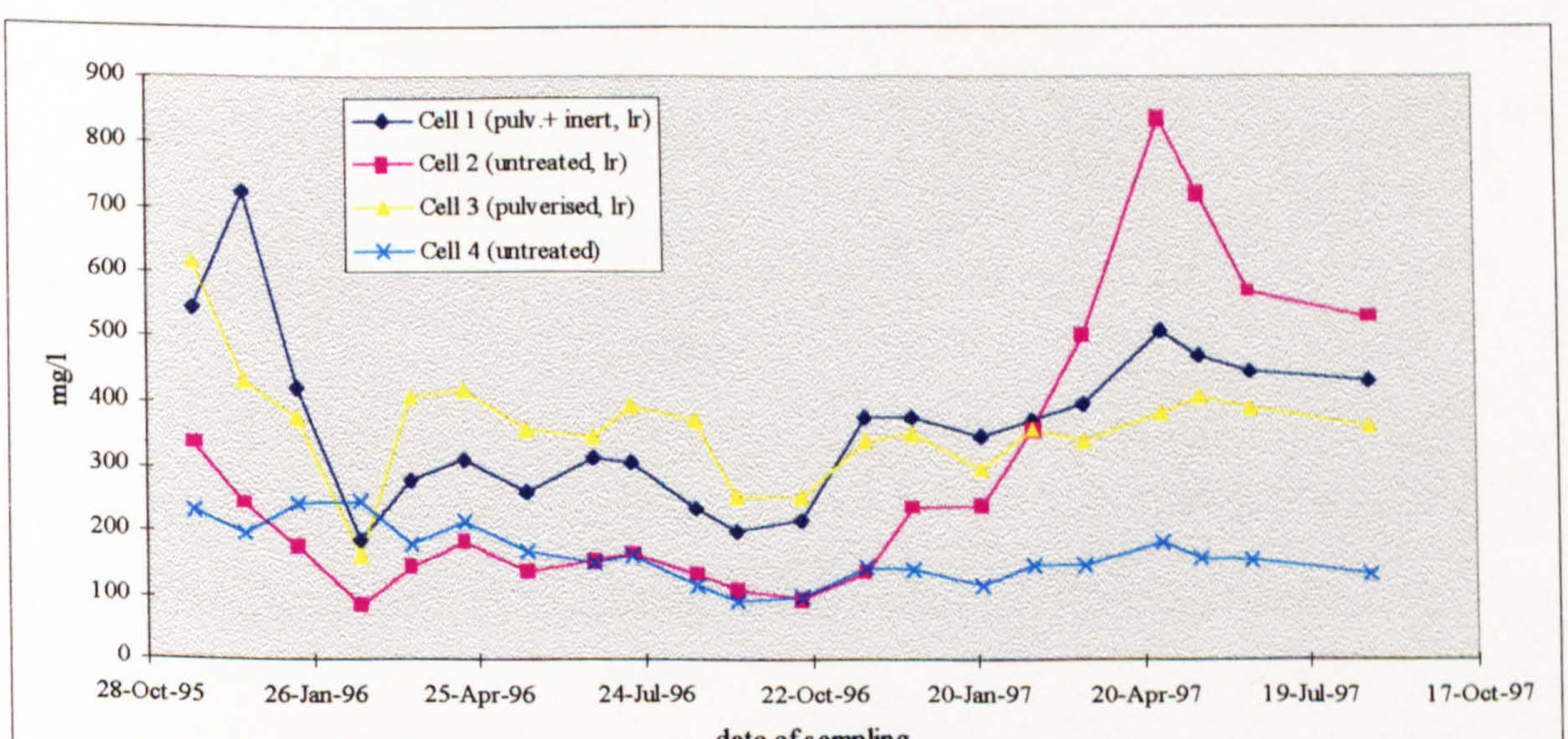
Sodium levels are roughly twice as high in the pulverised waste cells as the raw waste cells. This is probably due to higher moisture content leading to a higher leaching of sodium chloride. This is supported in the figure above in which chloride exhibits this same pattern in pulverised and raw waste cells. The sodium level in Cell 2 is elevated once recirculation begins, but stabilises at the same concentration as that in the pulverised waste cells.

Figure 9-29 Potassium



Potassium broadly follows the same trend as Sodium, although Cell 2 does not fall back to the same level as the pulverised waste cells.

Figure 9-30 Ammonia



Note: Nitrate and Nitrite levels continue to be zero in all cells

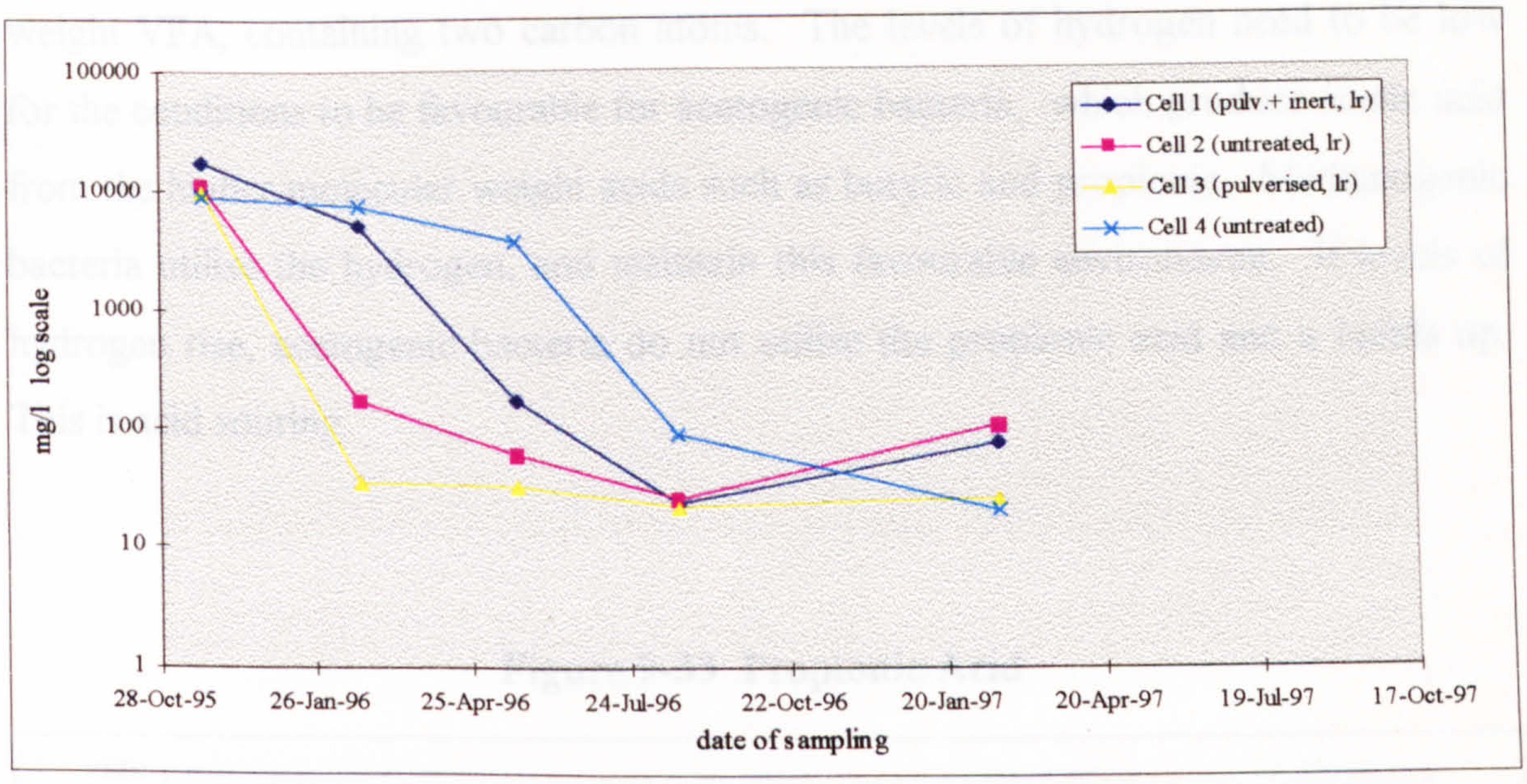
Ammonia is a by product of the hydrolysis of protein, and is a fundamental part of the nitrogen cycle. Cell 1 exhibits initial higher levels than other cells. This may be explained by higher rates of hydrolysis. As levels have stabilised the pulverised cells have approximately double the amount of ammonia in the leachate. This may be attributable to greater leaching and availability of protein substrate in these cells. Once leachate recirculation begins, the concentration in Cell 2 rises and exceeds that in the pulverised waste cells. The trends in the ammonia curves are strikingly similar to those of potassium in Figure 9-29.

In an anaerobic environment, it is not expected to find **nitrate** or **nitrite**. On site testing at sampling confirms that no nitrate or nitrite is present in the leachate. If subsequently nitrate or nitrite are found in the laboratory tests, this can be attributed to nitrification of ammonia during sample transit and storage.

Volatile Fatty Acids (VFA) are the product of the acidogenic phase, and as such are an intermediate in the production of methane. If their level becomes too high the pH will drop and methanogenisis will be inhibited.

The concentrations of Total Volatile Fatty Acids (TVA) are shown in the figure below. They are plotted on a log scale in order to see the lower values. The initial high levels explains the high COD, BOD and TOC.

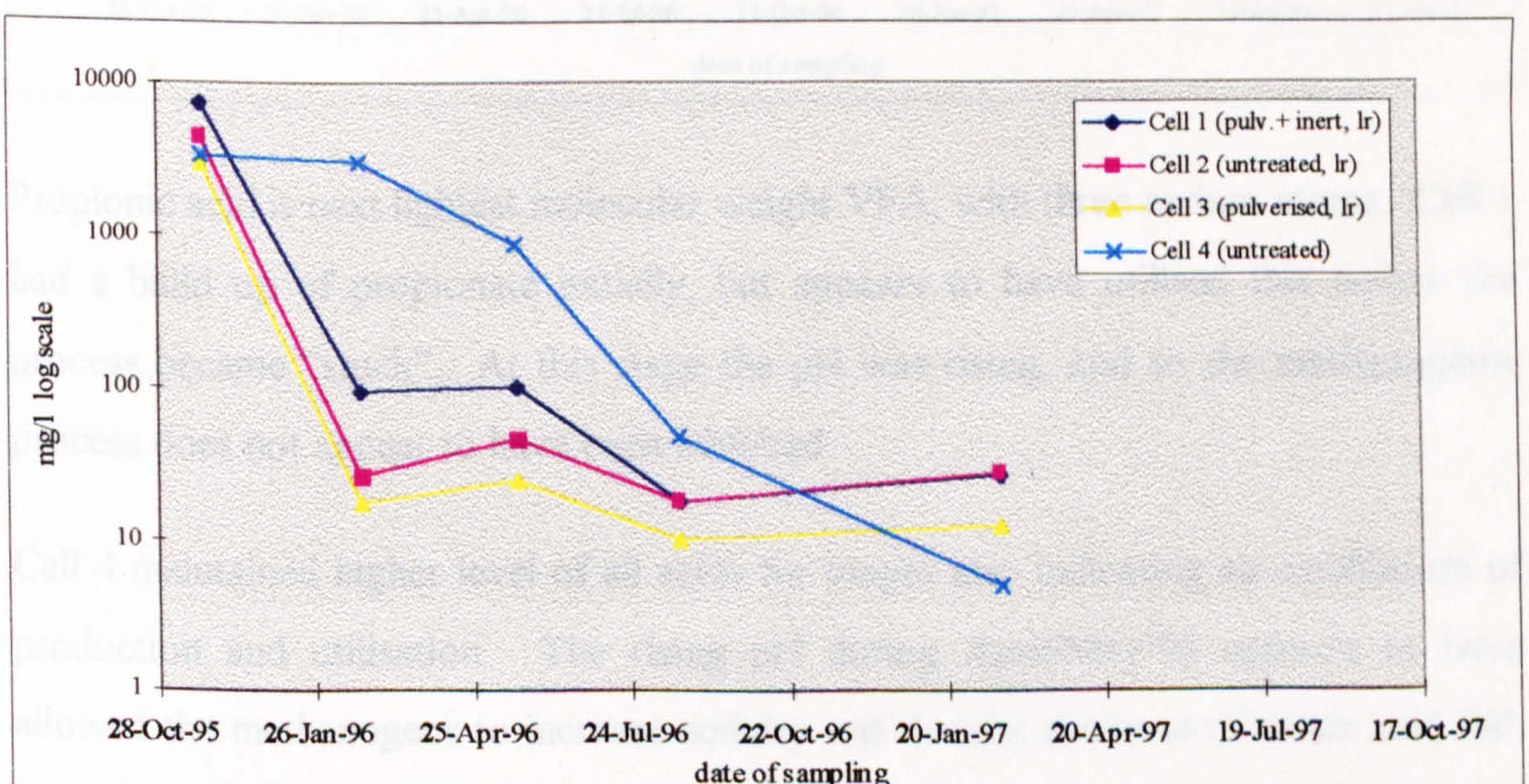
Figure 9-31 Total Volatile Acids



The levels of TVA fell fairly quickly in Cells 1- 3. In Cell 4 the levels remain high due to the accumulation of volatile fatty acids (VFA) during the acid souring episode.

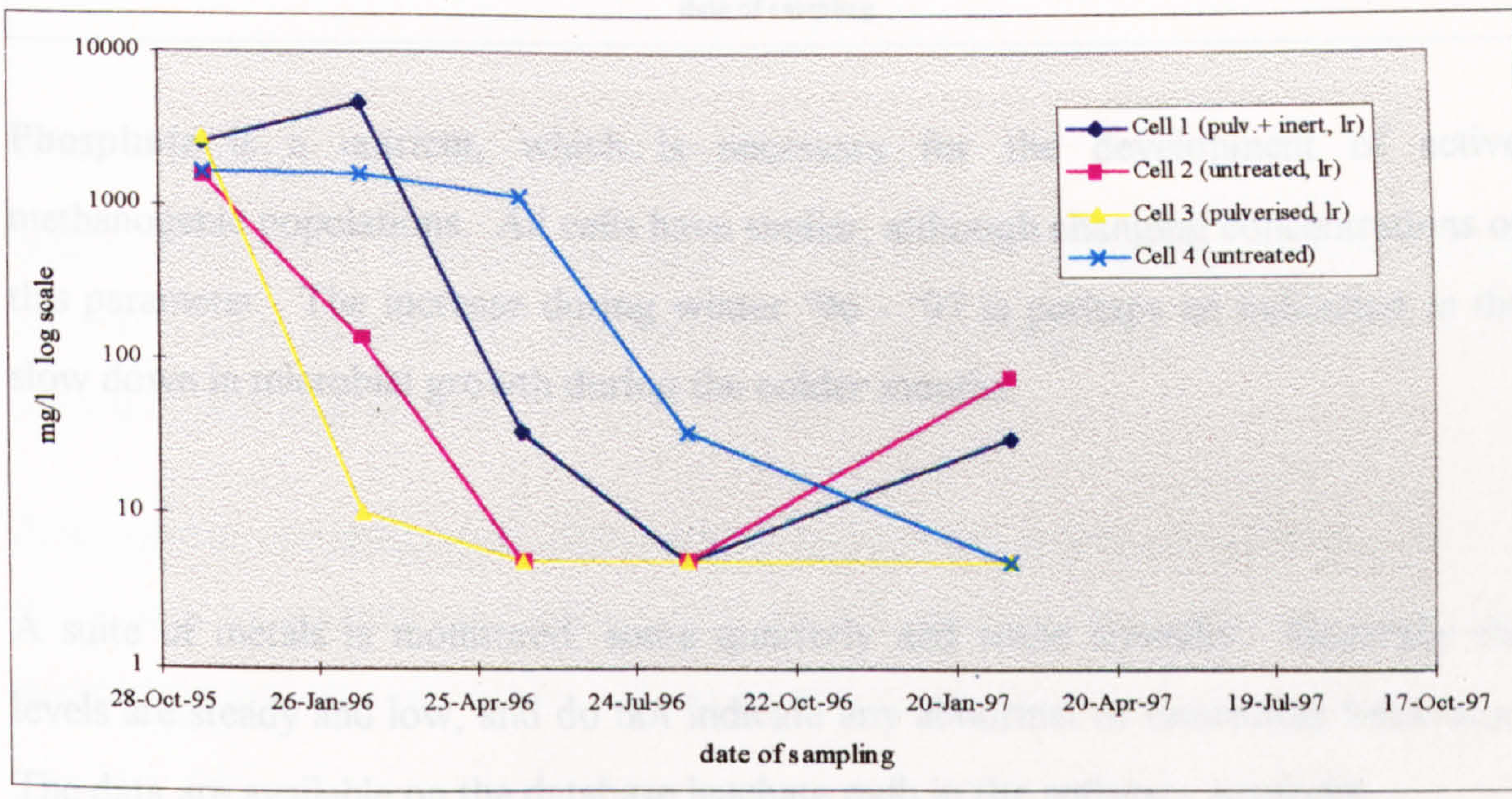
The most important individual VFAs are shown in Figure 9-32 Acetic Acid and Figure 9-33 Propionic Acid. After the initial high levels, there are now only trace concentrations of the heavier butyric and valeric acids.

Figure 9-32 Acetic Acid



Acetic acid is the principle substrate for methanogens. It is the lowest molecular weight VFA, containing two carbon atoms. The levels of hydrogen need to be low for the conditions to be favourable for acetogenic bacteria, which produce acetic acid from the higher molecular weight acids such as butyric and propionic. Methanogenic bacteria utilise the hydrogen, and maintain this favourable environment. If levels of hydrogen rise, acetogenic bacteria do not utilise the propionic acid and it builds up. This is acid souring.

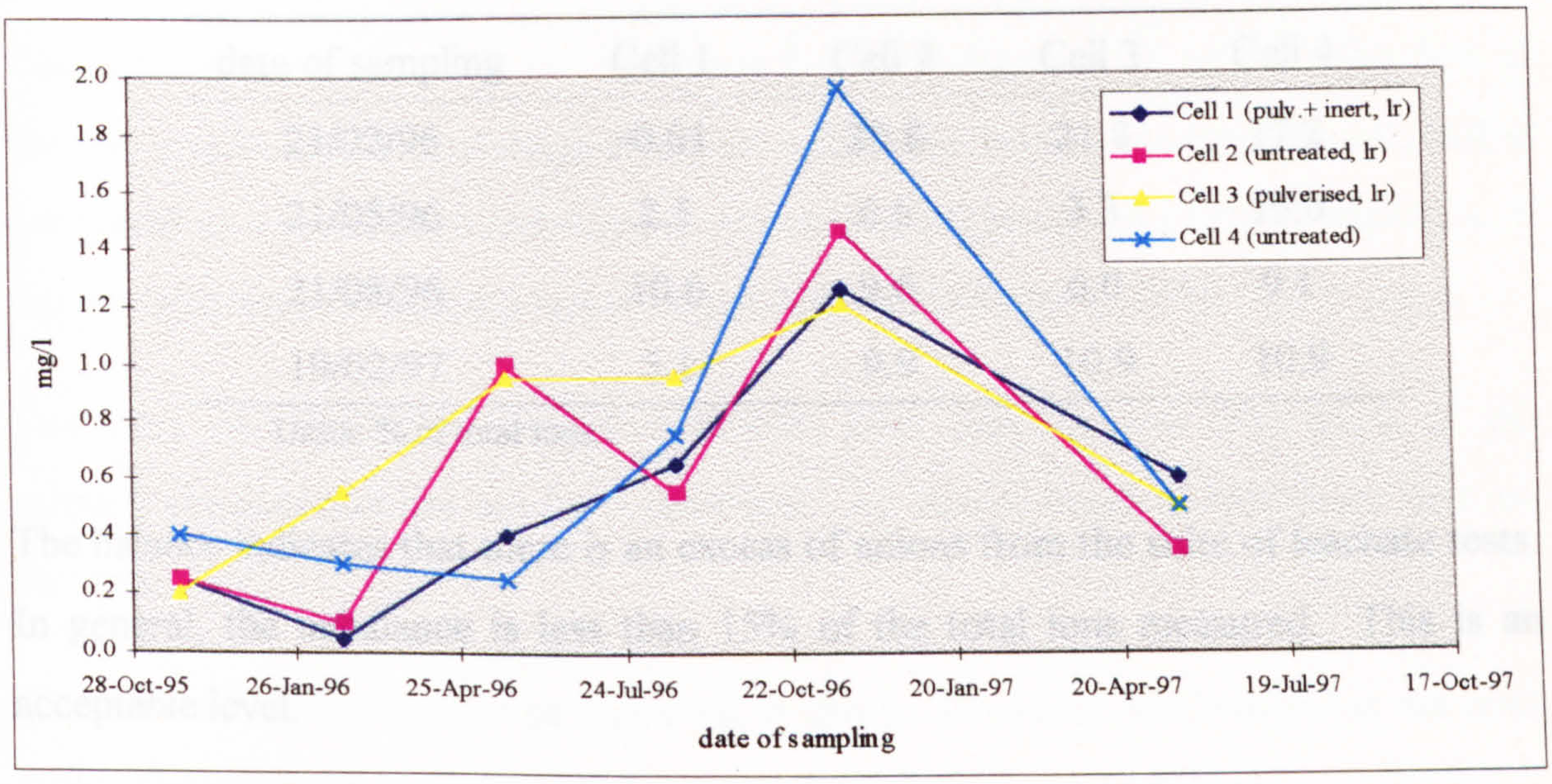
Figure 9-33 Propionic Acid



Propionic acid is next lightest molecular weight VFA, with three carbon atoms. Cell 1 had a build up of propionate initially, but appears to have utilised this before the process became "stuck". At this stage the pH was rising, and so the methanogenic process does not appear to have been inhibited.

Cell 4 maintained higher level of all acids for longer also indicating an equilibrium of production and utilisation. The rising pH during April/May'96 appears to have allowed the methanogens to increase activity and thereby the level of acetic acid fell. Conditions continued to become more favourable and the level of all the higher molecular weight acids fell as they were utilised by the acetogens.

Figure 9-34 Phosphate



Phosphate is a nutrient, which is necessary for the development of active methanogenic populations. All cells have similar, although changing concentrations of this parameter. The increase during winter '96 - '97 is perhaps an indication in the slow down in microbial growth during the colder months.

A suite of metals is monitored, some quarterly and some annually. Generally the levels are steady and low, and do not indicate any abnormal or interesting behaviour. The data are available on the database leachate.mdb in the software appendix.

9.9.1 Ionic Balance

An balance of anions and cations in the leachate was conducted. This is a method of verifying the quality of leachate analysis, as there will be an equilibrium of ions in solution.

Table 9.12 Ionic Balance of Leachate

date of sampling	Cell 1	Cell 2	Cell 3	Cell 4
21/02/96	-0.01	20.8	21.8	17.2
21/05/96	2.5	6.6	3.3	19.0
21/08/96	10.6	9.6	6.0	9.1
19/02/97	5.1	9.9	10.9	10.9

Units: % of total ions

The balance indicates that there is an excess of anions from the suite of leachate tests. In general, the imbalance is less than 15% of the total ions measured. This is an acceptable level.

9.9.2 Summary of Leachate Composition

Organic components in the leachate began at high levels. At this stage, approximately two years after capping, all cells have low levels of organics, as they have been utilised by microbial activity.

Acid souring occurred soon after capping in the comparison cell, Cell 4. At this stage, prior to leachate recirculation, Cell 2 and 4 were experimentally identical. The explanation for only one of these cells experiencing acid souring in not known.

The leachate data broadly shows that pulverised waste results in a higher concentration of soluble components in the leachate, with the exception of calcium, which results in a lower concentration.

Leachate recirculation on untreated waste (Cell 2) flushes soluble material into the leachate. The concentration of soluble materials in the leachate changes in time to a level similar to that in the pulverised waste cells.

Leachate recirculation does not appear to have a significant effect on the leachate chemistry of the pulverised waste cells.

9.10 Settlement

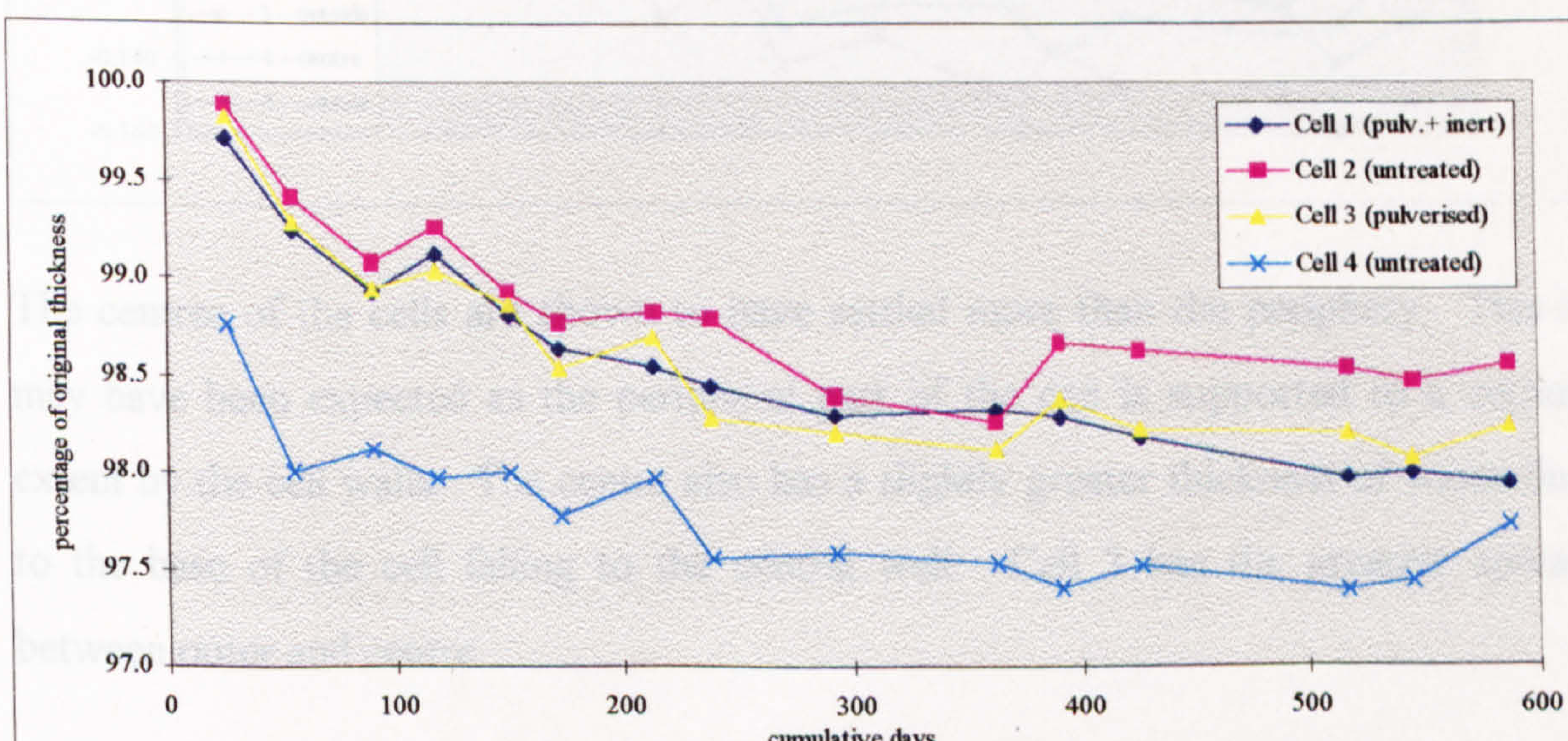
The cumulative settlement is shown Figure 9-35 and Figure 9-36 below. The first of the two graphs shows an average of the six settlement monuments for each cell, and is calculated as a percentage reduction in wastemass thickness. A nominal thickness of 5m has been used. Stabilised waste may reduce in thickness by 25%.

Day zero was 01/02/96, some two months after capping, and thus much of the primary compression has not been recorded. All curves begin at settlement zero on day zero.

The general trend, as would be expected, is down. However, settlement has not been rapid. The apparent heave in Cell 2 at around day 385 is not explained.

Cell 4 has consistently the greatest settlement, but was capped 3-4 weeks later than the other cells, and therefore the tail of the primary compression[1] may have been recorded. This is supported by the fact that the *rate* of settlement for Cell 4 after the first two data points is the same or less than the other cells.

Figure 9-35 Wastemass Settlement as a Percentage of Original Thickness



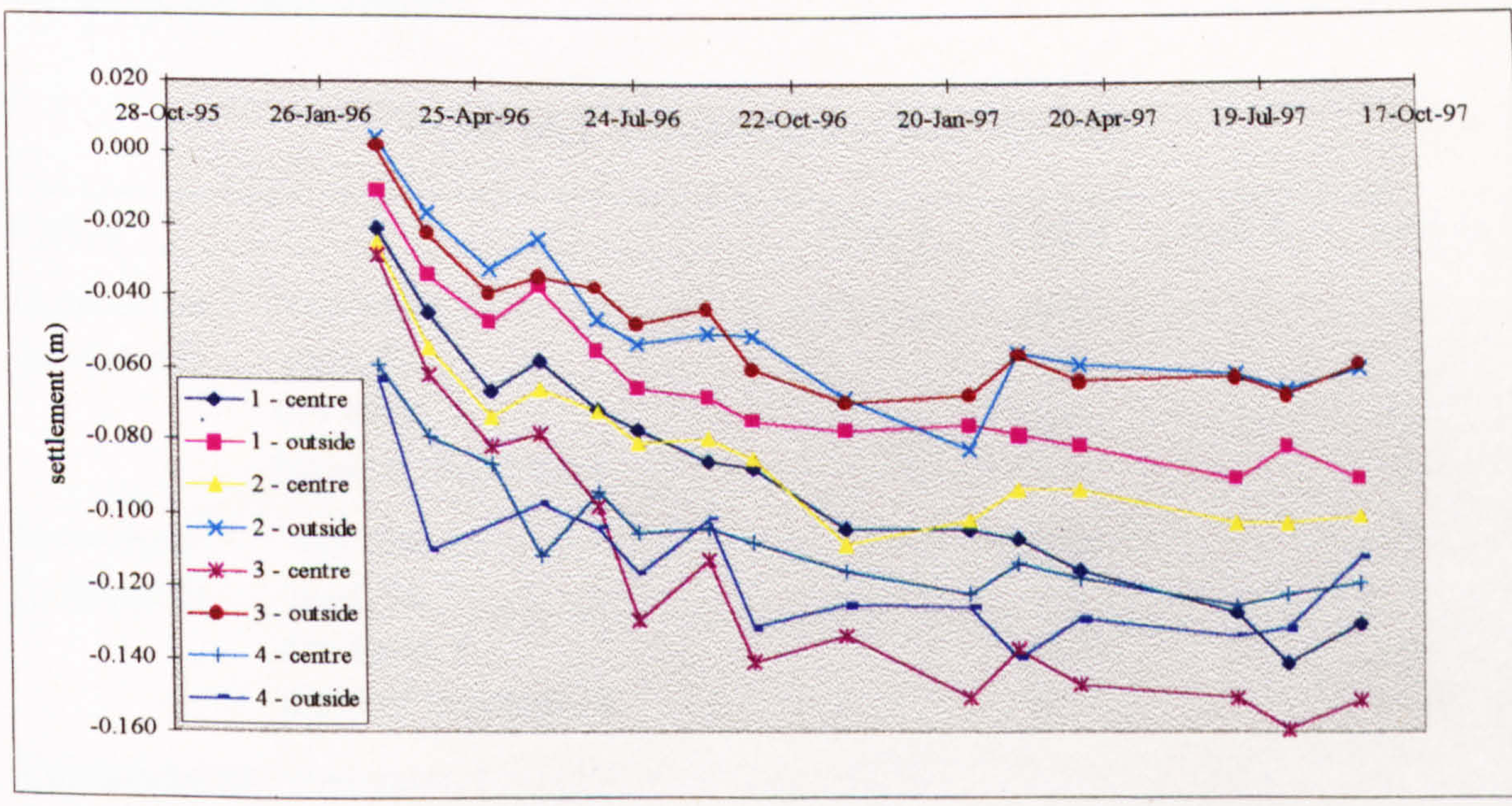
Note: Settlement monitoring began after capping, and as a result 'primary compression' of the waste is not included in this data. Original thickness nominally 5m.

[1] see Section 5.2.5

Assuming that the initial settlement of Cell 4 was indeed primary compression, then it is clear that the two pulverised waste cells, 1 & 3, have settled more than the untreated waste cells. At this stage, the difference is marginal in terms of the total settlement that may be expected.

Figure 9-36 shows two curves for each cell. For each cell, the four peripheral settlement monuments have been grouped together and averaged to produce the "outside" value. The two inner settlement monuments have been grouped to produce the "centre" value.

Figure 9-36 Cumulative Settlement at Centre and Periphery of Cells



The centres of the cells are shown to have settled more than the periphery. This is may have been expected as the peripheral part of the cap is supported to a certain extent by the cell walls. The centre also has a slightly greater thickness of waste due to the base of the cell falling to the central well. Cell 3 has the greatest spread between outer and centre..

The magnitude of settlement of all of the cells has been low during the first two years after capping, however it is clear that the centres of the pulverised waste cells are settling faster than the untreated cells.

9.11 Weather

Climatological conditions are recorded as supporting data. The data are presented where it is used. The full automatic weather station dataset is held on database file weather.mdb in the software appendix.

10 FURTHER ANALYSIS OF DATA AND DISCUSSION

10.1 Water Balance

10.1.1 Calculation of Bed Volume

Taking the waste input data, together with moisture content analysis and water additions, the total amount of moisture in each cell can be calculated. This figure is known as the Bed Volume.

Table 10.1 Calculation of Bed Volume

source		Cell 1	Cell 2	Cell 3	Cell 4
Dumbarton (untreated)	wet mass, t		816		823
	mcd, %		62		62
	dry mass, t		503		507
	mass of moisture, t		313		316
Inverclyde (untreated)	wet mass, t		2168		1813
	mcd, %		31		31
	dry mass, t		1655		1384
	mass of moisture, t		513		429
Cunninghame (pulverised)	wet mass, t	3579		3452	
	mcd, %	67		67	
	dry mass, t	2140		2064	
	mass of moisture, t	1439		1388	
Inert (sand)	wet mass, t	1696			
	mcd, %	13			
	dry mass, t	1501			
	mass of moisture, t	195			
	total dry mass of input, t	**3642**	**2158**	**2064**	**1892**
	moisture in waste stream, t	1634	827	1388	745
	added moisture before cap, t	264	319	230	328
	added moisture after cap, t		74		
Bed Volume:	total mass of moisture, t	**1898**	**1219**	**1618**	**1074**

Note: **mcd is moisture content on a dry mass basis.**

Cell 1 contains a larger amount of dry matter, however the cell is a little larger than the other three cells. The figures for dry mass should been considered in context of cell size, this has been done in Section 9.4 on waste density.

The bed volume for each of the cells is the total amount of moisture in the cell. Not surprisingly the bed volume in the pulverised waste cells is greater than in the cells containing untreated waste. The quantity of moisture in each of the cells is substantial.

The 'whole cell moisture: waste ratio' (MWR) may be defined as the bed volume divided by the total dry mass of waste in the cell. It is not a tangible measurement, but a calculated parameter. It tells us the ratio of moisture to dry matter within the cell as a whole, ignoring whether the leachate is free, or in a saturated or un-saturated zone.

Table 10.2 Whole Cell Moisture:Waste Ratio

	Cell 1	Cell 2	Cell 3	Cell 4
Whole Cell Moisture: Waste Ratio, %	52	56	78	57
Typical Leachate Head, m	2.5	0.5	3.5	1.4

What is surprising is that Cell 1 has the lowest MWR, which is a reflection of the low moisture content of the inert material element of that cell's input. However, it is not reflected in leachate levels, the progressive build up of which is given in the previous chapter. Cell 1 has a significantly higher leachate head than Cells 2 or 4, despite having less moisture per unit dry mass. This implies that the porosity of the material in Cell 1 is significantly lower than Cell 2 & 4, the untreated waste cells. A significant difference in porosity between Cells 1 & 3 is not indicated. The MWR of Cell 3 is higher than Cell 1, but so also is the depth of saturation, given by the level of the free leachate surface.

10.1.2 Hydraulic Retention Time and Other Ways of Expressing Flushing Rates

Background

In lysimeter trials, Knox (1996) determined that 7 bed volumes of liquid needed to be passed through the wastemass to reduce the concentration of pollutants by 3 orders of magnitude - a level which was fairly benign, ie. close to the walk away *final stage quality*. The aim is to achieve all this in the 30 year time frame allowed within the principles of sustainability. Flushing of pollutants from the wastemass requires clean water, or treated leachate, to be the recirculated. To date recirculation in the test cells has been with untreated leachate to enhance degradation. The following discussion is determining whether, during a future flushing phase, it would be possible to flush the cells within the prescribed time frame.

Flushing Rates

Flushing rates have traditionally been measured by a parameter called the Hydraulic Retention Time (hrt). This can be conceptualised as the amount of time required to pass one bed volume through the wastemass. The hydraulic retention times for each of the cells is given in the Table 10.3 below. The table shows that at the current rates of leachate recirculation it would be possible to flush 7 bed volumes through the pulverised waste cells in excess of 35 - 40 years. The untreated cell can according to this parameter be flushed in a shorter period.

Bioreactor enhancement techniques, such as wet pulverisation, intentionally result is an increase in bed volume. This should not prejudice the perceived sustainability of the enhancement technique - which is the case when using the parameter hydraulic retention time. A more appropriate measure of flushing is, the mass of liquid per unit dry mass of waste. Thus not only is added water eliminated from the parameter, but also variations in the moisture content of the waste stream.

Table 10.3 Comparison of Results for Different Method of Measuring Flushing Rates

	Cell 1	Cell 2	Cell 3
waste type	pulv. + inert	untreated	pulv.
bed volume, m^3	1898	1219	1618
volume recirculated, m^3 in 1 year	346	316	307
hydraulic retention time	5.5	3.9	5.3
time to flush 7 bed volumes, years	**38.4**	**27.0**	**36.9**
mass of leachate recirc. t/t dm msw only	0.162	0.146	0.149
mass of leachate recirc. t/t dm msw + inert	0.095		
time to flush 4.7t liquid/t dm msw only, years	**29.1**	**32.1**	**31.6**
time to flush 4.7t liquid/t dm msw + inert, years	49.5		

It has been calculated (Knox,K 1996) that 4.7 tonnes of liquid need to be passed through each tonne dry mass of waste to achieve a reduction of level of pollutants of 3 orders of magnitude. Thus when these calculations are applied to the three test cells that have leachate recirculation, a more realistic picture emerges. It appears that in around 30 years, flushing could be achieved. This parameter is a much a more reliable measure of flushing progress.

The additional figure for Cell 1 is the same calculation, but with the dry mass of inert material included. It has a significant impact. However whether it should be taken into account depends on the nature of the inert material. If it was a material, such as incinerator ash, that contained significant pollution potential, then it should be included. If it is truly an relatively inert material, such as uncontaminated demolition material, then it should not be included.

10.1.3 Post Capping Water Balance

The period over which this water balance is considered is the two years since capping. The source of the majority of moisture within the wastemass was the waste stream itself, although precipitation and other inputs played a part, as has been shown above. After the cells were capped, the scope for significant water efflux and influx was greatly reduced.

The main source of gain of water post capping is infiltration through the cap. The main source of water loss is as moisture in the landfill gas, and water that is used in the anaerobic fermentation of cellulose. Exchanges between groundwater and leachate have been assumed to be zero over the two year period since capping that is being considered. It is likely that there will have been some exchange, but without a more detailed knowledge of the surrounding groundwater conditions the magnitude and direction of the exchange is not easy to assess.

Gains and losses from various sources are considered in the following sections. These are then summarised in a water balance shown in Table 10.7.

Gain from Infiltration

Modelling infiltration on the basis of precipitation, using recorded rainfall data was considered, but was rejected due to the particular nature of the system. The system is as follows: The cap on a cell consists of around 1.2m of remoulded clay. Above this there is around 1.0m of peaty topsoil. The topsoil is vegetated with grasses.

Observations on site have shown that the top of the cap has water standing on it for around 9 months of the year. The depth of water within the survey staff tubes passing through the topsoil down to the settlement monuments on the cap, is typically 100 - 300mm, during this period. Therefore, individual precipitation events are having little effect on the availability of water for infiltration through the cap.

A simplified model has been developed, in which the infiltration through the cap is considered to be occurring at a constant rate over the whole surface of the cap, over an active period during the year. The active period is eight months, that is nine months as above, less one month during winter when the ground in frozen.

Although there is water standing in the staff tubes, it has been assumed that within the peat topsoil, the head of water on the cap is negligible, because of the capillarity of the peat. However, it has been assumed that the peat will provide sufficient water for infiltration during the active period. Therefore the term 'dh' in Darcy's equation will be the thickness of the capping, and will not include the head of water observed in the staff tubes. The table below shows the calculation.

Table 10.4 Gain of Water from Infiltration through Cap

Parameter	Value	Comments
Plan area of cell at top, m2	900	'A'. nominal 29x31m
Permeability of capping, m/s	10^{-9}	'K'. ex lab. tests on material from adj. site
Thickness of capping, m	1.2	this is 'dh' as well as 'dl'
Period to consider, months	16	over 2 yr from Nov.'95 - Nov.'97
Infiltration rate, m^3/day	0.07776	Mr Darcy's equation: Q = KAdh/dl
Infiltration over 2 years, m^3	**37.8**	

Losses as Vapour in Landfill Gas

The quantity of vapour in landfill gas is variable, and temperature dependent. It has not been measured at these experimental cells. The literature (Great Britain. DoE, 1986; Knox,K 1991) suggests that between 10 and 50 litres of water per 1000 m^3 of landfill gas is evolved. Some of the values put forward are those for air, but these agree with values found at landfill gas condensate removal plants.

Table 10.5 Loss of Water as Vapour in Landfill Gas

	Cell 1	Cell 2	Cell 3	Cell 4
Typical water content, l/1000m^3 lfg	25	25	25	25
Cum. gas output over 2 years, m^3	39701	18438	18647	13713
Loss over 2 years, m^3	**0.993**	**0.461**	**0.466**	**0.343**

Observations on site indicate that the gas is not saturated, and the gas is at a low temperature compared to many large landfills. Therefore a conservative figure of 25l/1000 m^3 lfg has been adopted. The cumulative gas output has been calculated on a 'single point + compensation' basis as described in Section 10.3.2. The average output over the period 27/09/96 to 05/11/97 was used to estimate the total landfill gas output over a two year period. During the majority of this period leachate recirculation was being carried out.

Water Loss Through Anaerobic Fermentation

Anaerobic fermentation of cellulose uses water. Using the Buzwell equation (Knox,K 1991), 1 mol (18g) of water are used for every 6 mols (72g) of carbon anaerobically fermented. Using typical gas outputs, this equates to 135litres of water/1000 m^3 landfill gas.

Table 10.6 Water Use in Anaerobic Fermentation

	Cell 1	Cell 2	Cell 3	Cell 4
Mass of water used, l/1000m^3 lfg	135	135	135	135
cum gas output over 2 years, m^3	39701	18438	18647	13713
Loss over 2 years, m^3	**5.36**	**2.49**	**2.52**	**1.85**

Net Change in Water Balance

The magnitudes of inputs and outputs are small. Table 10.7 below shows that there is modest gain of water in the cells. However the change in bed volume over this initial two year period is shown to be negligible.

Table 10.7 Post Capping Water Balance and Significance to Bed Volume

	Cell 1	Cell 2	Cell 3	Cell 4
bed volume	1898	1219	1618	1074
Gains:				
infiltration through cap	37.8	37.8	37.8	37.8
Losses:				
water vapour in landfill gas	0.993	0.461	0.466	0.343
anaerobic fermentation	5.36	2.49	2.52	1.85
Balance over 2 years, m^3 gain	**31.5**	**34.9**	**34.9**	**35.6**
% increase to bed volume	**1.7**	**2.9**	**2.2**	**3.3**

10.2 Hydraulic Properties of the Wastemass

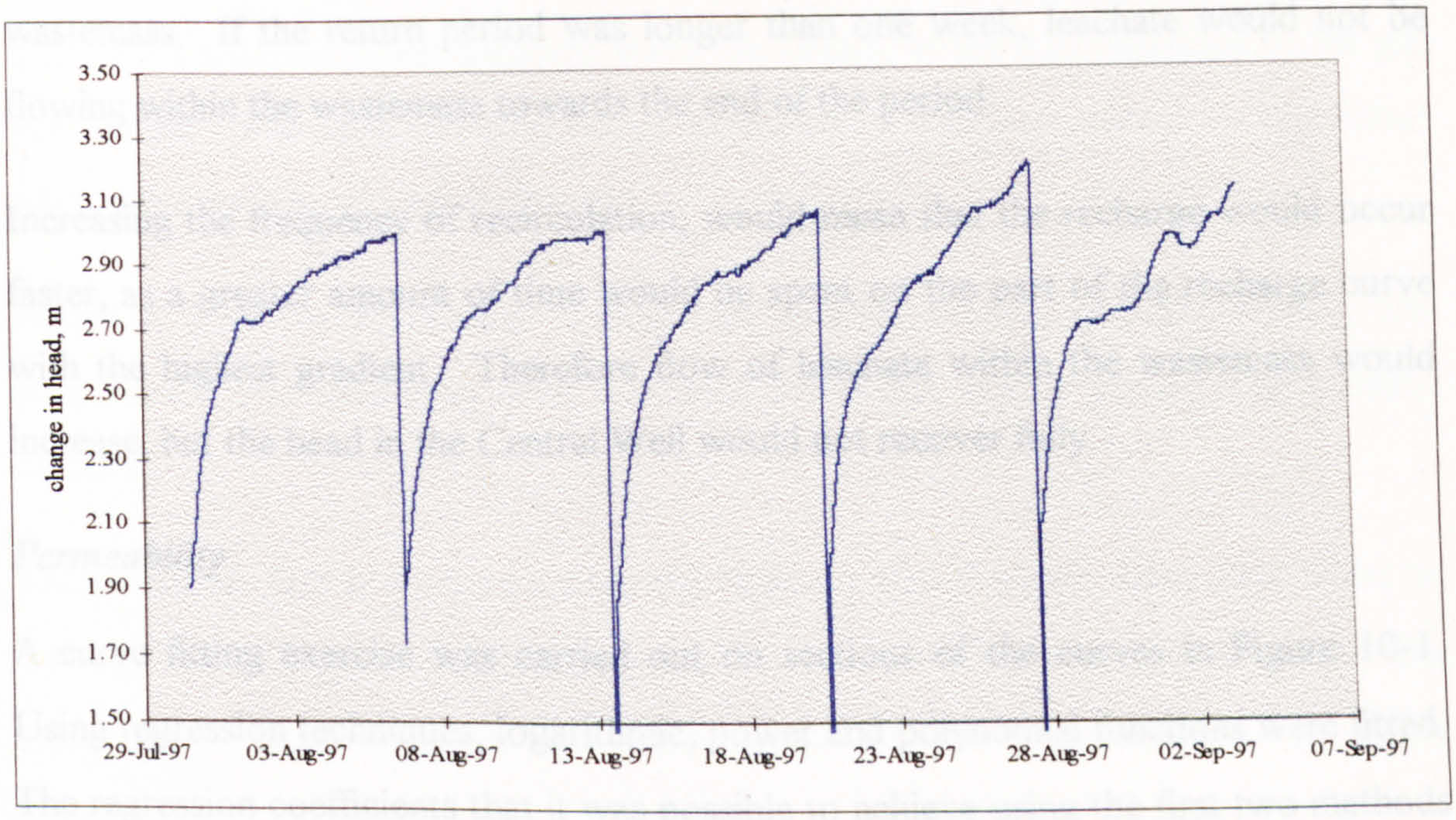
In an effort to ascertain some of the hydraulic properties of the wastemass, a programme of logging recharge of the leachate in the Central Well was undertaken. The methodology and equipment is described in Section 8.8. It was hoped that an indication of permeability of the wastemass could be established. Due to the Cell design, recharge of the Central Well is affected by both horizontal and vertical permeability. Landfilled waste is known to be anisotropic in this parameter. Despite, this, a composite figure for permeability would provide a greater understanding of the system and could provide calibration data for future modelling.

10.2.1 Logging of Leachate Recharge in Central Well

Logging was carried out over five weekly leachate recirculations, carried out on Cell 1 during August and September 1997. After pumping of leachate had ceased, the pump was withdrawn from the Central Well and the logger introduced.

Figure 10-1, below, shows five cycles of leachate recharge. The logging increment was 15 minutes and the accuracy of head measurement was 1cm.

Figure 10-1 Leachate Recharge Cycles in Cell 1



The curves are fairly smooth, although there does tend to be a step after about 3 days of recharge. The curve in the fifth week appears to be a little erratic. The instrument is not pressure compensated which may have affected measurements. Weather data[1] shows that barometric pressure was more variable during the fifth week, whereas the preceding four weeks were virtually static.

Logging was carried out on Cell 3 as well to establish whether the addition of inert material in Cell 1 had an affect on the recharge, and therefore the permeability. A number to cycles were logged during September '97, but unfortunately a setting up error made the data unusable. A further three cycles were logged in November '97, but the curves produced were rather erratic, for reasons that have yet to be established.

Time to Recharge

The curves in Figure 10-1 show that the leachate level was taking a full week to recharge. This is an important finding, in terms of scheduling recirculation. It shows

---

[1] see weather.mdb in software appendix

that the return period of one week is correct for the hydraulic characteristics of this wastemass. If the return period was longer than one week, leachate would not be flowing within the wastemass towards the end of the period.

Increasing the frequency of recirculation, would mean that the recharge would occur faster, as a greater amount of time would be spent on the part of the recharge curve with the highest gradient. Therefore flow of leachate within the wastemass would increase, but the head in the Central Well would not recover fully.

Permeability

A curve fitting exercise was carried out on sections of the curves in Figure 10-1. Using regression techniques, logarithmic, power and polynomial functions were fitted. The regression coefficients that it was possible to achieve using the first two methods were not good; between 0.9 - 0.95. A third order polynomial achieved a regression coefficient of 0.99. However the forms that equations of recharge take, according to the literature, are not polynomial. Nevertheless, this is not to deny that an equation may not be created which describes the curve, as none of the equations found in the literature address the particular hydrological set up of these experimental cells.

Within the time and scope of this thesis, it was not feasible to create a model to describe the recharge in terms of permeability. In the future this may happen, and the data collected may be used to calibrate the model.

10.3 Gas Output

Gas output from the experimental cells is the key method of assessing the progress of degradation. In terms of remaining within the timeframe allowed by the goals of sustainability, the rate of gas output is therefore crucial.

10.3.1 Quality and Reliability of Gas Flow Data

There have however, been concerns about the quality of the data collected by the gas flow meters. The measured spot values are highly variable and there have been times when there were large gaps in the data.

Figure 10-2 shows the number of days that no daily average gas flow reading was established. The data have been corrected for power supply failures and propane outages.

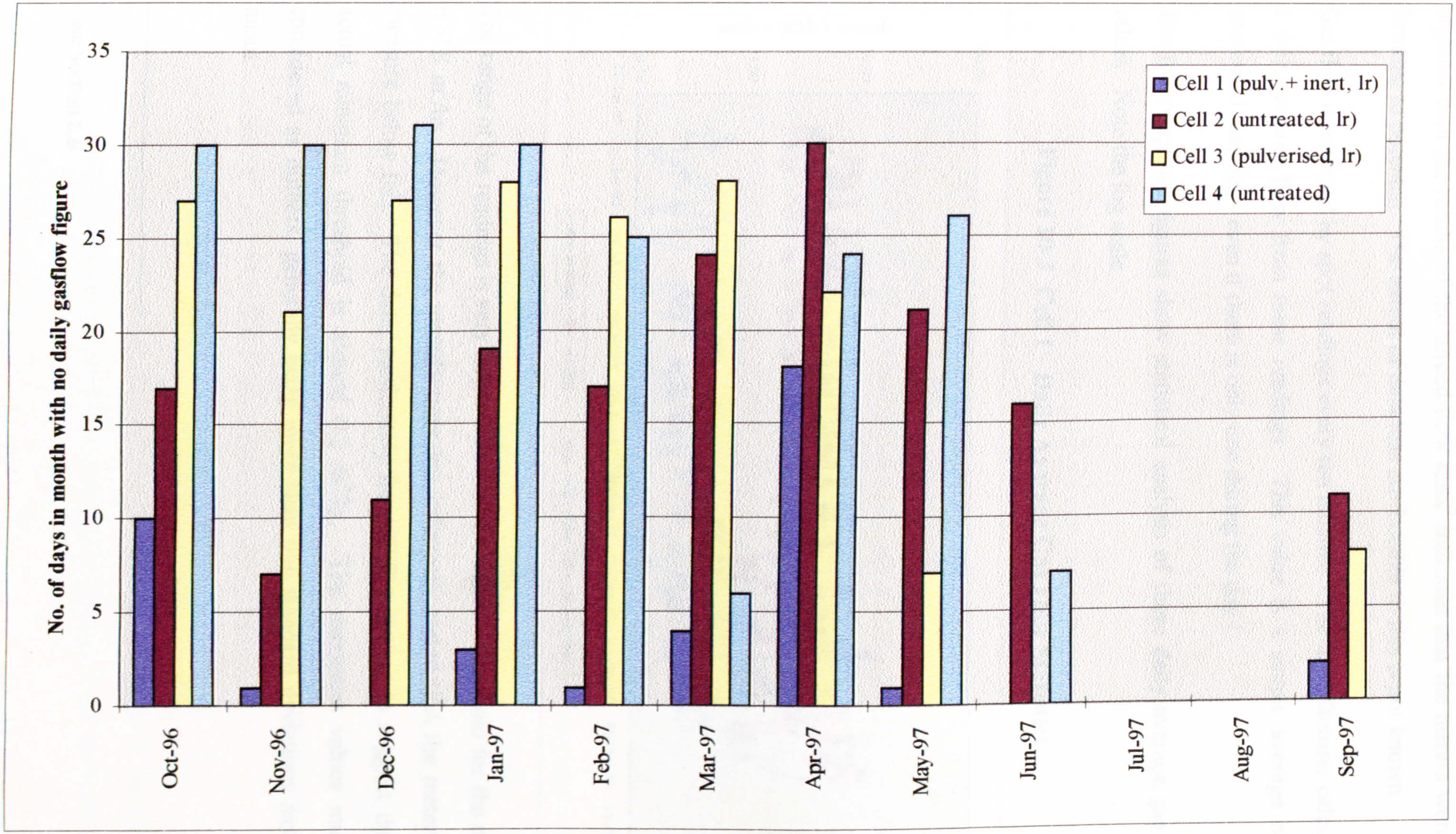
The immediate fact to be drawn from the Figure is that there are many days when no readings are collected. Cell 4 was particulary poor during winter 96-97, recording very few readings during a five month period. Cell 1 in contrast was highly successful.

There are a number of explanations for this:

- the gas flow was below the minimum threshold for the meter
- wind or other climatological factors adversely affected the flow of gas at the time the spot reading was taken
- the gas was relatively cold compared to many sites, and an inadequate thermal gradient was created by the vapourising propane
- the gas flow meter was not functioning satisfactorily

The first point probably played a part in the poor performance of Cell 4. However, after the service visit of June'97, the increase in performance was quite remarkable.

Figure 10-2 Frequency Distribution of Days When No Daily Average Gas Flow Value Was Established

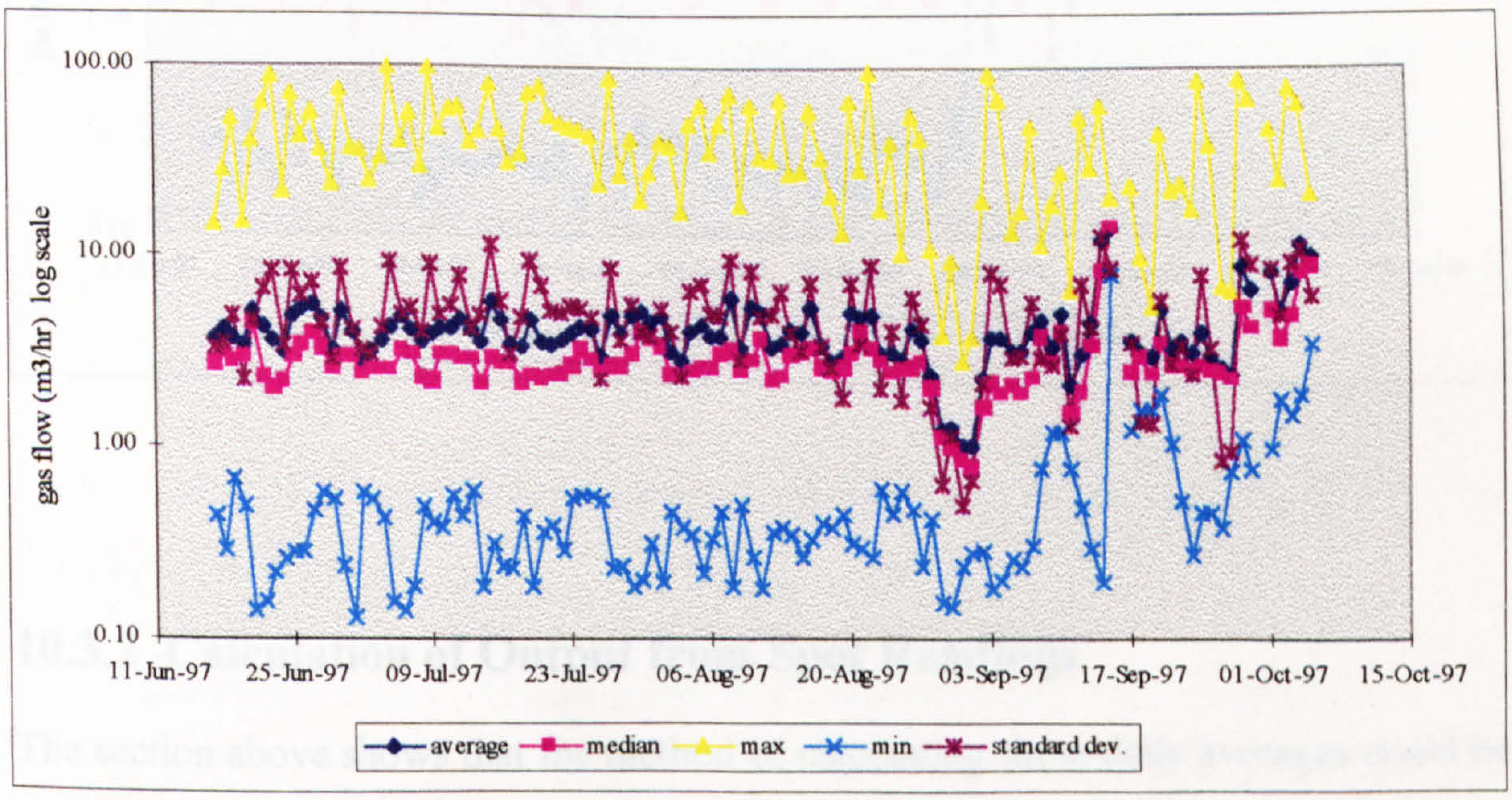


A flow was established every day in all the cells for the subsequent two months. This, together with the results of the forced flow tests[1] indicates that the meters were not working to potential. The extent of data loss attributable to this is not known.

Gas flow is recorded by spot readings every ten minutes. The manufacturer calculates a daily average flow from these readings. This value is a simple average of the successful readings - even if there is only one during the day !

The following two figures show statistical analysis of these daily average gas flow values. Note the log scale.

Figure 10-3 Cell 1 - Daily Average Gas Flow Statistics

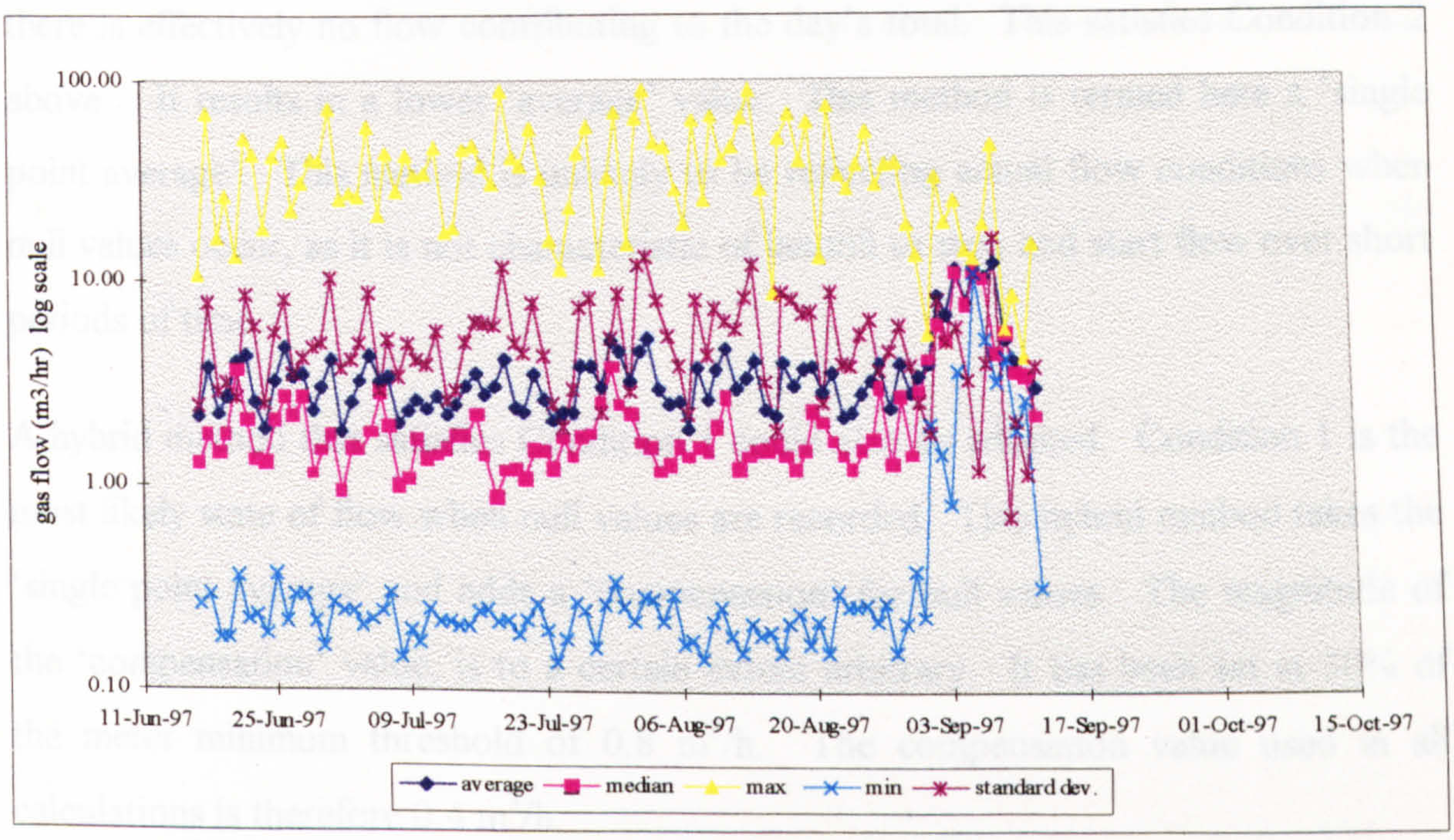


The range of the readings is very large. The stated minimum threshold for the meters is 0.8 m^3/hr. However the manufacturer has informally stated that the meters *will* measure below this. The data, particularly from Cell 4 appear to suggest that the actual minimum threshold is around 0.2 m^3/hr. The maximum values must be considered as outliers, generally being more than five standard deviations from the mean.

[1] see Section 8.6

The average is slightly above the median in both cells, indicating that the distribution of data are skewed from a normal distribution. The standard deviation is large, and in fact is typically larger than the value itself.

Figure 10-4 Cell 4 - Daily Average Gas Flow Statistics



10.3.2 Calculation of Output from Spot Readings

The section above shows that the method of calculating these daily averages could be improved upon. The crux of the matter is how to deal with null values in the 10 minutes reading dataset. The possible reasons for null values have been outlined above for daily values. The same reasons apply for the 10 minute values. Perhaps, just two states in which null values occur, can be considered, in order to simplify the problem:

1. gas flow is below threshold, but above zero
2. gas flow is zero

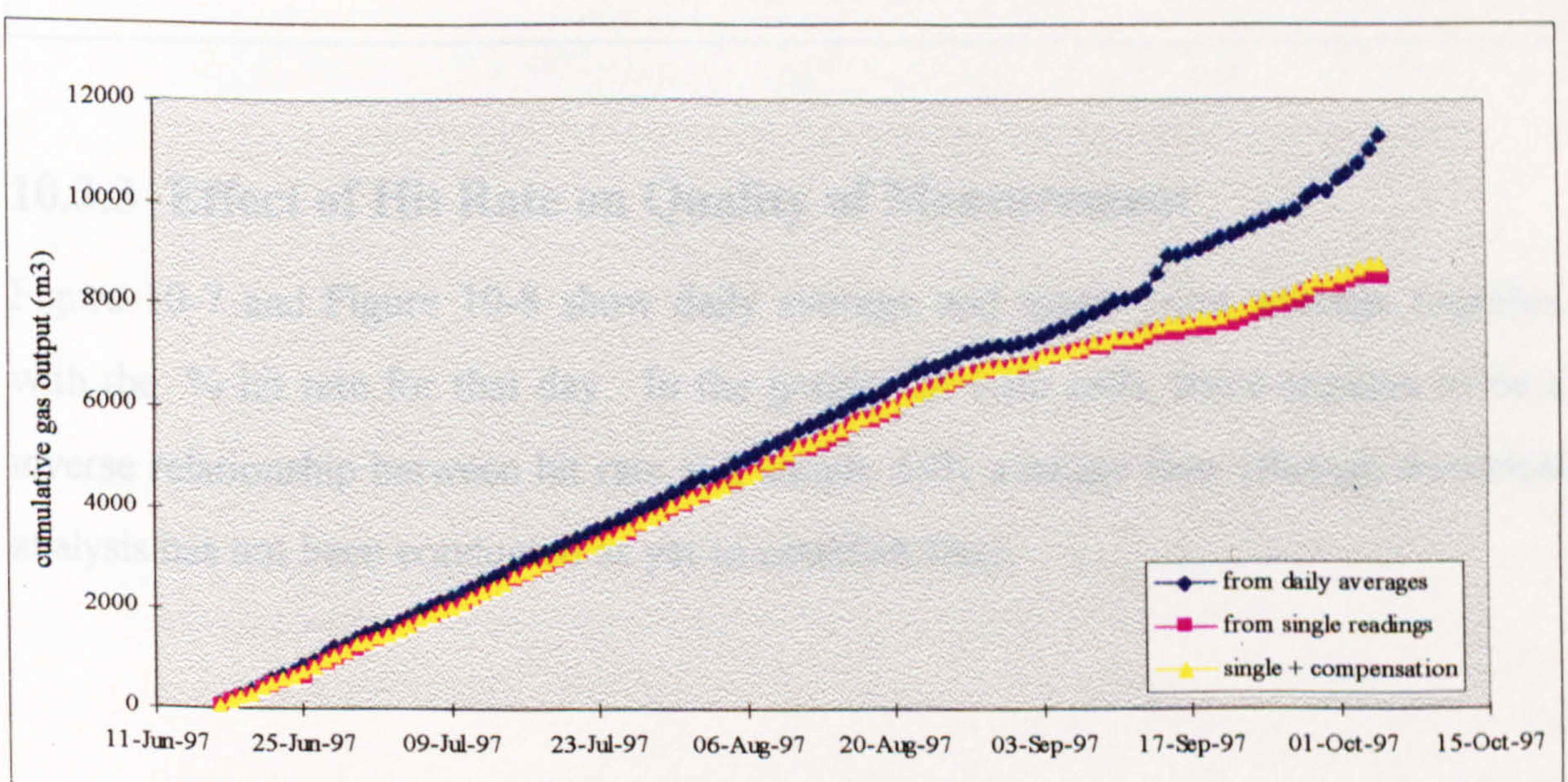
The simple average is effectively filling the gaps with the average of the available readings. This is unlikely to be providing an accurate picture of gas flow, because if the flow was around the average, a reading would have been successful (assuming the meter are functioning correctly). It satisfies neither of the above conditions.

An alternative is to take the successful spot readings and attribute that flow for 10 minutes. This method does not fill the gaps. Where there is no successful reading, there is effectively no flow contributing to the day's total. This satisfies Condition 2 above. It results in a lower 'average' value. This method is termed here a 'single point average'. This method is unlikely to be reflecting actual flow conditions when null values occur, as it is not characteristic of landfill to stop and start flow over short periods of time.

A hybrid method that satisfies Condition 1 could also be adopted. Condition 1 is the most likely state of flow when null values are recorded. This hybrid method takes the 'single point average' and adds a 'compensation' for null values. The magnitude of the 'compensation' value, is to a certain extent arbitrary. It has been set at 50% of the meter minimum threshold of 0.8 m^3/h. The compensation value used in all calculations is therefore 0.4 m^3/h.

A comparison of cumulative flow using the three methods is shown in the Figure 10-5 and Figure 10-6 below.

Figure 10-5 Cell 1 - Comparison of Cumulative Gas Flow Calculations

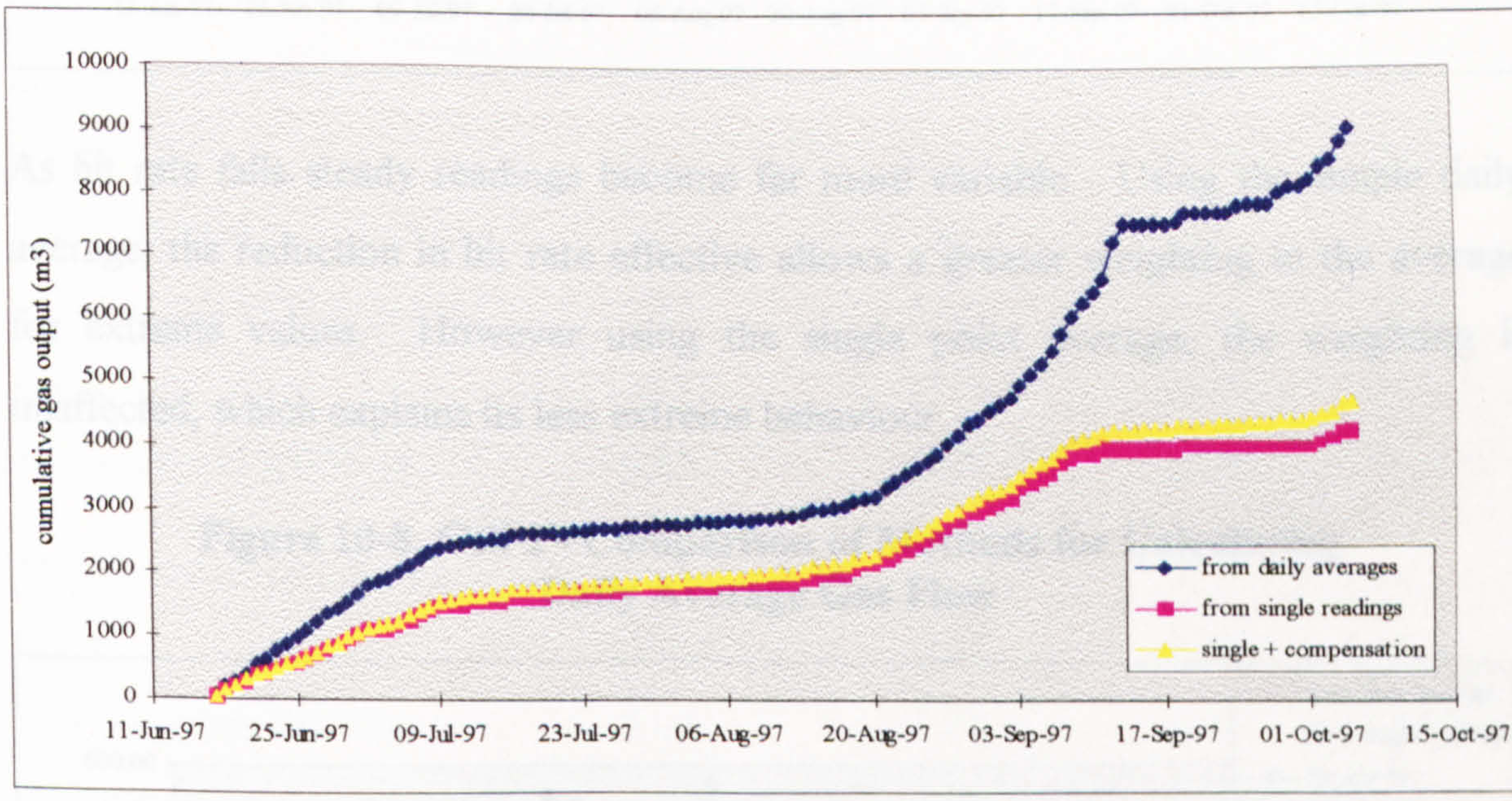


Cell 1 has a high rate of successful readings (the hit rate) , and so does not have many null values. 100% hit rate results in the same cumulative flow, by all three methods. Therefore the spread between the methods for Cell 1 is not great.

Cell 2, below, shows a much greater spread, having a lower hit rate. This is evidence of the significant effect that outliers can have on the simple average, compared to the single point average.

The compensation value does not appear to make a significant difference to the cumulative total.

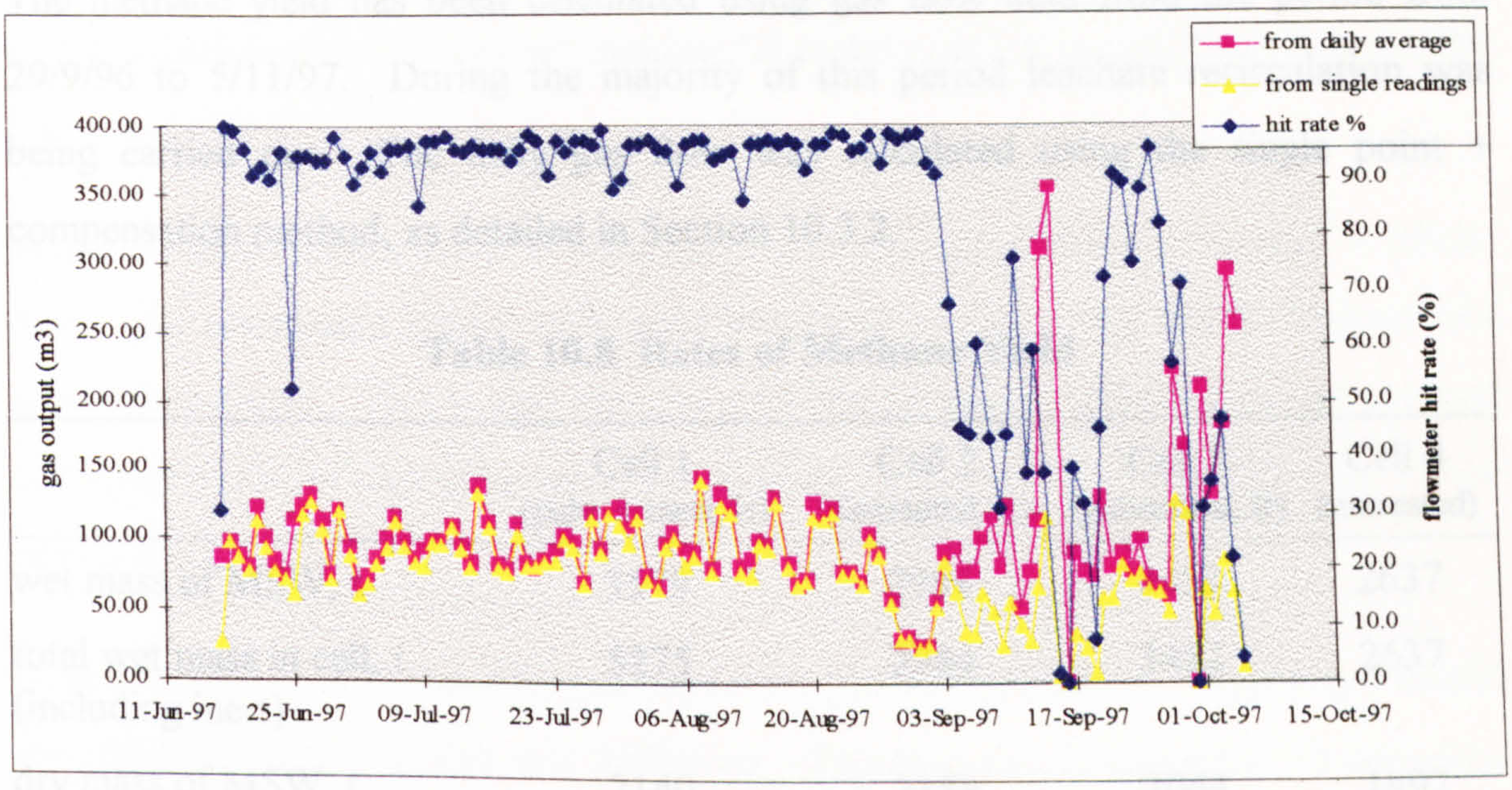
Figure 10-6 Cell 2 - Comparison of Cumulative Gas Flow Calculations



10.3.3 Effect of Hit Rate on Quality of Measurement

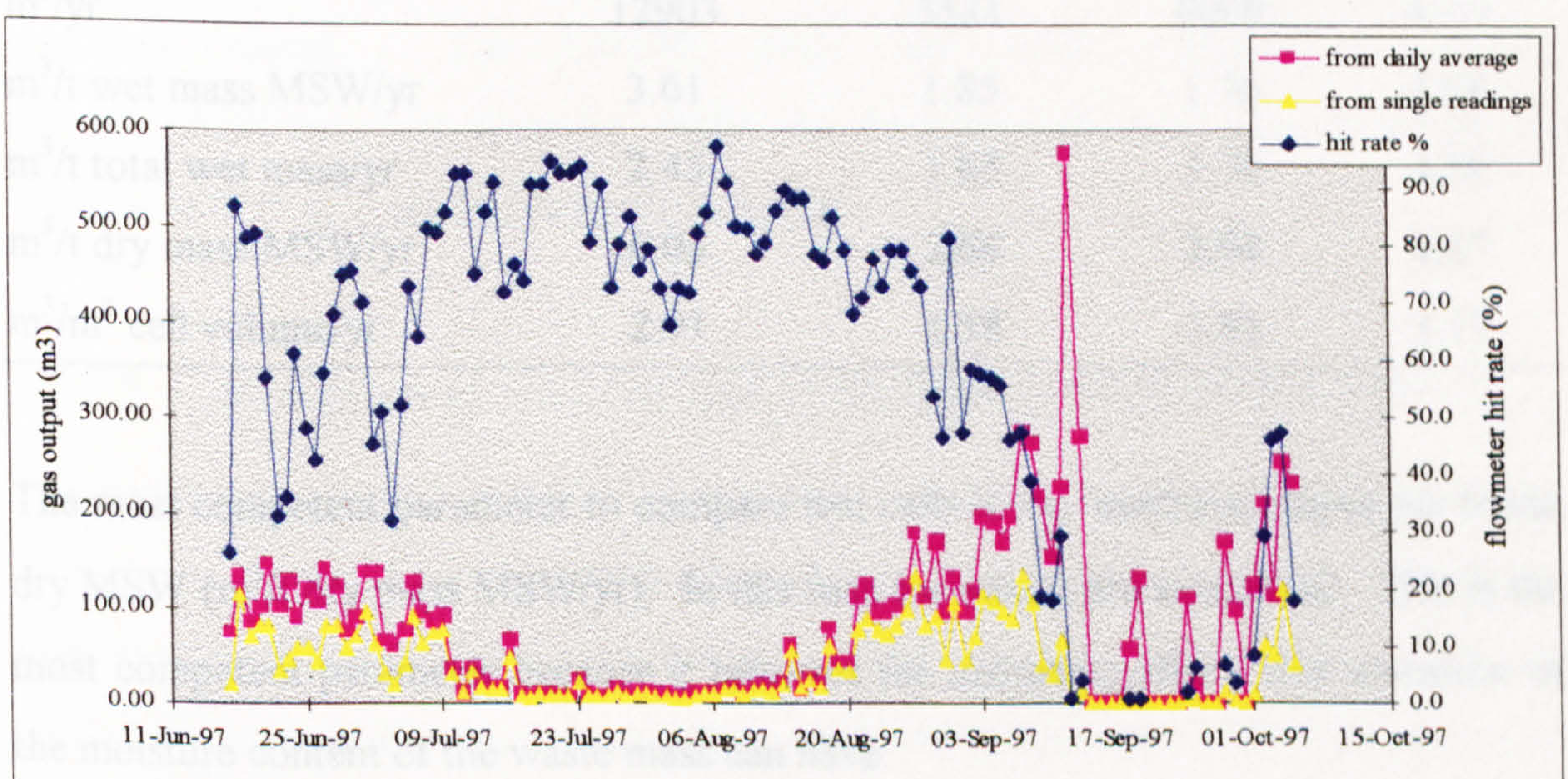
Figure 10-7 and Figure 10-8 show daily average and single point average together with the % hit rate for that day. In the graphs for both cells, there appears to be a inverse relationship between hit rate and simple daily average flow (though statistical analysis has not been conducted as yet to establish this).

Figure 10-7 Cell 1 - Comparison of Methods for Calculating Daily Average Gas Flow



As hit rate falls steady readings become far more variable. Using the simple daily average, the reduction in hit rate effective allows a greater weighting in the average for extreme values. However using the single point average, the weighting is unaffected, which explains its less extreme behaviour.

Figure 10-8 Cell 2 - Comparison of Methods for Calculating Daily Average Gas Flow



10.3.4 Methane Yield

The methane yield has been calculated using gas flow data from the period from 29/9/96 to 5/11/97. During the majority of this period leachate recirculation was being carried out. The daily gas flow was calculated using the single point + compensation method, as detailed in Section 10.3.2.

Table 10.8 Rates of Methane Yield

	Cell 1 (pulv. + inert, lr)	Cell 2 (untreated, lr)	Cell 3 (pulverised, lr)	Cell 4 (untreated)
wet mass of MSW, t	3579	2984	3452	2637
total wet mass in cell, t (including inert)	5275	2984	3452	2637
dry mass of MSW, t	2140	2158	2064	1892
volume, m^3	4440	4022	3357	3633
nom. methane % vol. in gas	65	60	65	60
av. flow rate m^3/h in period	2.27	1.05	1.06	0.78
gas output, m^3/yr	19851	9219	9324	6857
m^3 LFG/t wet MSW/yr	**5.55**	**3.09**	**2.70**	**2.60**
Methane Output Rates				
m^3/yr	12903	5531	6060	4114
m^3/t wet mass MSW/yr	3.61	1.85	1.76	1.56
m^3/t total wet mass/yr	2.45	1.85	1.76	1.56
m^3/t dry mass MSW/yr	**6.03**	**2.56**	**2.94**	**2.17**
m^3/m^3 cell volume/yr	2.91	1.38	1.81	1.13

The most competent parameter to compare test cells is the 'methane output per tonne dry MSW'(m^3/t dry mass MSW/yr). In this case the values are annualised. This is the most competent parameter because it removes the distorting effect, that elevation of the moisture content of the waste mass can have.

The data in the table shows that the output of methane per tonne dry MSW from Cell 1, is significantly higher than the other cells. It is approximately three times that of Cell 4, which represents conventional landfill techniques. It is also more than double Cell 2 and Cell 3.

When the mass of inert waste is included in the calculation, in the parameter 'methane output per tonne total waste' (m^3/t total wet mass/yr) Cell 1 still has the highest rate of methane output. This is also the case with the parameter 'methane output per unit cell volume' (m^3/m^3 cell volume/yr) which gives an indication of the efficiency of use of cell space.

In commercial landfill the common parameter for comparison is, 'landfill gas output per tonne MSW'(m^3 LFG/t wet MSW/yr). This is a simple parameter to calculate. However, in commercial landfill, the comparison is usually being made with similar unmanipulated waste streams. This is not the case for test cells.

Comparison With Other Test Cells

Although the comparison between cells shows the enhancing effect of the treatments, the absolute output is lower than may have been expected. In comparison to other test cell projects[1] the methane yield is low, although in mitigation the cells are relatively young. The Landfill 2000 test cells produced 19.9 and 8.9 m^3 LFG/tonne wet waste/yr, while the Brogborough test cells produced an average of 5.75 m^3 methane/tonne wet waste/yr.

10.3.5 Correlation of Gas Output With Meteorological Parameters

There was some interest in the effect that meteorological parameters might be having on both the output of gas and successful operation of the gas flow meters. The simple daily average flows for Cell 1 were correlated with a variety of parameters. This was carried out using a six month dataset from 28/09/96 to 31/03/97. The data increment

---

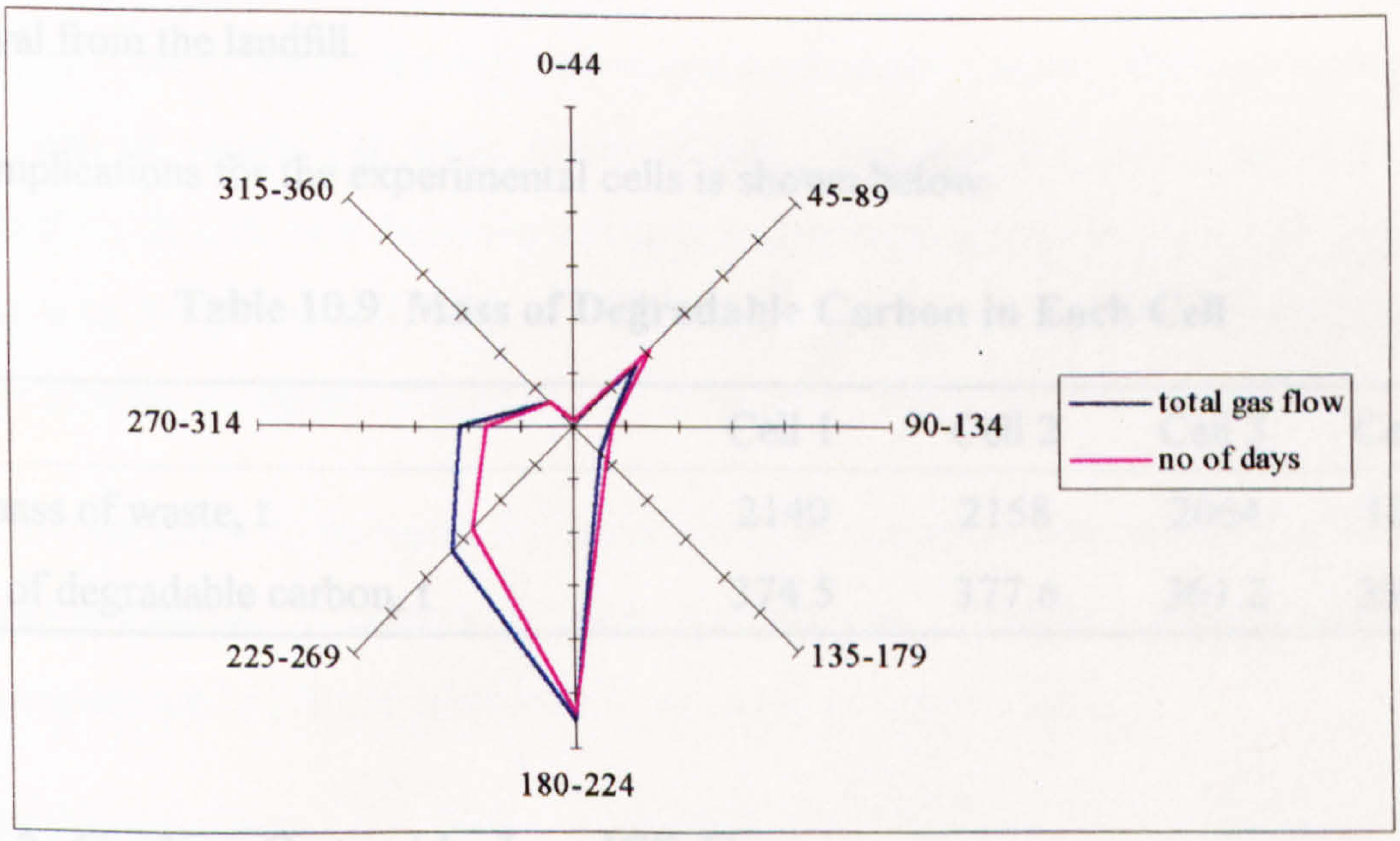
[1] see Section 5.5

was one day. Daily average barometric pressure, change in barometric pressure since the preceding day, daily average temperature, maximum daily wind speed and average daily wind speed were correlated with daily average gas flow.

Various groupings of the proposed independent variables were used. Broadly speaking, the outcome of all the exercises was that there was little correlation; the correlation coefficient typically being around 0.15.

A correlation between wind direction and gas flow was also conducted over the same period. In this test, the wind direction was divided into eight points of the compass. The number of days that the wind was in a particular direction has been compared to the total gas flow for those days, as shown in Figure 10-9.

Figure 10-9 Distribution of Gas Flow and Wind Direction for Cell 1



The two lines on the graph are very similar in shape. This indicates that wind direction does not affect the quantity of gas output. Further qualitative regression analysis by representing wind direction as 8 dummy variables confirms that there is negligible correlation with gas flow.

10.4 Mass Balance of Carbon

Carbon is input to the system as a constituent of elements in the waste stream. Some Carbon remains in an immobilised state within the wastemass, but the majority is available. It is potentially output in both gas and leachate. The Mid Auchencarroch test cells have not had any leachate removed to date, and thus the only efflux of carbon has been in landfill gas.

10.4.1 Carbon Input as Waste

Current research (Porteous, A., 1997; Beaven and Walker, 1997) suggests that around 35% of the dry mass of municipal solid waste is carbon, and that approximately half of this carbon is biodegradable in the landfill environment. Therefore, around 17.5% of the dry mass of MSW is carbon that will be available for removal from the landfill.

The implications for the experimental cells is shown below.

Table 10.9 Mass of Degradable Carbon in Each Cell

	Cell 1	Cell 2	Cell 3	Cell 4
dry mass of waste, t	2140	2158	2064	1892
mass of degradable carbon, t	374.5	377.6	361.2	331.0

10.4.2 Carbon Output in Landfill Gas

From the gas flow data, volumetric gas output has been calculated. The volumetric output data can then be used to calculate the carbon efflux in the landfill gas from each cell.

Method of Calculation

One mol of any ideal gas occupies 22.41 litres at s.t.p. [273.15K and 1013 mbar] (ex Stark and Wallace, 1982). One mol of methane [CH_4] contains 12g of carbon and 4g of hydrogen, and one mol of carbon dioxide contains 12g of carbon and 32g of oxygen, as shown in the table below.

Table 10.10 Calculation of Mass of Carbon in 1 m^3 of Gas

		methane	carbon dioxide
atomic masses	molecule	CH_4	CO_2
hydrogen	1	4	
carbon	12.011	12.011	12.011
oxygen	15.9994		31.9988
molecular mass		16.011	44.0098
volume occupied by 1mol at stp.(l)		22.41	22.41
mass of carbon in 1mol (g)		12.011	12.011
mass of carbon in 1m3 of each gas at stp (g)		**535.97**	**535.97**

Therefore because the molecules both contain one carbon atom, they both contain the same mass of carbon per cubic metre of gas. This has the useful implication for calculations, that the split between methane and carbon dioxide in the landfill gas does not have to be considered. So 1m^3 of landfill gas, consisting of only methane and carbon dioxide, contains 536g of carbon at standard temperature and pressure.

A correction needs to be made for deviation from standard temperature and pressure. The gas is assumed to behave in 'ideal' fashion, and therefore volume, temperature and pressure are in a linear relationship, as stated in Charles Law.

The following equation was used:

$$\frac{\text{mass carbon output (kg)}}{\text{unit time}} = \frac{\text{gas output (m}^3\text{)}}{\text{unit time}} * \frac{\%(CH_4+CO_2)}{100} * \frac{1013 * \text{gas temp (K)}}{273.15 * \text{atmos. press. (mbar)}} * \frac{535.9}{1000}$$

This calculation was performed on a daily increment. The gas output was a daily value calculated by the single point + compensation method, as described in Section 10.3.2. The daily average atmospheric pressure was taken from automatic weather station data. The gas temperature was taken to be daily maximum air temperature, as this was found to approximate well with gas temperature, which is recorded on a weekly basis when measuring gas composition. There is a known diurnal fluctuation in gas temperature, as measured at the gas composition sampling port, which is immediately upstream of the gas flow meter. However, at this stage of analysis, the diurnal fluctuation is not being taken into account. Hourly weather data are available, and so calculations could be conducted on an hourly basis. The results of the calculation are given in Section 10.4.4, after other efflux of carbon have been considered.

10.4.3 Carbon Mobilised in Leachate

The literature shows that the composition of leachate within a leachate collection system can be markedly different to leachate within the wastemass. Therefore, the concentration of various components within the leachate will be different in the wastemass to the collection system. This makes it difficult to assess the mass of carbon mobilised in leachate. However, a figure for the minimum amount of carbon mobilised can be calculated, if we consider just the leachate within the collection system - the basal drainage blanket containing an estimated 75 m^3 of leachate. For the pulverised waste cells, this represents less than 5% of the bed volume of a cell, but probably closer to 10% of the free leachate. For the untreated cells, this represents over 6% of the bed volume, but probably in excess of 90% of the free leachate.

The significance of the free leachate as opposed to the bed volume is that the free leachate is that which is available for removal from the cell. The leachate volume that remains is that held in the wastemass at field capacity.

Sources of Carbon In Leachate

There are two parameters for assessing Carbon in leachate. Total Organic Carbon will give a value for the total mobilised biodegradable carbon. Also mobilised is inorganic carbon in the form of carbonate. Alkalinity is expressed in units of carbonate, and it is an accurate assessment of carbonate at neutral pH. The leachate in the experimental cells is neutral.

Table 10.11 Carbon Available in Free Leachate

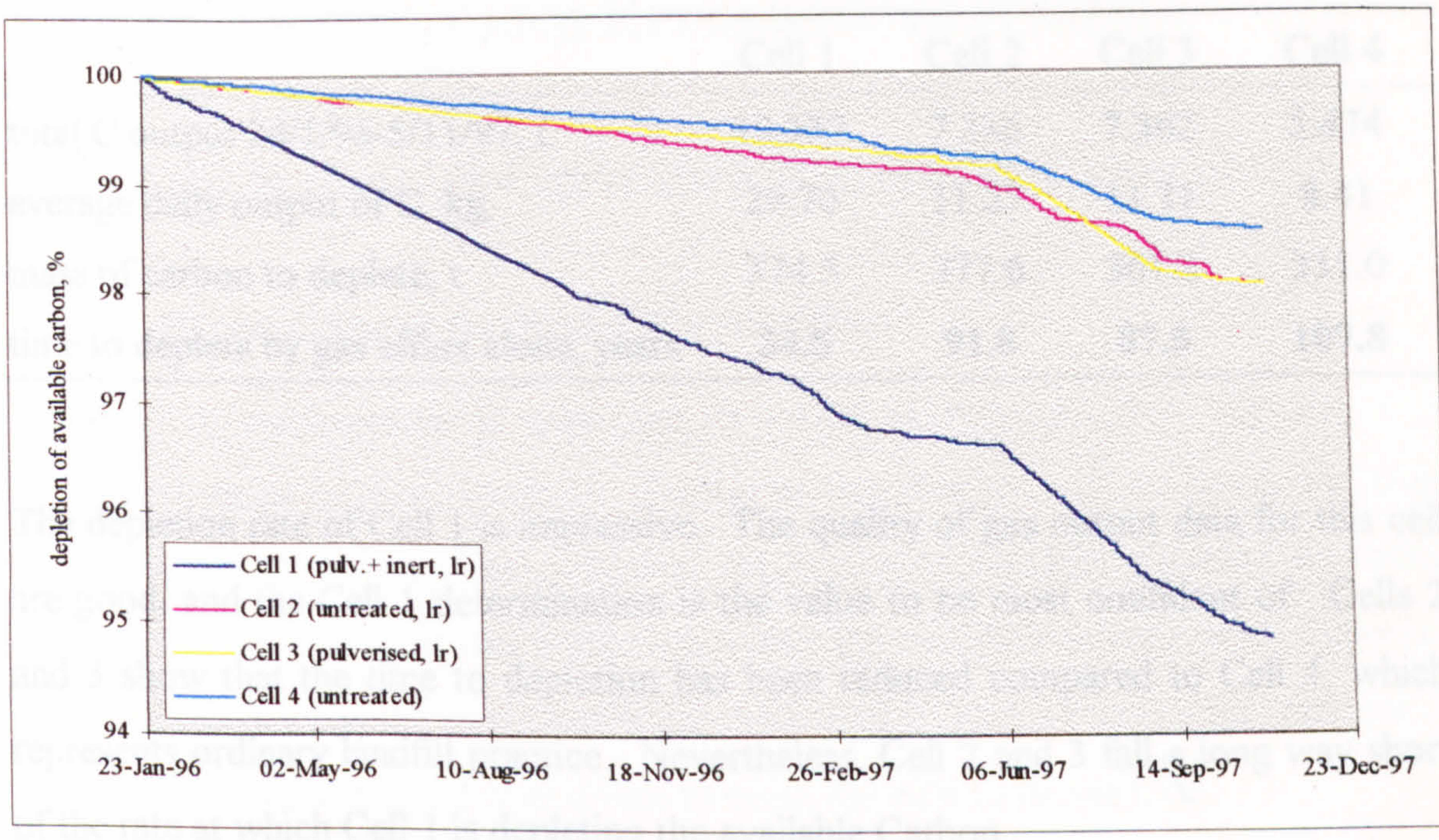
	Cell 1	Cell 2	Cell 3	Cell 4	Comments
TOC, mg/l	495	1150	470	210	sampled 20/08/97
Alkalinity as CaCO3, mg/l	4400	5200	3825	2800	sampled 20/08/97
Carbon from Alk, mg/l	528	624	459	336	12% by mass of CaCO3 molecule
carbon in leachate, mg/l	1023	1774	929	546	
estimated volume of leachate in cell, m3	700	77	700	77	
mass of carbon in free leachate, tonnes	**0.716**	**0.137**	**0.650**	**0.042**	

The calculation shows that an insignificant amount of carbon is held in the free leachate, compared with the total carbon reservoir.

10.4.4 Actual Depletion of Carbon in Wastemass

As the quantity of carbon mobilised in the leachate is of little significance compared to the total degradable carbon reservoir, the depletion of carbon will be considered through landfill gas efflux alone. The depletion of carbon has been calculated as described in Section 10.4.2, and the results are shown in Figure 10-10 below. Depletion over the six month period, between 29/03/96 and 26/09/96, during which the gas flow meters were not operational, has been estimated. The rate of depletion during that period has been taken to be the average rate over the preceding period, from 21/01/96 to 28/03/96. This is likely to be a modest underestimation, as the warmer summer months were 'gap-filled' with the rate from the colder winter months. The period of estimation can be seen as a straight line on each of the curves.

Figure 10-10 Depletion of Available Carbon



The graph clearly shows Cell 1 is well in advance of the other three cells. In the first two years after capping, just over 5% of the available carbon has been depleted in Cell 1.

The other three cells are fairly closely grouped, with Cell 3 performing surprisingly poorly. In reality the low hit rate of the gas flow meter in Cell 4 may have artificially increased the 'average' value.

10.4.5 Rate of Depletion and Implications for Sustainability Issue

Gas flow rates are likely to vary over the period in which the carbon is depleted. However, experience shows that it is unlikely that they have achieved the maximum rate yet. By taking the average carbon depletion over the last year for each cell, and extrapolating forward, it is possible to tentatively suggest a time when substantial depletion may have occurred.

Table 10.12 Rate of Depletion

	Cell 1	Cell 2	Cell 3	Cell 4
total C output 24/1/96-5/11/97, t	19.337	7.336	7.362	5.474
average daily output of C, kg	29.70	11.27	11.31	8.41
mass of carbon to deplete, t	374.5	377.6	361.2	331.0
time to deplete by gas efflux alone, years	**34.5**	**91.8**	**87.5**	**107.8**

The depletion rate of Cell 1 is impressive. The quality of gas output data for this cell are good, and the Cell 1 determination is the value to be most confident of. Cells 2 and 3 show that the time to depletion has been reduced compared to Cell 4, which represents ordinary landfill practice. Nevertheless, Cell 2 and 3 fall a long way short of the rate at which Cell 1 is depleting the available Carbon.

The Implications for Sustainability

Despite the fact that the timeframe for sustainability is 30 years, carbon depletion would have to be complete well before that, as a considerable number of years will be required to flush the wastemass as discussed in the water balance analysis. However, the data from Cell 1 is a highly encouraging indication that although the 30 year timeframe may not be achievable at the moment, this form of flushing bioreactor moves landfill much closer to a sustainable operation.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions on Controlled Bioreactor Concept

11.1.1 Pretreatment by Wet Pulverisation

Onset of methanogenisis is expedited as would be expected from experience of pulverised waste in other landfills. Inspite of this, the pace of the onset has been shown to be surprisingly fast. Within six weeks of capping, methane exceeded carbon dioxide in the gas and within ten weeks the methane concentration exceeded 60%. In comparison the untreated waste cells took around 30 weeks for methane to exceed carbon dioxide, and over a year to reach the 60% methane level.

Free Leachate: The addition of water during pretreatment results in a significantly greater bed volume than is required to satisfy the absorptive capacity of the in situ wastemass. The excess - free leachate - forms a large standing head in the base of the cell. In a commercial landfill, a high leachate head might not be acceptable.

The mechanism by which free leachate is produced is not clear. Consolidation leading to a reduction in porosity of the wastemass is a possible explanation. This was the mechanism attributed to the rise in leachate head at the Landfill 2000 test cells[1]. However, the small amount of settlement experienced so far indicates that consolidation is probably not the only cause in these test cells.

Saturated Wastemass: The standing leachate creates a saturated zone at the base of the wastemass. The depth of the saturated zone in both pulverised cells is in excess of 50% of the depth of the wastemass. Therefore an effect of wet pulverisation in this experiment has been to saturate over half the degradable substrate.

---

[1] see Section 5.5.1

Mobilisation of Pollutants: In order for the wastemass to reach 'final stage quality', soluble pollutants need to flushed out. Wet pulverisation has been shown to have increased the concentrations of pollutants in the leachate, therefore making them available for removal and treatment. In addition, the greater volume of free leachate, means that many times the mass of pollutant species has been mobilised in the pulverised waste cells, than in untreated waste without leachate recirculation.

The mass of pollutant species mobilised has not been calculated as the quantity of free leachate in each cell is not known accurately. Future trials to ascertain the porosity of the wastemass will allow this calculation to be carried out.

Waste Density: Dry density is greater in the pulverised waste cells. This may be partly due to particle size reduction, and partly due to 'lubrication' of the waste particles allowing greater compaction for a given compactive effort.

Preferential Drainage Paths: Field experience indicates that there is a greater apparent permeability in untreated waste. However, pulverisation may have the effect of reducing preferential drainage paths in the wastemass.

Settlement: There has been little settlement in any of the cells over the first two years after capping. The two cells with pulverised waste have exhibited a marginally greater settlement, and have reduced in thickness by around 2% of the depth of waste.

Settlement in the two pulverised waste cells could be limited by their low permeability, resulting in a slow consolidation process akin to a clay soil.

11.1.2 Addition of Inert Material

Permeability: Experience indicates that, so far, the addition of inert material has not improved permeability, although any differences have not been quantified. Preliminary trials to ascertain differences in hydraulic characteristics have as yet been inconclusive.

Gas Output: The cell with inert material added has consistently shown greater and steadier output of gas. Gas output per dry tonne MSW is greater than the other cells. The mechanism by which addition of inert material increases gas output to such an great extent is not known. Initially, Cell 1 experienced very high organic loads in the leachate, but subsequently leachate composition has been very similar to Cell 3, the other pulverised waste cell.

A number of effects could be responsible for the increase in the scale of methanogenisis, caused by addition of inert material:

1. physical effect - increased surface area available for microbial colonisation in biofilms.
2. dilution of degradable substrate - reduction in density of microbial colonies, so methanogenisis can operate on a greater scale before colonies become self limiting.

Leachate Composition: Despite being 'inert', the sand that was added to Cell 1 appears to have had a significant, if short term effect on the leachate chemistry. COD, BOD, and TOC were all elevated in that cell, as was the concentration of Iron. The latter is thought to be due to leaching from staining in the sand particles. Reasons for the former are not known. Laboratory research into the interaction between leachate and inert material is on-going.

Void Efficiency: The efficiency of use of landfill void, in terms of rate of gas production, is shown to be increased. This is despite the fact that 20 - 25% of the void is occupied by inert material.

11.1.3 Leachate Recirculation

Gas Composition: The composition of gas from Cell 2 was effected by recirculation. Soon after recirculation began, in November '96, gas composition became unstable, from the steady 50:50 ratio that had developed in the untreated waste cells. After six months the composition stabilised at a higher level of around 60% methane. During this six month 'transition', gas output was reduced.

Gas Output: Enhancement of biodegradation as measured by output of gas has not been shown to be significant as yet. Problems with measurement of gas flow mean that a larger dataset may be required to show a significant difference.

Effect on Pulverised Waste: The effect of leachate recirculation on pulverised waste appears to be limited, for both gas output and leachate composition.

Mobilisation of Pollutants: Leachate recirculation has created a dramatic mobilisation of pollutant species, in terms of concentration in leachate, in the untreated waste cell. There has been a negligible effect on the pulverised waste cells. Interestingly, the concentration in the untreated cell, Cell 2, of many species, has risen to the same level as that already established in the pulverised cells. Empirically, this suggests that there is some mechanism controlling the maximum concentration of a species in the leachate. It is unlikely that this concentration is controlled by the mass of soluble material in the wastemass, because, in the pulverised cells a larger volume of leachate has mobilised a larger mass of pollutant.

Flushing Rates: Rates of leachate recirculation have shown that flushing of pollutants from the wastemass would be significantly complete in a 30 year flushing programme.

Dynamic Saturation: Leachate recirculation is a technique that could be developed to allow saturation of the wastemass without creating large heads of leachate on the basal liner. This could be achieved by utilising the low permeability characteristics of a homogeneous wastemass, and creating a 'dynamic saturation' by supplying leachate to the top of the wastemass at a rate equal to the infiltration rate. The basal drainage layer would be maintained at a low head by pumping. Some intermediate storage may be required, depending on the bed volume.

A further advantage of this technique would be the 'live storage' of leachate within the wastemass. In this way relatively large bed volumes could be stored within the landfill, without the danger of groundwater pollution posed by high leachate heads on the lining system.

11.1.4 General

Temperature of the wastemass is low at around 15°C in all cells. This is conventionally thought to be too low for significant methanogenic activity, but this has been shown not to be the case.

Variability of landfill: During the first year after capping the cells, the treatments for Cells 2 & 4 were considered to be the same, leachate recirculation not having begun in Cell 2. However, Cell 4 appears to have passed through an acid souring phase whereas Cell 2 appears to have developed to methanogenesis without this problem. This perhaps demonstrates the variability of the degradation process during the early stages.

Correlation of Gas and Meteorological Parameters: Correlation between various meteorological parameters and gas composition/output has shown that there is not a significant relationship over the short term.

Correlation of Gas and Leachate Parameters: A comparison between the pattern of gas output for the various cells and their leachate parameters, shows that there is little correlation. This is perhaps evidence that leachate held in the sump of a cell is not indicative of the leachate within the wastemass.

11.1.5 Control of the Landfill Bioreactor

An element of control over the landfill bioreactor has been achieved over two distinct phases of the process. The first phase involves activities prior to and during the placement of waste in the landfill. It includes the engineering of the landfill and manipulation of the substrate material; the waste. The scope for manipulation during the first phase is great. The second phase commences at the time of sealing of the waste mass in the landfill, and the scope for manipulation is thus much reduced, although the timeframe is much greater. During this second phase leachate becomes the key parameter that is controllable.

Prior to Capping

Manipulations of the engineering of the landfill have affected the ability to manage leachate in the second phase. For instance, the use of granular blankets has allowed efficient leachate collection and recirculation.

Manipulations of the waste stream by pulverisation, and alteration of content, have been shown to have a distinct effect on the landfill process, as has already been discussed above.

Post Capping

After capping leachate recirculation has been the key tool for control of the landfill.

Switch on: In Cell 2, leachate recirculation on an untreated waste stream has been shown to have a clear effect, both in terms of leachate composition and gas output and composition. Thus, leachate recirculation can be used to 'switch on' the enhanced degradation of the wastemass.

The ability to control the time when the wastemass begins enhanced activity has important implications for 'sustainable landfill'. The main parameter of concern is the release of methane into the global atmosphere. In the pulverised waste cells, enhanced activity had already begun when the waste was placed in the landfill. Thus, well before the cell was capped and the gas collection system put in place, enhanced activity had increased the amount of methane being released to the atmosphere. In Cell 2, elevation of the moisture content of the wastemass (a major element of enhancement) was carried out after the capping and gas collection system had been installed. Thus, all the methane produced by enhancement could be utilised or at least flared.

Methods of Enhancement

Wet pulverisation has been shown to expedite the onset of stable methanogenisis, and increase the rate of degradation, as measured by gas output. The mechanisms by which this is achieved are probably a result of three modifications to the waste substrate:

1. reduction of particle size
2. homogenisation of substrate through mixing
3. elevation of moisture content

However, leachate recirculation has been shown to achieve the latter, in a manner which is potentially more controllable. Therefore, there are possible benefits from pretreating waste in a way that achieves only the first two modifications, for example by dry shredding. The benefits of wet pulverisation would be realised in the long term, but the initiation of enhanced degradation would be delayed until leachate recirculation was used to 'switch on'. Apart from improved control, there are also potential benefits of greater permeability due to lower density of the wastemass. In addition, the costs of processing by dry shredding are likely to be significantly lower.

11.1.6 A Priori Assumptions

A Priori assumptions for the experimental work were first stated in the Introduction to the thesis.

> **A Priori Assumption 1**
>
> Shallow landfill of municipal solid waste is feasible in terms of establishing and maintaining a suitable environment for methanogenic degradation to occur at significant rates.

This assumption is clearly proven for the cells that have had enhancing manipulations. However, despite the temperature in all the cells being similar, Cell 4, the un-manipulated comparison cell, has experienced very low outputs of methane during some periods. It now appears to be achieving a more reliable output, and thus the assumption can be considered proven for this cell as well, albeit at a reduced margin.

A Priori Assumption 2

> It is possible to control and enhance landfill gas production, and flush potential pollutants from the wastemass, by manipulating the whole process of landfill.

The manipulations have clearly shown that it is possible to exercise a degree of control over the landfill process, and also to achieve enhancement. Therefore A Priori Assumption 2 has been proven.

A Priori Assumption 3

> It is possible to expedite the degradation, stabilisation and flushing of the wastemass, to the extent that final stage quality is achieved within a 30 year timeframe.

Projections of when final stage quality will be achieved, have been calculated by extrapolating the first two years of monitoring data. Extrapolation on this scale is unlikely to be a highly accurate forecast. Nevertheless, the extrapolations show that depletion of available carbon may be achieved within 35 years for Cell 1, and flushing of the wastemass in 32 years. Thus, the extrapolations show that final stage quality may be reached over a little longer than the 30 year timeframe allowed. A Priori Assumption 3 is therefore not proven.

However, the rate of depletion of available carbon is unlikely to have reached the maximum yet, and in addition the flushing rate could be increased, so it is possible that final stage quality may be achieved within the 30 year timeframe. A longer period of monitoring will allow a more accurate forecast to be made.

11.2 Implications for Sustainable Waste Management

11.2.1 Sustainable Waste Management

Chapters 2 and 3 showed that any means of **disposal is inherently unsustainable.** This is primarily on grounds of loss of finite resource. It also showed that there were potentially great disbenefits to the environment from poor waste management techniques.

Introducing the concept of the Cycle of Resources in Society puts waste management into context. The way forward to truly sustainable waste management is by closing the loop of the Cycle of Resources. Thus, **product design** and **material selection** are key waste management issues, as they control what may be recycled and reused.

11.2.2 The Role of Enhanced Landfill

Although disposal is not sustainable, it is accepted that it will continue for the foreseeable future to a greater or lesser extent. Landfill is by far the most common method of disposal in Britain. Pragmatism dictates that despite the fact that there are preferable waste management options to landfill, if the practice is going to continue, techniques need to be developed to reduce its environmental disbenefits. In this way landfill may be moved much closer to the ideals of sustainability than is currently the case.

The aim of the 'sustainable landfill' is to achieve *final stage quality* of the wastemass - a non polluting 'walkaway' state - within a 30 year timeframe. It was suggested that this be accomplished by:

- enhancing degradation by optimising environmental conditions for the microbial population
- flushing pollutants from the wastemass

The flushing bioreactor landfill has been put forward to achieve this, and a number of techniques along these lines have been evaluated in this experimental work.

11.2.3 A Sustainable Waste Management Option for the 21st Century?

Landfill as a practice may not truly be sustainable because of the loss of resource - however this experimental work has shown that the enhanced landfill bioreactor moves the practice of disposal very much closer to the goals of sustainability.

Projections based on extrapolating the experimental data to date indicate that Cell 1 could deplete all the available carbon in a period of a little over one generation. In addition, the rates of recirculation indicate that flushing of the wastemass could be achieved in a similar period. However, these operations cannot operate totally concurrently; significant depletion of carbon must have occurred before flushing commences. Therefore, it would be realistic to estimate a feasible timeframe to *final stage quality* of around 50 years.

Strictly speaking this period is greater than one generation. Nevertheless, in comparison to the several hundred years that conventional landfill may take to reach the same state, the flushing bioreactor method of landfill represents a close approximation to the goals of sustainability.

11.3 Recommendations

11.3.1 Recommendations for Experimental Practice

Waste Characterisation

Moisture content determination should be carried out during waste characterisation. The variation in moisture content between the various elements of the waste stream is great. Therefore a change in composition will also often result in a change in overall moisture content. The moisture content of particular fractions should also be measured so that comparisons can be made on a dry mass basis.

Test Methods for the Waste Stream

There is a scarcity of standardised test methods for the waste stream. In particular, development of simple classification tests like moisture content and particle size distribution would be useful. Applying soils test methodology is not always appropriate, as was found out during moisture content analysis. With the oven temperature set at 105°C, plastics in contact with the metal container tended to melt, and no doubt volatile matter other than water was driven off the sample. The alternative soils test would be a 50°C 'air drying'. This would probably be too low to remove moisture at an adequate speed from the sample. A temperature at which plastics are unaffected and the sample dries out adequately should be established.

Leachate Recirculation

Short circuiting to the central well during leachate recirculation should be minimised. The design of the central well should be altered to prevent its occurrence, methods for achieving this have been discussed in the body of the thesis[1].

In the interim, the amount of leachate that is being recirculated should be more carefully controlled, so that excessive short circuiting is avoided. The ceiling values

---

[1] see Section 8.7

used in the calculation of leachate recirculation volumes could be applied on site. To take account of variations in leachate pumping rate, the pumping durations could be expressed in multiples of the time required to fill the calibrated drum (205 litres). The appropriate values are:

For Cells 1 & 2 a multiple of 39 should be used, amounting typically to 72 minutes.

For Cell 3 a multiple of 34 times should be used, amounting to 63 minutes.

11.3.2 Recommendations for Application of Research Findings

Landfill can and should be operated as a wet bioreactor. Various combinations of enhancement techniques achieve different results. This experiment has shown that all are an improvement over conventional landfill practice. In terms of sustainable development, enhancement not only moves landfill closer to the timeframe of sustainability, but it also makes utilisation of the landfill gas resource more feasible. This has positive implications for methane release into the global atmosphere.

New Landfill

Landfilling of waste with a significant biodegradable content may or may not be allowed to continue in the European Union. Where and when it is permitted, the Mid Auchencarroch experiment provides a good model on which to base more sustainable practice in waste disposal.

This is particularly true in rural circumstances, in Scotland or anywhere in the world. The combination of small-scale shallow landfill and appropriate technology for enhancement, could provide a more environmentally and economically sound - and sustainable - solution than shipping and trucking waste to incinerators or disposal facilities hundreds of miles away.

Existing Landfill

Within Scotland, and the world at large, there is a vast mass of landfilled waste, degrading slowly at rates well below the optimum, and at rates which make any attempt at exploitation of the landfill gas resource less viable.

Although the opportunity for manipulation of the waste stream and waste mix is broadly forgone on an existing landfill, the opportunity for enhancement is not. The design of recirculation system at Mid Auchencarroch is highly suited to installation on an existing site at closure, or even retrofitting post closure. Therefore exploitation of an under-utilised resource and enhancement go hand in hand.

Appropriate Technology

The environmental costs of over-engineering are unlikely to be outweighed by the benefits in terms of enhanced degradation. Therefore, the use of technology appropriate to the application is essential, and cost-benefit analysis on environmental, as well as economic grounds should be carried out.

11.4 Further Research

11.4.1 Progress to Final Stage Quality - Carbon Balance

Measurements

Measurement of the carbon content of various waste streams, would enable a detailed calculation of carbon input can be carried out.

Logging of gas temperature would enable corrections to gas output to be made accurately. This would be possible with an addition to the gas flow meters, which already have spare measuring circuits available.

Calculations

Removal of statistical outliers from gas flow dataset would allow a more realistic appraisal of cumulative gas flow and hence carbon depletion.

The carbon mass balance could be refined by modelling gas composition with flow rate, instead of assuming a fixed composition.

Modelling Theoretical Methane Potential

Theoretical methane yield should be modelled specifically for the waste categorisation that was measured. Established methods are available (EIRU, 1992).

11.4.2 Progress to Final Stage Quality - Waste Parameters

A programme of waste sampling is ongoing, as part of another research project. The cellulose: lignin ratio has been found to be useful in determining the degree of degradation of waste (Bookter and Ham, 1982; Suflita et al, 1992). This parameter should be determined for these test cells in order that a further assessment can be made of the progress to final stage quality. Analysis of material in both the saturated and unsaturated zones would provide information on whether there is a differential rate of degradation.

11.4.3 Water Balance Calculations

Installation of standpipe piezometers around site so that groundwater conditions could be assessed, would enable the recalculation of water balance to include groundwater/leachate exchange.

The measurement of the moisture content of landfill gas should be carried out for water balance purposes. The significance to the water balance is likely to be small, but there is a paucity of published data on this.

11.4.4 Waste Hydraulics and Hydrology

Measurements

Leachate level should be logged automatically on all cells, including Cell 4. Logging has already been carried out for a number of recirculation cycles on Cells 1 & 3. Longer term collection of data would allow a better understanding of waste hydraulics, in particular hydraulic conductivity.

Monitoring the level of Cell 4 (no recirculation) would indicate how atmospheric pressure affects the phreatic surface in a landfill.

Porosity

Monitoring of leachate recharge alone is unlikely to provide sufficient information to accurately assess porosity of the wastemass. A test could be conducted in which a quantity of leachate was temporarily removed from the wastemass. The volume would need to be in excess of 20 m^3 to cause a significant fall in head. Thermal loss from the leachate would be a consideration.

Moisture Distribution

The distribution of moisture within the wastemass is of interest in terms of efficiency of distribution of leachate to enhance biodegradation, and in terms of preferential drainage paths for effective and complete flushing of the wastemass.

Resistivity surveys are feasible, and offer a cheap 'non-intrusive' method of assessing moisture distribution in three dimensions.

Capacitive coupling tests could be used to indicate passage of leachate around the irrigation pipeline, as in the Landfill 2000 test cells[1].

Tracer tests would also be suited to the experimental cells, particularly since the lack of daily cover means that low permeability horizons are not introduced.

---

[1] see Section 5.5.1

Piezometers and conductivity probes could be installed in the wastemass in a similar way to the driven temperature probe.

11.4.5 Bioclogging

An assessment of bioclogging should be made on both the gas collection and leachate irrigation pipelines on all cells. Concern over bioclogging of engineering features is a topical issue. Anecdotal evidence suggests that severe clogging can build up in a matter of two or three years in leachate collection systems, and Knox reports anecdotally that systems which are periodically saturated then unsaturated, build up faster than those that are permanently saturated. The leachate irrigation system in these test cells is a periodically saturated system.

The pipelines have been designed for CCTV survey. The cost per day for a CCTV team is £600 - £1000 (1995 prices).

11.4.6 Additional Sampling Locations

Currently, the composition of gas and leachate are measured outwith the wastemass. The Landfill 2000 project[1], amongst others, has shown that the composition of these parameters is markedly different in the interstices of the wastemass itself. Probes in the wastemass for sampling gas and leachate should enable a better understanding of the reasons for differences between the cells.

11.4.7 Gas Migration

A survey to assess gas migration through containment should be conducted.

---

[1] see Section 5.5.1

11.4.8 Novel Leachate Treatment

A collaborative research project with the Department of Pure and Applied Chemistry, at the University of Strathclyde should be put forward to assess the potential of Polymer Supported Ion Exchange Resins in leachate treatment, as discussed in Section 5.4.4. An assessment of cost and benefit would have to be prepared as part of a proposal to convince those within the Ion Exchange Resin industry that this type of effluent treatment may be a financially viable application for the technology, and therefore a market opportunity worth exploiting.

Glossary of Terms

Abiotic	Without life, inanimate (Chambers Concise Dictionary; Schwarz, 1991)
Absorptive Capacity	The difference between the initial moisture content of the waste and its moisture content at field capacity ie., when it can retain no further water against the pull of gravity.' (Waste Management Paper 26B; Great Britain. DoE, 1995)
Acetogen/ Acetogenic	Collective term to describe the bacteria which convert VFA to acetic acid. (AFRC, 1988)
Acidogen/ Acidogenic	Collective term to describe the bacteria which convert the products of waste hydrolysis to VFA. (AFRC, 1988)
Albedo	The ratio of incident solar energy that is reflected and absorbed. Typical values: fresh white snow 0.9, short grass 0.25, and water surface of a reservoir 0.05 (Shaw,E 1988)
Anabolism	The form of metabolism in which the reactions are synthetic; such as the manufacture of proteins and fats. cf Catabolism. (Penguin Dictionary of Chemistry, 1983)
Aromatic	An organic compound with a benzene ring structure. (AFRC, 1988)
ATP	Adenosine Triphosphate. The most important of the so-called 'high energy compounds', a group of naturally occurring organic phosphates, and is the primary source of energy in the metabolism of plant, animal and bacterial cells. (Penguin Dictionary of Chemistry, 1983)
ATU, Allyl ThioUrea	Compound used to suppress the nitrogenous contribution to Biochemical Oxygen Demand, so that only the carbonaceous contribution is measured. See BOD.
Bed Volume	The total moisture content of the wastes in a particular landfill, including free leachate and any absorbed moisture. (Waste Management Paper 26B; Great Britain. DoE, 1995.)
Bioclogging/ biofouling/ bioaccumulation	The biological growth or chemical deposition of material in features such as leachate collection systems and geotextiles, which results in a loss of performance.

Bioreactor Landfill	Landfill designed and operated to accelerate degradation of waste by optimising environmental conditions for the microbial population.
BOD	Biochemical Oxygen Demand. A measure of the amount of a material that can be oxidised by micro-organisms and hence a measure of the ability of waste to remove oxygen from the environment. (AFRC, 1988). See ATU.
BOD_5	The version of a test to determine BOD over a duration 5 days. This is the standard duration of the test that is a quoted parameter in pollution regulation. In research the BOD_{20} is sometimes used for materials with high organic content.
BPEO	Best Practicable Environmental Option. First used in the Royal Commission on Environmental Pollution's Fifth Report on Air Pollution Control in 1976 and subsequently discussed in detail in the Twelfth Report in 1988.
Catabolism	The form of metabolism in which the reactions are destructive; e.g. the breakdown of sugar to carbon dioxide and water, which release large amounts of energy. cf. Anabolism. (Penguin Dictionary of Chemistry, 1983)
Cellulolysis /Cellulolytic	Cellulose degrading. (AFRC, 1988)
Cellulose	$(C_6H_{10}O_5)_x$ The chief constituent of the cell wall of all plants, and the most abundant organic substance found in nature. It is a polymer of glucose with over 3500 repeat units in a chain. (Penguin Dictionary of Chemistry, 1983)
Clean Technology	Techniques of manufacture that produce no waste, pollution or unwanted byproducts.
Consolidation	The process whereby soil particles are packed more closely together over a period of time under the application of continued pressure. It is accompanied by drainage of water from the pore spaces (voids) between solid particles. (Head,KH 1994)

Daily Cover	Material used to cover solid wastes deposited in landfills. Daily cover is used to cover each lift or layer at the end of each working day to prevent odours, wind blown litter, insect or rodent infestation, and water ingress. (Great Britain. DoE, 1986)
Endogenous	Increasing from internal growth. (Chambers Concise Dictionary; Schwarz, 1991)
Factory Blindness	Mundane familiarity with factory situation to the extent that there is inability to recognise sub-critical problems or spot improvements to the system status quo.
Facultative Anaerobes	Anaerobic bacteria which are tolerant of low levels of oxygen.
Field Capacity	The total amount of water that may be retained against gravity by landfilled solid wastes, e.g. after saturation and draining.' (Waste Management Paper 26B; Great Britain. DoE, 1995)
Final Stage Quality	The walk away state, when the landfill mass no longer represents a threat to pollution of air, water or soil. The precise definition varies from country to country.
Heterotroph	Exemplified by animals, an organism dependent on an organic carbon source [cf. autotroph, exemplified by plants, an organism which can use completely inorganic nutrients] (Stanier, Adelberg, and Ingraham, 1997)
Hydraulic Retention Time	The total moisture content of the wastes in a particular landfill, divided by the rate at which water passes into, or out of, that portion of landfill. (Waste Management Paper 26B; Great Britain. DoE, 1995)
Hydrogen	A flammable gas with an explosive range in air between 4% and 74% by volume. (Waste Management Paper 26B; Great Britain. DoE, 1995)
Hydrolysis	A term used to signify reactions due to the presence of hydrogen or hydroxyl ions of water. In organic chemistry the term is used to describe the conversion of an ester to an acid and an alcohol, the addition of the elements of water to a molecule. (Penguin Dictionary of Chemistry, 1983.) Enzymatic breakdown of polymeric material such as

	polysaccharides to simple sugars, proteins to amino acids and lipids to fatty acids. (AFRC, 1988)
Immiscible	Not capable of being mixed (Chambers Concise Dictionary; Schwarz, 1991)
KWhe	Kilowatt hour electrical. A unit useful for expressing energy yield in terms of electricity, therefore taking into account the energy losses associated with electricity generation.
Leachate Recirculation	Removal of free leachate from base of landfill wastemass and re-application to upper levels of wastemass via an irrigation system. Aim of process to homogenise environmental conditions in landfill, such as moisture content and microbial population.
Lignin	A complex three dimensional polymer based on phenyl propane subunits. It is generally considered non-degradable under anaerobic conditions. (AFRC, 1988)
Mesophile	An organism characteristically growing in the temperature range 10 - 45 °C, with optimal growth usually between 30 - 40°C . (AFRC, 1988)
Methanogenic	Methane producing. (AFRC, 1988)
Monomer	A simple molecule which can be polymerised. (Penguin Dictionary of Chemistry, 1983)
Motile	Capable of self propulsion
MSW	Municipal Solid Waste. The mixed solid waste stream that is typically collected by or for a municipality. It is predominantly household waste but includes waste from schools, shops, offices, garden waste and often waste from the municipality's own departments, such as parks, building.
MtC	million tonnes of Carbon. A unit used when comparing relative sources of carbon dioxide emission.
Obligate	The ability to grow under only aerobic conditions or under only anaerobic conditions. (AFRC, 1988)
Pathogen	A micro-organism considered to be a potential health hazard. (AFRC, 1988)

PET	Polyethene Teraphthalate. A plastic; commonly used for beverage containers due to it's low carbon dioxide permeability.
Phagotroph	Bacterial predator
Phenols	Compounds containing at least one hydroxyl group attached directly to a carbon atom of an aromatic ring. They are widely distributed in natural products e.g.. tannins, anthocyanins and tyrosines. (Penguin Dictionary of Chemistry, 1983)
Phthalates	A salt or ester of phthalic acid ($C_6H_4(COOH)_2$). Some phthalates have been implicated as hormone disrupting chemicals. Their main use is as softener in plastics, especially PVC.
Polymer	A long chain molecule made up of repeated units of monomer.
Preferential Drainage Path	The flow of leachate along a Preferential Drainage Path. *Within* the wastemass itself, there will be routes of flow that offer lower resistance than other. For instance the interface between bags of refuse may offer a lower flow resistance than going through the bag. Thus leachate will flow more readily along the interface, therefore becoming unevenly distributed. This is a problem associated with the characteristics of the waste stream. See Shortcircuiting.
Redox Potential	Symbol, Eh. A measure of the oxidising or reducing potential of a system, usually expressed as a voltage, relative to a standard hydrogen electrode. Low Eh indicates reducing conditions and high Eh indicates oxidising conditions. (Great Britain. DoE, 1996)
RDF	Refuse Derived Fuel. A solid fuel derived from solid waste. Typically paper and plastic are the main constituents. The material may be loose, or densified into pellets. RDF pellets may be burned with coal in conventional plant, due to their low ash content.

Rumen	A large forestomach found in ruminants and where plant material is digested anaerobically by a complex microbial ecosystem to provide nutrients for the host animal. (AFRC, 1988)
Shortcircuiting	Shortcircuiting of leachate within a wastemass. Within this thesis, the term shortcircuiting is used to mean leachate *bypassing* the wastemass. This will occur along or down an engineered feature of the landfill, for instance the containment wall or well structures. This is a problem predominantly associated with the design of the landfill. See Preferential Drainage Path.
tce	tonnes of coal equivalent. A unit for measuring and comparing energy as a raw material.
Thermophile	Micro-organism characteristically growing in the temperature range 55 - 75 °C, with a minimum temperature requirement for growth around 40°C . (AFRC, 1988)
Thermoplastic	A polymer that softens when heated and hardens when cooled. Thermoplastics can be re-softened and re-moulded into a new shape. The most important thermoplastics are polyethylene, polypropylene, PVC and polystyrene. [cf. thermoset](Norsk Hydro, 1992)
Thermoset	A plastic that solidifies when first heated under pressure, and which cannot be remelted or remoulded without destroying its characteristics. [cf. thermoplastic](Norsk Hydro, 1992)
Trophic	from French = nourishment (Odum, 1971)

REFERENCES

AFRC. Agriculture and Food Research Council, Institute of Food Research (1988) A Basic Study of Landfill Microbiology and Biochemistry. Report to Dept. of Energy, No. ETSU B 1159. ETSU: Harwell, Oxon

anon (1996a) Anaerobic Digestion makes faltering progress. *ENDS Report.* No. 263, pp 11-12, December 1996. Environmental Data Services: London

anon (1996b) Rank Xerox: Towards waste-free products from waste-free factories. *ENDS Report.* No. 261 pp 18-21 October 1996. Environmental Data Services: London

anon (1996c) USA achieves 25% target. *Wastes Management.* April 1996 p18. Institute of Wastes Management. Northampton

anon (1997a) Plastics head for cement kilns. *The Waste Manager.* Vol. 26 No. 4 p5. Environmental Services Association: London

anon (1997b) Take back scheme launched for mobile phones. *ENDS Report.* No. 264 p17 January 1997. Environmental Data Services: London

Archer,D Reynolds,P and Blakey,NC (1995) A Review of Landfill Microbiology Research. Contractor WRc plc. ETSU Report No. B/LF/00416/REP. ETSU: Harwell, Oxon

Atkins,G (1996) Energy from waste - progress to date and the barriers faced. *Wastes Management.* May 1996 pp38-39. Institute of Wastes Management: Northampton

Bagnara,C Toci,R Gaudin,C and Belaich,JP (1985) Isolation and characterization of a cellulolytic micro-organism Cellulomonas fermentans sp.nov. *International Journal of Systematic Bacteriology.* Vol. 35 pp502-507.

Barlaz,MA Ham,RK and Schaefer,DM (1989) Mass Balance Analysis of Anaerobically Decomposed Refuse. *Journal of Environmental Engineering - ASCE.* Vol. 115 No. 6 pp 1088-1102.

Barlaz,MA and Ham,RK (1993) Leachate and Gas Generation. In *Geotechnical Practice for Waste Disposal*, edited by David E. Daniel. Chapman & Hall: London

Bear,J (1979) Hydraulics of Groundwater. McGraw - Hill International: New York

Beaven,RP and Powrie,W (1995) Determination of the Hydrogeological and Geotechnical Properties of Refuse Using a Large Scale Compression Cell. *Proc. Sardinia 95, Fifth Internat. Landfill Symp., Cagliari, Italy. 2-6 Oct 1995.* CISA: Cagliari, Italy

Beaven,RP and Walker,AN (1997) Evaluation of the Total Pollution Load of MSW. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 1 pp57-71. CISA: Cagliari, Italy

Blowers, A (1992) Planning A Sustainable Future. Pollution and waste - a sustainable burden ?. *Town & Country Planning.* October 1992 pp265 - 268.

Bookter,TJ and Ham,RK (1982) Stabilization of solid waste in landfills. *Journal of Environmental Engineering - ASCE.* Vol. 108 No. 6 pp1089-1100.

Braber,K (1995) Anaerobic-Digestion of Municipal Solid-Waste - a Modern Waste Disposal Option on the verge of breakthrough. *Biomass & Bioenergy.* vol. 9, no. 1-5, pp. 365-376.

Bradshaw,K Reynolds,PJ and Blakey,NC (1993) Landfill 2000: Progress Report November 1992 to June 1993. Report to DoE. No. 3466 (limited distribution). WRc: Medmenham

British Geological Survey (1958) Glasgow. Solid Edition. Scotland Sheet 30. 2nd Impression.

British Geological Survey (1961) Glasgow. Drift Edition. Scotland Sheet 30. 2nd Impression.

British Technology Group (1995) Patent Application UK 930508. 8 and EPC 94909205. Device manufactured by Bartington Associates Ltd. under BTG licence No. L23653/01.

BSI, British Standards Institution (1990) BS 1377 : Part 9 : 1990. Soils for Civil Engineering Purposes, Part 9 In-situ tests. BSI: London

BSI, British Standards Institution (1992) BS EN60529: 1992 Degrees of protection provided by enclosures (IP code) . BSI: London

Buchanan,D (1994) Hydrological and Hydraulic Models for Landfill Practice (Course Notes), Dept. of Civil Engineering, March 1994. University of Strathclyde: Glasgow, (unpublished)

Burton,SAQ and Watson-Craik,IA (1997) Ammonia Production and Turnover in Landfilled Refuse. *Proc. Sardinia 1997, Sixth Int. Landfill Symp. , Cagliari, Italy. 13 - 17/10/97.* Vol 1 pp127-136. CISA: Cagliari, Italy

Caine,M and Davies,S (1996) Continued Monitoring of the Brogborough Test Cells. ETSU Report B/LF/00470/REP. ETSU: Harwell, Oxon

CalPoly (1987) LANDLAB. A laboratory for Education and Research in the Sustainable Use of Land Resources. California State Polytechnic University: Pomona, California

CEMS, Centre for Environmental Management Studies (1994a) Field Trials of Waste Manipulation Techniques. Proposal to Department of the Environment. October 1994. Centre of Environmental Management Studies: 5th Floor, Wolfson Centre, Glasgow, G4 0NG

CEMS, Centre for Environmental Management Studies (1994b) Mid-Auchencarroch - Field Trials of Site Manipulation Techniques. Research Proposal to Dumbartonshire Enterprise. Report No. 517, June 1994. Centre for Environmental Management Studies: 5th Floor, Wolfson Centre, Glasgow, G4 0NG

CEMS, Centre for Environmental Management Studies (1995) The Hydrogeology of Mid Auchencarroch Phase Two Experimental Site. Report No. 558. Centre for Environmental Management Studies: 5th Floor, Wolfson Centre, Glasgow, G4 0NG

Chapman,RE (1987) Fluid Flow in Sedimentary Basins. In *Fluid Flow in Sedimentary Basins and Aquifers,* edited by Goff,JC and Williams,BPJ. Blackwell Scientific: Oxford

Clark,C (1994) Lecture Notes for course 17. 478 'Solid Waste Management'. Department of Civil Engineering. University of Strathclyde: Glasgow, (unpublished)

Coopers & Lybrand (1996) Cost Benefit Analysis of the Different Municipal Solid Waste Management Systems: Objectives and Instruments for the Year 2000. Final Report to European Commission, DG XI.

Cosslett,G (1997) Worlds apart in recycling. *The Waste Manager.* Vol. 26 No. 4 p11. Environmental Services Association: London

Craighill,AL, Powell,JC (1996) Life-cycle Assessment and Economic-Evaluation of Recycling - a case-study. *Resources Conservation And Recycling.* Vol. 17, No. 2, pp. 75-96.

Croft,B & Fawcett,T (1993) Landfill Gas Enhancement Studies The Brogborough Test Cells. Report to DTI, No. ETSU B/B5/00080/REP. ETSU: Harwell, Oxon

CSERGE (Centre for Social and Economic Research on the Global Environment) Warren Spring Laboratory (1993) Externalities from Landfill and Incineration. Study for Department of the Environment. Department of the Environment: London

Design Council (1997) More for Less. Design for Environmental Sustainability. Design Council: London, SW1Y 4EE

Dickson,A (1987) The Hydrology of Landfill and Land Management. PhD Thesis, Department of Civil Engineering. University of Strathclyde: Glasgow

EnviroCentre (1995) The Hydrogeology of Mid Auchencarroch Phase Two Experimental Site. Report No. 558. to G&A Munn & Son (Landfill) Ltd. 28th February 1995. EnviroCentre Ltd: 5th Floor, Wolfson Centre, Glasgow, G4 0NW

EIRU, Environment and Industry Research Unit (1992) Theoretical Estimates of Methane Yields From Refuse. ETSU Report No. B 1318. ETSU: Harwell, Oxon

Ersoz,M Pehlivan,E Duncan,HJ Yildiz,S and Pehlivan,M (1995) Ion Exchange Equilibria of Heavy Metals In Aqueous Solution on New Chelating Resins of Sporopollenin.*Reactive Polymers.* Vol. 24 No. 3 pp195-202.

ETSU (1995) Review Supplement: NFFO-3/SRO-1 Results Announced. Issued February 1995. ETSU for the Department of Trade and Industry: Harwell, Oxon

ETSU (1997) NFFO News.
URL: http:/www.etsu.com/NR/NR32/html/nffo.html.*New Review.* Issue 32, May 1997. ETSU for the Department of Trade and Industry: Harwell, Oxon

European Communities. Commission (1993) Towards Sustainability, the European Community Programme of policy and action in relation to the environment and sustainable development. Updated with news of progress.
URL: http://europa.eu.int/en/comm/dg11/actionpr.htm on 23/07/97. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1996a) Proposal for a Council Directive on the Landfill of Waste. Draft Proposal dated 18 September 1996. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1996b) Communication from the Commission on the review of the Community Strategy for Waste Management. COM (96) 399 final, 30th July 1996. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1996c) Communication from the Commission. Progress Report on the Implementation of the EC Programme of Policy and Action in Relation to the Environment and Sustainable Development " Towards Sustainability". COM (95) 624. 10/01/96. URL: http://europa.eu.int/en/comm/dg11/env-act5/prog-rep.htm on 22/07/97. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1996d) Strategy Paper for Reducing Methane Emissions (Communication from the Commission to the Council and to the European Parliament) COM (96) 557 final. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1997a) Draft Proposal for a Council Directive on the Landfill of Waste. 5th March 1997. Office for Official Publications of the European Communities: Luxembourg

European Communities. Commission (1997b) Waste. URL: http://europa.eu.int/en/comm/dg11/waste-en.htm on 26/06/97.

European Communities. Council (1989a) Council Directive 89/369/EEC of 8th June 1989 on the Prevention of Air Pollution from New Municipal Waste Incineration Plants. *Official Journal.* L163 14 June 1989 p32. Office for Official Publications of the European Communities: Luxembourg

European Communities. Council (1989b) Council Directive 89/429/EEC of 21June 1989 on the Reduction of Air Pollution from Existing Municipal Waste-Incineration Plants. *Official Journal.* L203 15 July 1989 p50. Office for Official Publications of the European Communities: Luxembourg

European Communities. Council, European Parliament (1994) Directive 94/62/EC of 20 December 1994 on Packaging and Packaging Waste, 94/62. *Official Journal.* L365 Vol. 37 p10 31 Dec 94. Office for Official Publications of the European Communities: Luxembourg

European Environment Agency (1996) Environmental Taxes. Implementation and Environmental Effectiveness. URL: http://www.eea.dk/frseain.htm on 23/07/97. European Environment Agency: Copenhagen, Denmark

EVC, European Vinyls Corporation (1992) Ecobalances. Company literature. European Vinyl Corporation International: Boulevard du Souverain, 360, B-1160 Brussels

EVC, European Vinyls Corporation (1995) The Positive Choice. European Vinyl Corporation International: Boulevard du Souverain, 360, B-1160 Brussels

EVC, European Vinyls Corporation (1996) REPRISE. New Life for Plastics. Company literature. European Vinyls Corporation: Brussels

Farqhuar,GJ and Rovers,FA (1973) Gas Production During Refuse Decomposition. *Water, Air, and Soil Pollution.* No. 2 pp 483-495.

Feder,BJ (1995) Newspapers, tin cans join pork bellies in Chicago. *New York Times.* 15 October 1995. New York Times.

Fermor,TR (1993) Applied Aspects Of Composting And Bioconversion Of Lignocellulosic Materials - An Overview. *International Biodeterioration & Biodegradation.* Vol. 31, No. 2, pp. 87-106.

Financial Times (1997a) CO_2 emissions continue to climb. *Financial Times Energy Newsletter - Power in Asia.* Issue No. 230 p2 14 July 1997. Pearson Professional: London

Financial Times (1997b) Earth Summit : Dire Warnings About Hot Air. *Financial Times Energy Newsletter - Power in Asia.* Issue No. 230 pp1-5 14 July 1997. Pearson Professional: London

Fleming,G (1988a) Landfill and Water - A Difficult Mix. In *Proc. Scottish Hydrological Group/British Hydrological Society Symposium, Hydrology of Landfill Sites, on 3/11/88, at Albany Hotel, Glasgow.*

Fleming,G (1988b) The Hydrogeology of Auchencarroch Quarry. Private report to George Munn, Mid Auchencarroch Farm. G. Fleming: 50 Randolph Road, Glasgow, G11 7LG

Fleming,G (1990) Monitoring the Methane Gas Generation from Different Classifications of Waste Using the Clay/Waste Sandwich Method of Landfill. Research Proposal. University of Strathclyde: Glasgow. (unpublished)

Fleming,G (1991) Recycling Derelict Land. Thomas Telford: London

Fleming,G (1992) Landfills and Contaminated Land: Time Delayed Responses. Based on workshop at University of Strathclyde on Chemical Time Bombs Project of VROM-IIASA-MA . 2 - 5/9/92. Dept of Civil Engineering. University of Strathclyde: Glasgow

Fleming,G (1994) Landfills - Emissions to Groundwater and Air and the Role of PVC. *Proc. Seminar Long Term Behaviour of PVC In Landfills, 8/9/94 at Norsk Hydro, Oslo.*

Fleming,G and Macdonald,M (1993) Gas and Leachate Trends at Craigmuschat Quarry and a Number of Scottish Landfill Sites in Central Scotland. Private report to Scottish Enterprise. Department of Civil Engineering. University of Strathclyde: Glasgow

Fletcher,P (1992) Practical Landfill Gas Flow Monitoring. ETSU Report No.B1317. ETSU: Harwell, Oxon

Forstner,U (1996) Waste Treatment: Geochemical Engineering Approach. In *Geochemical Approaches to Environmental Engineering of Metals*, edited by Reuther, R. Springer-Verlag: Berlin

Gasparini,PA Saetti,GF and Nizzoli,V (1997) Experimental Assessment of Landfill Gas Extraction and Transport. *Proc. Sardinia 1997, Sixth Int. Landfill Symp. , Cagliari, Italy. 13 - 17/10/97.* Vol 2 pp541-547.

Gendebien,A et al (1992) Landfill Gas: From Energy to Environment. Commission of the EC: Luxembourg

Goldsmith,J (1994) The Trap. Macmillan: London

Great Britain (1990) This Common Inheritance. Britain's Environmental Strategy. *Cm 1200.* HMSO: London

Great Britain (1993a) Royal Commission of Environmental Pollution. Seventeenth Report: Incineration of Waste. *Cm2181.* HMSO: London

Great Britain (1993b) The Prospects for Coal: Conclusions of the Government's Coal Review. *Cm 2235.* HMSO: London

Great Britain (1994a) Climate Change: The UK Programme. *Cm 2427.* HMSO: London

Great Britain (1994b) Sustainable Development: The UK Strategy. *Cm 2426.* HMSO: London

Great Britain (1994c) United Nations Framework Convention on Climate Change. New York, May 1992. *Cm 2833.* HMSO: London

Great Britain (1995) British Government Panel on Sustainable Development. First Report January 1995. HMSO: London

Great Britain (1996a) Royal Commission on Environmental Pollution. Nineteenth Report. Sustainable Use of Soil. *Cm 3165.* HMSO: London

Great Britain (1996b) This Common Inheritance. 1996 UK Annual Report. *Cm 3188.* HMSO: London

Great Britain (1997) This Common Inheritance. UK Annual Report 1997. *Cm 3556.* The Stationary Office: London

Great Britain. Department of the Environment (1986) Waste Management Paper 26: Landfilling Sites. HMSO: London

Great Britain. Department of the Environment (1991) Waste Management Paper 28: Recycling. HMSO: London

Great Britain. Department of the Environment (1992) The UK Environment. HMSO: London

Great Britain. Department of the Environment (1994a) Minerals Planning Guidance: Guidelines for Aggregates Provision in England . MPG 6 April 1994. HMSO: London

Great Britain. Department of the Environment (1994b) Review of the Recycling Credits Scheme. Study by MEL Research. HMSO: London

Great Britain. Department of the Environment (1995a) Waste Management Paper 26A: Landfill Completion. HMSO: London

Great Britain. Department of the Environment (1995b) Waste Management Paper 26B: Landfill Design, Construction and Operational Practice. Prepared by Aspinwall & Co. Shrewsbury, SY4 2HH. HMSO: London

Great Britain. Department of the Environment (1996a) A Preliminary Assessment of Trace Organic Compounds in Household Waste. Report No. CWM 133/95. HMSO: London

Great Britain. Department of the Environment (1996b) Digest of Environmental Statistics. No 18, 1996. HMSO: London

Great Britain. Department of the Environment (1996c) Waste Management Paper 26D Landfill Monitoring. Draft for public consultation, January 1996. HMSO: London

Great Britain. Department of the Environment (1996d) Waste Management Paper 26F: Landfill Co-disposal. HMSO: London

Great Britain. Department of the Environment (1997) British Government Panel on Sustainable Development. Annual Report January 1997. Department of the Environment: London

Great Britain. Department of the Environment/Welsh Office (1995) Making Waste Work. A Strategy for Sustainable Waste Management in England and Wales. *Cm 3040.* HMSO: London

Great Britain. Department of Trade and Industry (undated) Anaerobic Digestion for the Treatment of Municipal Solid Waste. DEMOS Project Information Brochures No. 1 - 3. Department of Trade and Industry: London

Great Britain. Department of Trade and Industry (1993) An Assessment of the Potential Renewable Energy Resource in Scotland. Resource Study Summary No. 351. ETSU: Harwell, Oxon

Great Britain. Department of Trade and Industry (1997a) Case Studies of Biotechnology in Action. BMB Bulletin. Issue 3. Department of Trade and Industry: London

Great Britain. Department of Trade and Industry (1997b) Digest of United Kingdom Energy Statistics 1997. The Stationary Office: London

Great Britain. Scottish Office (1994) Statistical Bulletin Environment Series Env/1994/3. Waste Collection, Disposal and Regulation Statistics, 1991. HMSO: London

Great Britain. Scottish Office (1995) Statistical Bulletin: Environment Series. December 1995. Waste Collection, Disposal and Regulation Statistics for 1993. HMSO Scotland: Edinburgh

Great Britain. Scottish Office (1996) Statistical Bulletin. Environment Series. November 1996. Waste Collection, Disposal and Regulation Statistics 1994. HMSO Scotland: Edinburgh

Great Britain. Scottish Office. Industry Department, Energy Division (1992) Outline Proposals for a Scottish Renewables Obligation. A Discussion Paper. Scottish Office: Edinburgh

Greenpeace (1996a) Building the Future. A Guide to Building Without PVC. Greenpeace: Canonbury Villas, London, N1 2PN

Greenpeace (1996b) What's Wrong with PVC?. Greenpeace: Canonbury Villas, London, N1 2PN

Gurijala,KR and Suflita,JM (1993) Environmental Factors Influencing Methanogenisis From Refuse In Landfill Samples. *Environmental Science and Technology.* Vol. 27 pp 1176-1181.

Guyonnet,D and Come,B (1997) Bioreactor Landfill Optimisation. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 1 pp351-357. CISA: Cagliari, Italy

Hansen,D (1995) Untitled paper in seminar at 11th International Conference on Solid Waste Management and Technology, Philadelphia,12 - 15th November 1995. Landfill Services Corporation: Apalachin, NY13732, USA

Harris,RC (1992) Strategic Planning for New Waste Disposal Sites and Groundwater Protection Policy. *Waste Planning.* Issue 2, March 1992.

Harris,RC Knox,K and Walker,N (1994) A Strategy for the Development of Sustainable Landfill Design. *Proceedings of the Institute of Wastes Management.* Vol. 6, January 1994.

Head,KH (1994) Manual of Soil Laboratory Testing. Volume 2: Permeability, Shear Stress and Compressibility Tests. Pentech: London

HMIP, Her Majesty's Inspectorate of Pollution (1995) A Review of Dioxin Emissions in the UK. Research Report No.DOE/HMIP/RR/95/004. HMSO: London

IWM Waste Minimisation Working Group (1996) Waste Minimisation. Institute of Waste Management: Northampton

Jones,P (1996) Effects of Landfill Tax on Local Authorities and Industry. At 'The Costs of Waste: Towards Sustainability' Conference held at SECC, Glasgow. 22 May 1996. Biffa Waste Services Ltd: Coronation Road, Cressex, High Wycombe, HP12 3TZ

Khan,TA (1996) Numerical Modelling of Leachate Production and Movement Within Landfill Sites. PhD Thesis, Department of Civil Engineering. University of Strathclyde: Glasgow

Knox,K (1985) Leachate production, control and treatment. In *Hazardous Waste Management Handbook,* edited by Porteous, A. pp98 - 145. Butterworths: Sevenoaks, Kent.

Knox,K (1990) The Relationship Between Leachate and Gas. In *Proc. of Int. Conference on Landfill Gas; Energy and Environment. 16-19/10/90, Bournemouth.* pp. 367 - 386. Harwell Laboratory: Harwell, Oxon

Knox,K (1991) A Review of Waste Balance Methods and Their Application to Landfill in the UK. Report to DoE. Report No. CWM 031/91. Department of the Environment: London

Knox,K (1996) Leachate recirculation and its role in sustainable development. *Proceedings of the Institute of Wastes Management.* Vol 11, Pages 10-15.

Landva,A O et al (1984) Geotechnical Engineering and Refuse Landfills. *Proc. of 6th National Conference on Waste Management in Canada, Vancouver, B. C., Canada.*

Lea,WR (1996) Plastic Incineration Versus Recycling - A Comparison Of Energy and LANDFILL COST SAVINGS. *Journal Of Hazardous Materials.* Vol. 47, No. 1-3, pp. 295-302.

Leckie,JO and Pacey,JG (1979) Landfill Management with moisture control. *Journal of Environmental Engineering - ASCE.* Vol. 105 No. 2 pp337-355.

Luton,PE et al (1995) The Use of Molecular Techniques To Study Landfill Methanogens. In *Workshop Prospectus, Landfill Gas Microbiology Workshop, Solihull, UK on 15th March 1995. Organised by ETSU for the DTI.* ETSU: Harwell, Oxon

Mader,F (1996) Plastics into the melting pot. *The Waste Manager.* Vol. 25 No. 8 pp12-13. Environmental Services Association: London

Maule,A et al (1995) A Microbiological and Chemical Study of the Brogborough Test Cells. ETSU B/LF/00200/REP. ETSU. Harwell, Oxon

McHarry,J (1996) Closing The Loop. *Newsletter of the Buy Recycled Programme.* Issue 7. Winter 96/97. National Recycling Forum: 24 Holborn Viaduct, London

McHarry,J (1997) Making Sense of Recycling. *The Waste Manager.* Vol. 26 No. 4 pp12-13. Environmental Services Association: London

McSherry,V (1996) The Future of Landfilling Municipal Solid Waste in The United Kingdom. BSc Thesis, Department of Geography. University of Strathclyde: Glasgow

Meteorological Office (1981) Handbook of Meteorological Instruments. Vol. 5 Measurement of Precipitation and Evaporation. HMSO: London

Meteorological Office (1990) CAWS, Climatological Automatic Weather Stations. Data Transfer Formats and Codes. Met.Office: Bracknell

Mirza, A (1997) Hazards of Trace Compounds in Landfill Gas. M. Env. S Thesis. Graduate School of Environmental Studies. University of Strathclyde: Glasgow

Molgaard,C (1995) Environmental Impacts by Disposal OF Plastic From Municipal Solid-Waste. *Resources Conservation And Recycling.* Vol. 15, No. 1, pp. 51-63.

Moore,ER et al (1996) Recycling Fluorescent and High - Intensity Discharge Lamps. *The Journal of Solid Waste Technology and Management.* Vol. 23, No. 1, pp 44-52 February 1996. University of Pennsylvania: Philadelphia, USA

Musselman,CN Straub,WA Bidell,JN and Carpenter,JE (1997) Gas Generation at a Municipal Waste Combustor Ash Monofill - Franklin, New Hampshire. Paper 97-WA88. 01. *Proc. of Air & Waste Management Association's 90th Annual Conf. & Exhibition, June 8-13, 1997, Toronto, Ontario, Canada.* Air & Waste Management Association: One Gateway Center, Pittsburgh, PA 15222, USA

Norsk Hydro (1992) PVC and the Environment. Norsk Hydro: Oslo, Norway

Odum,EP (1971) Fundamentals of Ecology. W.B.Saunders Company: Philadelphia

OECD (1991) Climate Change. Designing A Practical Tax System. OECD: Paris

OECD (1995) Environmental Taxes in OECD Countries. OECD: Paris

OECD (1997) Cleaner Production and Waste Minimisation in OECD and Dynamic Non-Member States. OECD Proceedings. OECD: Paris

Pearce,F (1992) The Dammed. Rivers, Dams And The Coming World Water Crisis. The Bodley Head: London

Peters,T (1997) Treatment of Landfill Leachate by Reverse Osmosis. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 2 pp395-402. CISA: Cagliari, Italy

Pettigrew,CA Rece,GA Smith,MC King,LW (1995) Aerobic Biodegradation Of Synthetic and Natural Polymeric Materials - A Component Of Integrated Solid-Waste Management. *Journal Of Macromolecular Science-Pure And Applied Chemistry.* Vol. A32, No. 4, pp. 811-821.

Phillips,PS and Carey,P (1997) The Pyrolysis of Wastes: A Technology for the Future. *Proceedings of the Institute of Wastes Management.* Vol 14, pp 6-13.

Pinker,B (1997) The Use of Granular Activated Carbon for the Treatment of Landfill Leachate. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 2 pp445-452. CISA: Cagliari, Italy

Porteous,A (1997) Energy-from-waste: a rigorous and environmentally sound option. *Proceedings of the Institute of Wastes Management.* Vol 14, pp 20-28.

Price,M (1985) Introducing Groundwater. Chapman & Hall: London

Rathje,WL (1991) Once and Future Landfills. *National Geographic.* Vol. 179 No. 5 pp116-134 May 1991.

Reitzel,S Faquhar,S and McBean,E (1992) Temporal Characterization of Municipal Solid Waste Leachate. *Canadian Journal of Civil Engineering.* Vol. 19, pp 668-679.

Reynolds,PJ & Blackey,N C (1992) Landfill 2000: Report on Construction, Installation of Monitoring Equipment and Cell Wetting Procedure. Report to DoE. No. CWM 050/92 (limited distribution) WRc: Medmenham

Robinson,HD Last,SD Raybould,A Savory,D and Walsh,TC (1997) State of the Art Landfill Leachate Treatment Schemes in the United Kingdom. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 2 pp191-209. CISA: Cagliari, Italy

Rose,J (1996) Current Affairs. *The Waste Manager.* Vol. 26 No. 1 pp 27 - 29. Environmental Services Association: London

Rowe,KR Quigley,RM Booker,JR (1995) Clayey Barrier Systems For Waste Disposal Facilities. E & FN Spon: London

Rowe,RK et al (1997) Recent Advances in Understanding the Clogging of Leachate Collection Systems. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 3 pp383-390.

Schwarz,C (ed.) (1991) Chambers Concise Dictionary. W&R Chambers Ltd: Edinburgh

Scottish Environmental Protection Agency (1996) State of the Environment Report 1996. SEPA: Stirling, Scotland

Shaw,E (1988) Hydrology in Practice. Chapman & Hall: London

Shayler,M (1998) Design of the Environment. *Engineering Designer.* Vol. 24 No. 1 January 1998.

Singer,J (1995) Does The Uk Government Target To Recycle 25-Percent Of Household Waste by the year-2000 represent an economic-approach to recycling - a case-study of plastic. *Resources Conservation And Recycling.* Vol. 14, No. 2, pp. 133-155.

Soil Association (1946) Editorial. *Mother Earth.* Vol. 1 No. 1.

Solantausta,Y Bridgewater,AT and Beckman,D (1995) Feasibility of Power Production With Pyrolysis and Gasification Systems. *Biomass and Bioenergy.* Vol. 9 No. 1-5 pp 257-269.

Stanier,RY, Adelberg,EA, and Ingraham,JL (1977) General Microbiology. Macmillan: London

Stark,JG and Wallace,HG (1982) Chemistry Data Book. John Murray: London

Stearns,RP (1987) Settlement and Gas Control: Two Key Post-Closure Concerns. *Waste Age.* Vol. 33 No. 3 pp 55-60.

Suflita,JM et al (1992) The World's Largest Landfill: A Multidisciplinary Investigation. *Environmental Science and Technology.* Vol. 26 pp1486-1495.

Thames Waste (undated) Anaerobic Co-digestion of MSW and Sewage Sludge. Company Literature. Thames Waste Management Ltd: Leatherhead, KT22 7PG

Tindale,S and Holtham,G (1996) Green taxes: pollution payments and labour tax cuts. Briefing. Institute of Public Policy Research: 30-32 Southampton Street, London, WC2E 7RA

UNCED; United Nations Conference on Environment and Development (1992) Agenda 21: Programme of Action for Sustainable Development, including Rio Declaration on Environment and Development. United Nations: New York

United Nations (1993) Yearbook of the United Nations 1992. Volume 46. Martinus Nijhoff: Dordrecht, Netherlands

Van Berkel,PM Driessen,WL Anthony,GJ Kodhaas,A Reeddijk,J and Sherrington,DC (1995) A Novel, Highly Copper(II)-selective Chelating Hydrophilic Ion Exchanger based on Imidazole modified Poly(glycidyl methacrylate) . *Journal of the Chemical Society - Chemical Communications.* 1995, No. 2 pp147-148.

Van Den Broek,B Lambropoulos,NA and Haggett,K (1995) Bioreactor Landfill Research in Australia. *Proc. Sardinia '95, Fifth International Landfill Conference, Cagliari, 2 - 6/10/95.* pp 183-192. CISA: Cagliari, Italy

von Weizsacker,E Lovins,AB and Lovins,LH (1997) Factor Four. Doubling Wealth - Halving Resource Use. Earthscan: London

Walker,AN Beaven,RP and Powrie,W (1997) Overcoming Problems in Development of a High Rate Flushing Bioreactor Landfill. *Proc. Sardinia 1997, Sixth Int. Landfill Symp., Cagliari, Italy. 13 - 17/10/97.* Vol 1 pp397-408. CISA: Cagliari, Italy

Wall,DK and Zeiss,C (1995) Municipal Landfill Biodegradation And Settlement. *Journal Of Environmental Engineering - ASCE.* Vol. 121, No. 3, pp. 214-224.

Ward,RC and Robinson,M (1990) Principles of Hydrology. McGraw-Hill: London

Warren Spring Laboratory and Aspinwall & Company Ltd (1993) Development of The National Household Waste Analysis Programme. Summary Report. DoE Research Contract PECD 7/10/288. Report No. CWM/059/93. Department of the Environment: London

Watson-Craik,I and Robin-Jones,L (1994) Assessment of The Role of Surfaces in Refuse Degradation. Draft Final Report to Department of the Environment. unpublished.

Watson-Craik,IA (1994) Lecture Notes. Course: Waste Biotechnology. Dept. of Bioscience and Biotechnology. University of Strathclyde: Glasgow

Wayman,M Chen,S and Doan,K (1993) Production Of Fuel Ethanol From The Waste Paper In Garbage. *Process Safety And Environmental Protection.* Vol. 71, No. B2, pp. 141-143.

Westlake,K (1994) Microbial Metabolism In The Brogborough Landfill Gas Enhancement Test Cells. ETSU Report No. B/LF/00201/REP. Department of Trade and Industry: London

Westlake,K Archer,DB Boone,DR (1995) Diversity Of Cellulolytic Bacteria In Landfill. *Journal Of Applied Bacteriology.* Vol. 79, No. 1, pp. 73-78.

Willey,R (1997) Seminar on Waste Minimisation given to CBI West of Scotland Environment Business Forum, on 22 January 1997 at University of Strathclyde. Centre for Environment and Waste Management: Paisley University.

Wingfied-Hayes,C (1994) Mid Auchencarroch Phase One: An Experiment of the Feasibility of Small Scale Shallow Landfill. MSc Thesis, Dept. of Civil Eng. University of Strathclyde: Glasgow

Wingfield-Hayes,C Fleming,G and Keenan,CJ (1997) Developing Appropriate Technology for Small Scale Shallow Landfill - The Mid Auchencarroch Landfill Research Facility. *Journal of Solid Waste Technology and Management.* Vol. 24 No. 1 pp19-26.

Wingfield-Hayes,C Fleming,G and Gronow,J (1997) Gas Generation as a Function of Leachate Management: Mid Auchencarroch Experimental Landfill. *Proc. Air & Waste Management Association's 90th Annual Meeting, on 8-13/6/97 at Toronto, Canada.*

Wingfield-Hayes,C Fleming,G and Gronow,J (1998) Field Trials of Waste Manipulation Techniques: The Mid Auchencarroch Experimental Landfill. *Proceedings of the Institute of Wastes Management.* March 1998.

Withers,B and Vipond,S (1974) Irrigation: Design and Practice. Batsford Academic and Educational: London

Yen,BC and Scalon,B (1975) Sanitary Landfill Settlement Rates. *Journal of Geotechnical Engineering - ASCE.* Vol. 101 No. 5 pp 475-487.

Zehnder,AJB (1978) Ecology of Methane Formation. In *Water Pollution Biology,* edited by Ralph Mitchell, p. 349. John Wiley & Sons: New York

Zeikus,JG (1980) Microbial populations in digesters. In *Anaerobic Digestion,* edited by Stafford,DA. Applied Science Publishers: London

EXPLANATION OF SOFTWARE APPENDIX

Reasons for a Software Appendix

The quantity of data that the experiment has yielded is great. It would not be feasible to include hard copy of the data in the thesis - the gas flow data alone runs to 65,000 records and would occupy over 1000 pages. Furthermore, hard copy of this data is not desirable, as it is of little use in a form in which it cannot be easily manipulated. Raw experimental data is therefore presented only in software format.

Once it became obvious that a software appendix would be provided, the decision was made that all other material destined for the appendix would also be available only in software format. The main body of this other material is a full photographic record of the construction and monitoring of the experiment landfill cells.

Location

The Software Appendix is stored on CD-ROM which is located inside the back cover of this volume.

Accessing the Appendix

The appendix is constructed along the same lines as an internet site. Using a web browser, such as Netscape Navigator, or Microsoft Internet Explorer, open the file *index.html* on the root directory of the CD-ROM. From this page hypertext links provide access to:

- a full description of the structure of the databases that comprise the main body of the appendix
- over 75 photographs of the construction and monitoring of the experiment
- trial pit logs from the ground investigation at the experimental site

Windows 95 or later operating system is required.

Accessing Raw Data

Raw data is stored on a number of databases in Microsoft Access v2.0 format. The contents of the databases are described in the 'web pages' as detailed in the section above. However, the data itself is not accessible using a web browser. A database package, such as Microsoft Access v2.0, should be used to open the '*.mdb*' files directly. These files are located in the sub-directory *datasets*. If using a later version of Microsoft Access or another proprietory database package, it may be necessary to 'import' the *.mdb* files into that package for conversion.

Windows 95 is not required to access this part of the CD-ROM.

LIST OF TABLES

List of Figures