THE EFFECT OF SEWAGE SLUDGE CO-DISPOSAL AND LEACHATE RECYCLING ON REFUSE STABILIZATION

by

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SYNOPSIS

Urbanization is causing increased pressures on sanitary landfill sites in that more people produce more garbage and occupy more land making it more difficult to find suitable new landfill sites. These pressures have changed the approach to landfill practice from one of simply dumping and storage to one of containment and treatment. With the latter approach the landfill site is regarded as a bioreactor and any economical or practical strategy that can accelerate the degradation is implemented to facilitate stabilization of the refuse as rapidly as possible. Landfill stabilization proceeds principally via anaerobic methanogenesis and the landfill operations of sewage sludge co-disposal and leachate recycling are claimed to promote this. From the literature it appears that when enhanced refuse degradation took place with the above two operations, it was not clear whether it was attributed to the operation *per se* or to the increase in moisture content of the refuse towards field capacity that resulted from the operation. Consequently a pilot scale lysimeter investigation was undertaken to examine the effect of sludge co-disposal and leachate recycling on the onset and progress of methanogenesis.

Six column lysimeters (4,25m high, 0,6m diameter and 1m^3 refuse volume) were filled with selected refuse and five of these had anaerobic sewage sludge co-disposed with the refuse. Each lysimeter contained about 500kg of organic material (60% by mass), paper and cardboard (15%), cloth (20%), shredded plastic (3%), and ash (2%) which was brought to field capacity (65% moisture content by wet mass) by the addition of water, taking due account of the moisture already added with the sludge (200l at 5% solids). The contents of each lysimeter had a final density of about 700kg/m^3.

The lysimeters were operated in different ways to investigate the effect of sludge co-disposal and leachate recycling on the onset of methanogenesis in the refuse. Since sludge addition affects a number of parameters in the refuse, such as alkalinity addition, nutrient addition, methanogenic inoculum addition and moisture addition, these effects were, where possible, separated so that each parameter could be investigated individually.

After refuse placement the lysimeters were monitored for a period of 50 weeks during which ambient and refuse temperatures were monitored on a daily basis and leachate pH, COD, Conductivity, $H_2CO_3^*$ alkalinity, short-chain fatty acids (SCFA), NH_4^+,

TKN, PO_4^{3-} and SO_4^{2-} were measured on a weekly basis. From the investigation the following observations and conclusions were made:

(1) Sludge addition

1.1 An increase in moisture content due to the sludge addition to the refuse enhanced the degradation of the refuse in its acid phase.
1.2 The co-disposed sludge added alkalinity to the refuse in that NH_3 added in the sludge formed NH_4^+. However this extra alkalinity was completely neutralized by the high SCFA concentrations generated. Therefore the addition of anaerobic sewage sludge to "fresh" refuse does not appear to accelerate the onset of methanogenesis in the refuse in the short term.
1.3 Nutrients were added to the refuse by the sludge with the NH_4^+ having a longer lasting effect than the PO_4^{3-}.

(2) Leachate recycling

Recycling of leachate from refuse in its acid phase of decomposition back to this refuse resulted in an accumulation of SCFA in the refuse with a subsequent lowering of the pH. Therefore it is recommended that leachate from acid phase refuse should be recycled rather to refuse in its methanogenic stage of decomposition. This is so that the high SCFA concentrations in the leachate can be reduced by methanogenic activity.

(3) Buffer addition

3.1 Lime added to refuse containing co-disposed sewage sludge was not effective in maintaining the pH in the refuse at a near neutral value, mainly because insufficient lime was added for this purpose.
3.2 NaOH dosed to the refuse in recycled leachate followed by a high flux of water through the refuse elevated the pH and $H_2CO_3^*$ alkalinity of the refuse to values of about 7 and 2000mg/l as $CaCO_3$ respectively. Methanogenesis took place in this refuse about 7 weeks after these pH and alkalinity values had been obtained and this was the only refuse that became methanogenic during the 50 week investigation period. Therefore it appears that the onset of methanogenesis in refuse is dependant on a neutral pH (6,8-7,8) in much the same way that methanogenesis in anaerobic digestion of liquid wastes is dependant on a near neutral pH.

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Symbol	**Description**
$Ca(OH)_2$	Calcium Hydroxide (lime)
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand (mg/l)
Ct	Total carbonate species concentration (mol/l)
$H_2CO_3^*$ alkalinity	Carbonate system alkalinity (mg/l as $CaCO_3$)
HAc	Acetic acid
MC	Moisture content
$NaHCO_3$	Sodium bicarbonate
NaOH	Sodium Hydroxide
NH_3	Free ammonia (unionized form)
NH_4^+	Saline ammonia (ionized form)
^oC	Degrees Celsius
pH	Negative log(activity of hydrogen ions)
PO_4^{3-}	Orthophosphate ion
SCFA	Short-chain fatty acids (mg/l as HAc)
SO_4^{2-}	Sulphate ion
SS	Suspended solids
TKN	Total Kjeldahl nitrogen concentration (mgN/l)

CHAPTER 1

INTRODUCTION

1.1 CHANGING APPROACH TO SOLID WASTE HANDLING

In the past sanitary landfill sites for solid waste disposal were regarded simply as containment sites so that the waste contents were isolated from the population. Various degrees of effort were made to reduce the impact of the waste in and around the site - in some cases none in other cases considerable but the prevailing attitude was that it was a disposal site - not a treatment site; consequently the stabilization of waste in the site was largely disregarded and generally little effort was made to promote waste stabilization.

Rapidly growing cities as a result of urbanization of the rural communities has placed management and operation of sanitary landfill sites under increasing pressure from two directions in that an increased metropolitan population not only produces more solid wastes but also makes the acquisition of appropriate landfill sites increasingly difficult and expensive. These problems are exacerbated by a heightened environmental awareness in large sectors of the public who are concerned that municipal wastes in general, but solids wastes in particular are properly managed so as to maximize safe disposal of the wastes and minimize the environmental impact of these operations. Such developments have considerably increased the responsibilities of the municipal engineers in waste treatment and disposal and has demanded alternative and innovative measures for these operations. As a result sanitary landfills are becoming regarded as bioreactors in that much greater cognizance of the stabilization of the wastes in the landfill is being taken; also greater efforts are being made to reduce the impact of the landfill on its surroundings by installing liners to reduce leachate contamination of surrounding groundwater and by burning methane gas to reduce air pollution.

In the bioreactor approach to landfilling cognizance is taken in how the wastes are placed and compacted and this is done in such a way as to provide the greatest opportunity for bio-degradation of the wastes to take place. Factors considered to affect biodegradation are manipulated as much as possible to achieve safe, effective and economic solid wastes treatment and disposal.

Waste disposed of in a landfill passes through various phases of degradation before all of the biodegradable matter in the waste has been stabilized. The landfill is considered to be stable once no further appreciable degradation takes place in it and the production of degradation generated substances in the leachate and gas from the waste are minimal. In order to achieve this condition the waste needs to pass through a methanogenic phase of degradation prior to the landfill becoming stable.

1.2 ADVANTAGES OF LANDFILL STABILIZATION

There are several advantages in stabilizing the refuse in a landfill as quickly as possible:

(1) Volume reduction: the stabilization of landfill waste leads to significant volume reductions; therefore any operational procedure that can accelerate waste stabilization is desirable by virtue of the volume reduction it promotes. The refuse in a stable landfill can occupy as little as one third of its volume when freshly placed. This compaction in stabilization extends the life of the landfill site in that two to three times more refuse can be placed at the site which results in a large cost saving in terms of the land area required. Once a landfill site has stabilized fully and no further placement of refuse on the site is intended, the site can be used for a commercial venture such as a golfing green, fairground or parking lot so that revenue can be generated. And therefore the sooner stabilization of the waste site occurs, the sooner the site can be restored and put to a different use.

(2) Leachate constituents: leachate dissolved organic matter, most of which are volatile fatty acids, produced from a fill in its methanogenic stage of decomposition are one to two orders of magnitude lower than those in the leachate from a landfill in the acid phase of decomposition (Ehrig, 1980). Thus the costs of leachate treatment, if required, are much lower and less extensive monitoring and testing for pollution of the ground water by the leachate is necessary which results in a further cost saving. From an environmental point of view, the lower organic concentrations in the leachate from a fill in its methanogenic phase pose less of a pollution threat to underground aquifers and are less likely to destroy the integrity of ground barrier systems for containing the landfill in the long term.

(3) Gas production: the sooner gas is produced from the refuse the earlier revenue may be gained from the sale or utilization of the gas. With gas production commencing earlier and at a higher rate, as would be the case with the accelerated onset and

progress of methanogenesis, the pay-back period for the gas collection scheme would be shorter which has cost saving implications.

(4) Settlement of the landfill takes place earlier as a result of stabilization so that the design and operation of the gas extraction systems in the landfill are simplified and surface capping where required is made easier. Consistent gas extraction from the landfill reduces the risk of sudden subsidence of parts of the landfill due to erratic expulsions of gas.

(5) With a more rapid stabilization of the landfill the biodegradable matter in the waste is decomposed sooner and the landfill is less prone to become a habitat of disease vectors such as rodents and flies. Odors produced from the decaying refuse are also significantly reduced once the landfill has stabilized.

1.3 METHODS OF ACCELERATING LANDFILL STABILIZATION

A landfill operation strategy that is considered to be beneficial to the accelerated and improved stabilization of a landfill is that of co-disposal in the landfill of anaerobic sludge from a sewage treatment plant . The sludge is considered to seed the landfill with a methanogenic inoculum which is claimed to accelerate the onset and progress of methanogenesis in the landfill. Co-disposing sludge in a landfill also is advantageous for the sewage treatment plant in that it provides a means of sludge disposal. Apart from the environmental advantages gained from this sludge disposal method, large financial savings would also be made in sludge management operations. Approximately half of the operation costs of a sewage treatment plant are associated with the treatment and disposal of the sludge. In South Africa the most widely used disposal method for this sewage sludge involves thickening, anaerobic stabilization and dewatering on drying beds. If stabilized or even unstabilized liquid sludge could be disposed of on a sanitary landfill then much of sludge treatment and dewatering costs can be eliminated.

Co-disposal of anaerobic sewage sludge with refuse is thought to accelerate the onset and progress of methanogenesis in the refuse by providing (1) liquid to raise the moisture content of the refuse (65% moisture content by wet weight represents the optimum moisture content for biodegradation) (2) a methanogenic inoculum (3) nutrients for microorganism growth and (4) alkalinity to buffer the liquid fraction of the waste against pH changes during the acid phase.

Another landfill operation strategy considered to accelerate the onset and progress of methanogenesis in a landfill is the recycling of leachate produced from the refuse back on to the refuse. This is considered beneficial in reducing the organic concentrations in the leachate by taking advantage of the natural attenuation mechanisms in the landfill.

1.4 OBJECTIVES OF THESIS

The objective of this thesis is to investigate the above two claims i.e. codisposal of sewage sludge and leachate recycling, for accelerating the onset and progress of methanogenesis in a sanitary landfill. To achieve this, six test lysimeters 4.25m high and of diameter 0.6m were filled with $1m^3$ of selected refuse (60% organic, 20% cloth, 15% paper, 3% plastic, 2% ash) and tested over a period of 12 months. With one lysimeter as a control, anaerobic sewage sludge was co-disposed with the refuse in the remaining 5 lysimeters. The lysimeters were exposed to differing conditions so that where possible the claimed advantages of sewage sludge co-disposal and leachate recycling could be isolated to determine which has the greater influence on accelerating the onset and progress of methanogenesis.

1.5 SCOPE OF THESIS

In chapter 2 a review is presented of previous research carried out on the enhancement of refuse degradation using lysimeter studies. In chapter 3 the experimental set-up adopted for the investigation and the methods of monitoring and types of tests conducted are given. The results of the study and a discussion are covered in chapter 4. In chapter 5 the conclusions drawn from the research findings are given together with recommendations for the practical application of the findings to a full-scale situation as at a sanitary landfill.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

At about the same time that researchers were investigating the mechanisms of anaerobic fermentation (Buswell and Mueller, 1952) and establishing fundamentals for describing the anaerobic degradation process (McCarty, 1961, 1964), sanitary landfills drew the attention of researchers in the way that they exhibited anaerobic behaviour. Initial interest was focussed on the gas produced by landfilled refuse in terms of the quantity and composition of the gas (Merz, 1964; Farquhar and Rovers, 1973). The attention then shifted more towards leachates and their treatment once it was discovered that the liquids leaching into the ground after having percolated through a refuse mass posed a pollution threat to underground aquifers (Schoenberger, 1970; Boyle and Ham, 1972; Johansen, 1975). A great deal of research has subsequently been carried out on the treatment of leachates produced by lined landfills and the reduction of leachate strength (attenuation) in the ground layer below the landfill in unlined landfills. These aspects are not reviewed as they are not relevant to the theme of accelerated landfill stabilization.

It has been appreciated by the majority of researchers for some time now that the stabilization of refuse in a landfill is an important and desirable aspect in the management of the landfill. However it has been only recently that a landfill has become regarded as a bioreactor in which the degradation processes that lead to stabilization are to an extent controllable. This viewpoint has generated much interest in the last decade and methods by which the degradation of the refuse in the landfill can be manipulated have been investigated. One of these, which also holds advantages for the treatment and disposal of sludges produced at treatment plants, is co-disposal of wastewater sludges with municipal refuse in a landfill. Co-disposal research has been undertaken with sewage sludge (Craft and Blakey,1975; Scharf, 1982) and with industrial wastewater sludge (Stegmann, 1981; Pohland and Gould, 1986), and a number of advantages of this were noted. Before details of this work can be described it is necessary to briefly outline the various phases by which refuse is stabilized in a landfill.

2.2 PHASES INVOLVED IN SOLID WASTE STABILIZATION

In the stabilization of waste in a landfill, there are generally 5 phases of degradation i.e. aerobic, acid, transition, methanogenic and termination (Fig 2.1). In the first phase which commences immediately after landfilling the waste, easily degradable organic matter is aerobically decomposed while oxygen is still present in the refuse. Once all the available oxygen is depleted, the acid phase commences in which fermentation and acetogenic bacteria generate volatile fatty acids. Water originating from rainfall percolates through the waste and mixes with the liquids containing high concentrations of volatile fatty acids present in the waste and drains out of the base of the landfill as leachate. The concentration of these organic acids in the leachate increases during the acid phase of decomposition of the landfill. After the acid phase, which can last up to a year or more, phase 3 commences which is marked by the onset of anaerobic methanogenesis and methane production. In this phase, which is the transition between the acid and methanogenic phases, methanogenic bacteria begin to proliferate in the waste and the concentration of volatile fatty acids in the leachate begins to decrease as some of the acids are utilized by the methanogens in the production of methane. The decrease in volatile fatty acid concentrations in the leachate and rate of gas production and its composition during the transition phase are shown in Figure 2.1 (based on Farquhar and Rovers, 1973 and Ehrig, 1984). Phase 4 commences once stable methanogenic conditions are established and during this phase a relatively stable methane production takes place. Once most of the waste has been stabilized, methanogenesis slows down and phase 5 commences, at the end of which virtually all of the degradable organic material in the landfill has been degraded and only the more refractory organic carbon remains. Methane production in phase 5 shows a marked decrease.

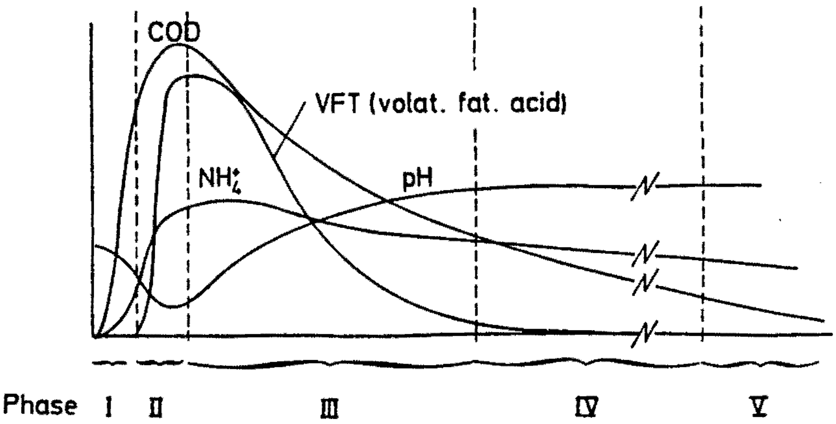

Fig 2.1a The 5 phases of refuse degradation (after Farquhar and Rovers, 1973 and Ehrig, 1984).

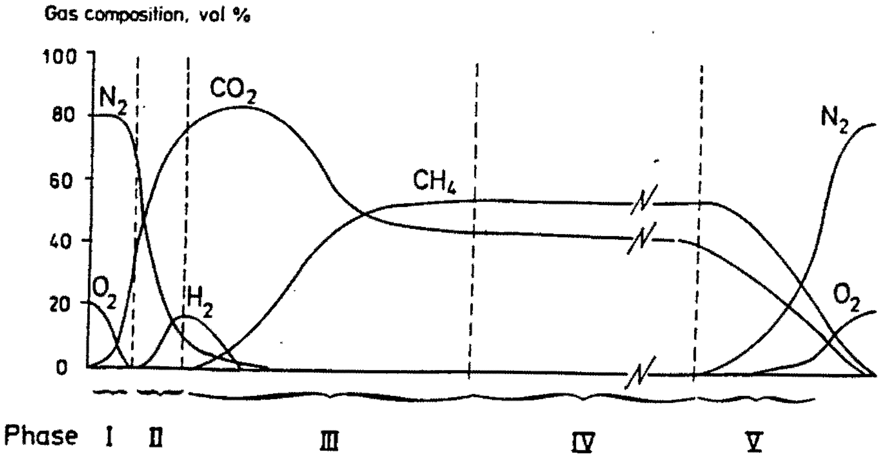

Fig 2.1b The 5 phases of refuse degradation (after Farquhar and Rovers, 1973 and Ehrig, 1984).

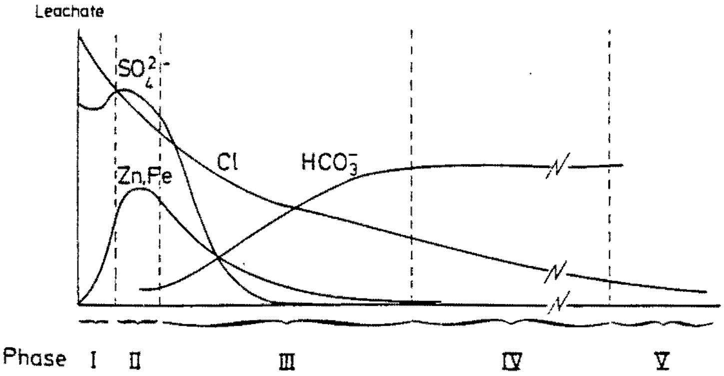

Fig 2.1c The 5 phases of refuse degradation (after Farquhar and Rovers, 1973 and Ehrig, 1984).

2.3 ENHANCEMENT OF REFUSE DEGRADATION

In an endeavor to enhance the degradation process taking place in a landfill, several landfill operation parameters have been assessed for their beneficial effects on promoting the onset and progress of landfill stabilization. These include: (1) elevating the moisture content of the refuse, (2) co-disposal of sewage sludge with refuse, (3) recycling leachate back to the landfill, (4) addition of nutrients to refuse and/or recycled leachate and (5) addition of buffer to refuse and/or recycled leachate[1] . Research into these aspects of landfill operation have been carried out with studies at full-scale (landfills themselves), pilot scale and laboratory scale with the dimensions of

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[1] Although research has been carried out on the effect of buffers on the degradation process in refuse, the details of this work were only published after the commencement of this project. Therefore it is not relevant to review this particular literature in the context of this thesis in this section.

the test units used in the different studies varying widely. Although the data generated by studies done at full scale and laboratory scale make a valuable contribution to furthering the understanding of the behaviour of landfilled waste stabilization, in this literature review more attention is given to the findings from pilot scale studies. This is because the investigation reported in this thesis was also a pilot scale study and therefore more meaningful comparisons can be made if references are made to pilot scale studies done elsewhere. The more pertinent aspects of the research findings concerning these operation parameters and the effect that each one had on the refuse degradation process are now discussed.

2.3.1 Moisture Content and Water infiltration rates

From anaerobic biodegradation theory (McCarty, 1964) it appears that a high moisture content in waste material facilitates the breakdown of the biodegradable matter in the waste. When considering a sanitary landfill conceptually as an anaerobic digester, similar findings have been reported on the effect of increasing the moisture content of refuse i.e. the gas production rate from the landfill increases (Buivid ,1980; Rees, 1980). A review of the literature by Christensen (1990) revealed that generally an exponential increase in the gas production rate can be expected for an increase in refuse moisture content between 25% and 60%. However attempts by some researchers at elevating the moisture content of refuse by means of increasing the infiltration rate of water irrigated to the refuse have proven the contrary. Kinman *et al.* (1987) and Leuschner (1990) among others found that very little gas production, if any, occurred with increased rates of water infiltration through the refuse. It appears that other findings regarding the benefits of increasing moisture contents in refuse also seem contradictory; however these contradictions may have arisen as a result of differences between the types of waste, both in constituents and age, that different researchers have used in their studies. Although not explicitly stated by researchers, where gas production enhancement has taken place with increased moisture application rates, this has generally occurred where the refuse used for the experiments was "old" *and* the moisture content of the refuse was less than the field capacity (60-65% moisture content by wet weight) before moisture additions were made. For example, Barlaz *et al.* (1987) found that refuse at 57% moisture content produced gas earlier relative to refuse that had a moisture content that was lower than 57%. However Barlaz *et al.* did not mention the age of the refuse, but can be considered "old" due to the fact that in other similar lysimeters of their investigation that contained the same refuse, methane production occurred within the first two weeks of refuse placement. In contrast, it appears that generally "fresh" refuse was used by researchers who failed to improve gas production rates by elevating moisture contents with increased water infiltration rates through the refuse mass.

Researchers working with "fresh" refuse also found that a higher through-put of moisture in the refuse accelerated decomposition of the waste material, indicated by higher concentrations of COD in the leachate produced from the refuse (Kinman *et al.*, 1987; Leuschner, 1990). Leuschner attributed this phenomenon to the stimulated hydrolysis of the particulate material in the refuse as a result of the higher moisture content.

It appears then that attempts at enhancing methane production from "fresh" refuse in lysimeter studies only by increasing the moisture content of the refuse have been unsuccessful. Also, where "old" refuse has been producing gas, the rate of gas evolution from the refuse has only been increased by increasing the moisture content of the refuse when the original refuse moisture content was below field capacity (65% by wet mass).

2.3.2 Co-disposal of sewage sludge

The use of anaerobic sewage sludge co-disposed with refuse for the purpose of enhancing refuse stabilization (usually detected by increased gas production) has been found to be effective by several researchers (Stamm *et al.*, 1985; Cossu *et al.*, 1987; Kinman *et al.*, 1987; Craft and Blakey, 1988). It is important to note however that not all these researchers achieved enhanced gas production by employing the sludge addition to the refuse in the same manner. For example Stamm *et al.* added the sludge to refuse that had been incubated for 3 years whereas Kinman *et al.* added sludge to 4 year old refuse that had previously been receiving recycled leachate. When these researchers found enhanced gas production to take place as a result of the addition of sludge to refuse, invariably the leachate contained lower COD concentrations compared to refuse that did not have sludge addition. In conformity with this observation, Craft and Blakey (1988) reported that during the methanogenic phase the COD concentrations in leachate from refuse that contained codisposed dewatered sludge were 50% lower than the COD concentrations in leachate from normal refuse, while the COD concentrations in leachate from refuse receiving liquid digested sludge were only 7% lower . This difference may have arisen because less solids were co-disposed with the liquid digested sludge (sludge:refuse = 1:9,7) than with the dewatered sludge (sludge:refuse = 1:4,1).

In contrast to the research reviewed above where it was observed that sludge addition caused lower leachate COD values during methanogenesis, in the experiments of Barlaz *et al.*, (1987) the opposite appears to be the case. Barlaz *et al.* claimed that sewage sludge addition for the purpose of seeding the refuse with methanogenic bacteria was not successful. Unfortunately Barlaz *et al.* do not mention as to what type of refuse ("fresh" or "old") they used when co-disposing sludge but it can be inferred that the refuse was "old" because methane was produced within the first 7 weeks of refuse placement which, from the literature, does not usually occur with "fresh" refuse. The pH of the leachate from this refuse with sludge addition dropped to a value of 5,3 whereas that from refuse without sludge addition was 5,8. The lower pH indicates that a higher short chain fatty acid concentration was produced as a result of addition of the sludge. Pohland (1975) found similar results.

It is important to note that where researchers have found that sludge addition to refuse enhanced methane production from the refuse, the moisture content of the refuse was often less than field capacity before the sludge addition took place. It is also true to say that the converse occurred, i.e. sludge addition to refuse that was at or near field capacity generally did not stimulate extra methane production from the refuse. Therefore it would appear that the dominant contributing feature of the sludge addition to refuse was to elevate the moisture content of the refuse towards field capacity. Consequently the increased moisture content was probably responsible for the enhancement of gas production and not sludge addition *per se*.

2.3.3 Leachate recycling

The recycling of leachate produced from refuse back to the refuse has drawn the attention of several researchers. However, the findings concerning the effects of recycling on the degradation process that takes place in refuse are contradictory. From pilot scale lysimeter studies, Pohland (1975) recommended leachate recycling, yet other researchers have suggested that no beneficial effects are obtained with recycling (Barlaz *et al.*, 1987; Kinman *et al.*, 1987). Generally it has been found that leachate recycling to freshly placed refuse resulted in higher COD concentrations in the leachate produced from the refuse (Rees, 1982; Kinman *et al.*, 1987). Studies done by Doedens and Cord-Landwehr (1990), however showed that COD concentrations in the leachate produced from refuse with leachate recycling were *lower* than the concentrations found in leachates from refuse that received no recycled leachate. These researchers also produced various other interesting results concerning leachate recycling that are not in conformity with other reported findings on this subject. Generally it appears that when improved degradation of refuse has taken place with leachate recycling it has often been associated with an increase in the moisture content of the refuse due to the recycled leachate. Hence it is not always possible to conclude that leachate recyling *per se* improved the degradation. It may have been as a result of the increase in moisture content caused by the recycling.

2.3.4 Nutrient Addition

Generally, nutrient addition to refuse in the form of urea ($(NH_2)_2CO$) and dipotassium hydrogenphosphate (K_2HPO_4) or ammonium phosphate ($(NH_4)_3PO_4$) has been found to be beneficial to the degradation of refuse although not as effective in this respect as sewage sludge addition (Kinman *et al.*, 1987; Leuschner *et al.*, 1990). Buivid *et al.*, (1981) concluded that sewage sludge was a good source of nutrients for the microorganisms in the refuse.

2.3.5 Gas Composition

The composition of the gas produced by degrading refuse has been monitored by nearly all researchers conducting lysimeter studies. Barlaz *et al.*, (1987) concluded from their studies that the methane composition of the gas produced was not always indicative of the methane production rate from a lysimeter. The general consensus, however is that the percentage of methane in the gas produced from the refuse increases as the gas production rate from the refuse increases (Kinman *et al.*, 1987; Leuschner , 1990; Stegmann and Spendlin, 1990).

Most researchers have concluded that the percentage of methane in gas produced from degrading refuse is on average about 50-60%. Gujer and Zehnder (1983) found that anaerobic fermentation of acetic acid, which is considered to be the substrate source for methane production (McCarty, 1964), results in a 50% methane composition in the gas generated. Leuschner (1990) reported methane compositions as high as 60% in the

(7) Once the rate of gas production from refuse started to increase, the percentage composition of methane in the gas also increased until a value of about 50% methane was obtained.

(8) Care should be exercised when interpreting literature information and data because different results are often reported depending on whether the refuse used in the experiments is "fresh" or "old".

gas produced from refuse in lysimeter studies and Stegmann and Spendlin (1990) have reported values as high as 65-70% from refuse in its methanogenic stage of decomposition.

2.4 CONCLUSIONS

The review of findings on lysimeter studies on the enhancement of refuse degradation would indicate the following:

(1) Attempts to stimulate methane production from fresh refuse by increasing the moisture content of the refuse have been unsuccessful.

(2) Increasing the moisture content of refuse that was already producing methane enhanced the production of methane only when the moisture content of the refuse was below field capacity (65% moisture by wet weight).

(3) Co-disposal of anaerobic sewage sludge with "old" refuse enhanced gas production from the refuse but it is uncertain whether or not the increase was caused by an increase in moisture content resulting from the sludge addition or from the sludge addition itself.

(4) Leachate recycling did not stimulate methane production from "fresh" refuse but it did from "old" refuse. Here also, it is uncertain whether or not the increased gas production from the refuse resulted from the leachate recycling *per se* or from the increased moisture content this indirectly caused; the increased gas production was observed only when the leachate recycling increased the moisture content of the refuse towards field capacity.

(5) From 3 and 4 above it appears that when co-disposed sewage sludge or leachate recycling enhanced the degradation of refuse, indicated by enhanced methane production from the refuse, this only occured with "old" refuse that previously had a moisture content below field capacity.

(6) Co-disposed sewage sludge is considered to be a sufficient source of nutrients for the refuse degradation process and superior to artificial forms of nutrients for this purpose.

CHAPTER 3

EXPERIMENTAL SET-UP

3.1 DESCRIPTION OF COLUMN LYSIMETERS

3.1.1 Construction of the lysimeters

In order to achieve the objectives set for the investigation, six identical column lysimeters 0,6m diameter and 4,25m tall were constructed. Each lysimeter was fabricated from 5 re-worked 2mm gauge cylindrical steel oil drums opened at both ends and welded together end to end. To protect the lysimeters against corrosion, they were hot dipped galvanized in their fabricated form and painted internally with epoxy paint for additional protection against the corrosivity of the degrading refuse and leachate. Durability of the lysimeters was important because although the research envisaged in this investigation would cover only a period of a year to 18 months, future research on such topics as co-disposal of toxic wastes and oil spills onto aging refuse could be carried out.

The base of the lysimeters was constructed from a 2mm gauge steel fabricated cone, with a 25mm hole at the apex, welded to the rim of a removable oil drum lid. A 450mm long, 25mm diameter steel pipe was welded to the apex of the cone for leachate extraction. The constructed base was hot-dip galvanized and internally coated with epoxy paint. The conical base was clamped to the bottom drum of the lysimeter column and sealed with silicone and a liberal coating of epoxy paint. A brass gate valve was fitted to the leachate drain pipe to facilitate leachate extraction.

To provide stability to the column lysimeter and to provide watertightness of the base cone - lysimeter joint, the lower 600mm of the column with its conical base was cast into a 840 x 840 x 600mm concrete block. When the concrete had set the lysimeter with its concrete block was placed on a supporting steel frame which could accommodate 3 lysimeters side by side. The supporting frame provided about 400mm clearance between the bottom of the concrete block and the ground to facilitate leachate extraction through the leachate drain pipe protruding from the bottom of the concrete block. Two supporting frames placed on specially prepared concrete footings were provided for the 6 lysimeters.

Once filled with refuse the tops of the lysimeters were sealed with removable oil drum lids that had been liberally coated with epoxy paint and silicone sealant. Two 60mm holes were provided on each lid for leachate or water recycling and gas extraction. These holes were sealed with rubber bungs through which passed the water/leachate recycling and gas collection tubing. The water tightness of the bottom cone joint was checked by filling the lysimeter with water and checking for leaks and the gas tightness of the top lid joint was checked by seeing if the lysimeter could hold a small positive gas pressure. Both joints were found satisfactory. A schematic drawing of a column lysimeter is shown in Figure 3.1.

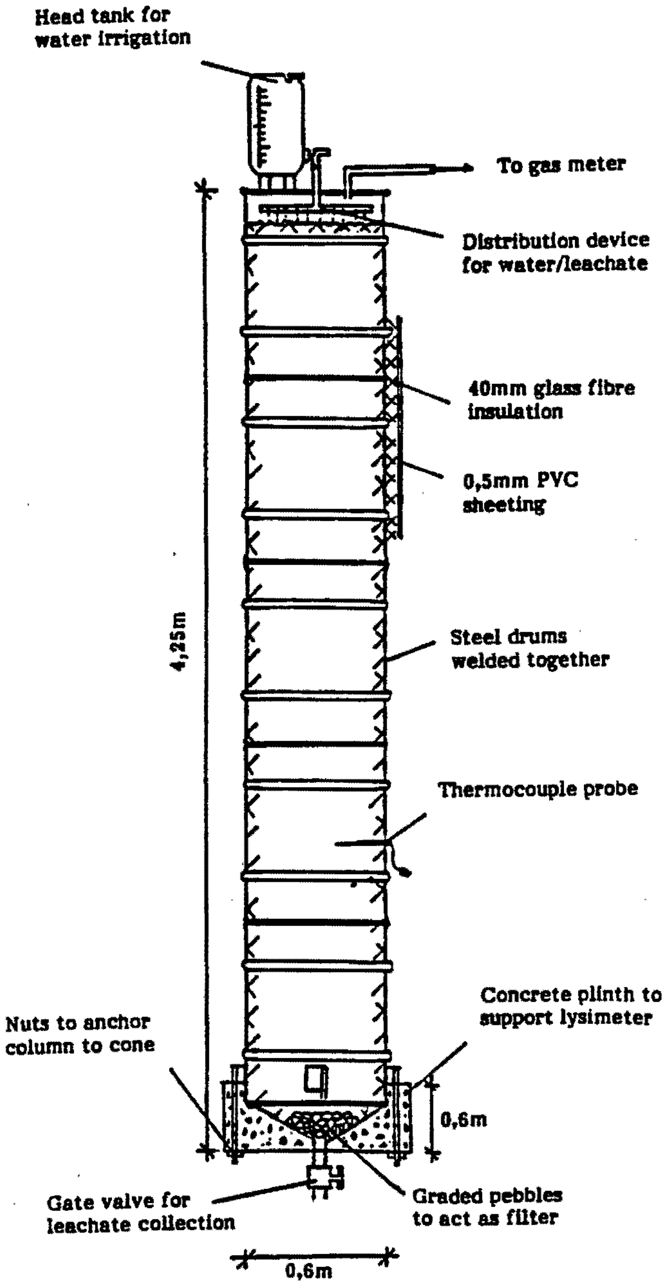

Fig 3.1 Schematic of column lysimeter.

3.1.2 Insulation of lysimeters

To minimize temperature variations of the refuse in the lysimeters, 40mm thick glass fibre wool was wrapped around each lysimeter along its entire length. To protect the glass fibre wool from sunlight deterioration and to keep it dry, 0,5mm PVC plastic sheeting was wrapped around the glass fibre wool. Large temperature variations in the refuse due to ambient temperature variations were regarded undesirable because in a full-scale landfill large temperature variations of the refuse do not take place due to the insulation effect of the surrounding refuse and ground cover.

The lids of the columns were also insulated with glass fibre wool covered with PVC plastic sheeting. A double layer of glass fibre wool was provided on the lids because the lids received direct sunlight for longer periods of time during a day compared to the vertical parts of the lysimeters. The double layer of insulation was necessary to minimize temperature variations of the gas in the headspace of the lysimeters, (which increased in volume as the investigation progressed due to compaction of the refuse); large expansions and contractions of gas in the headspace had to be minimized to minimize interference with the measurement of gas production rates from the lysimeters as much as possible.

3.1.3 Water replacement head tank and distribution system

201 plastic gerry-cans were placed on the lids of the four lysimeters that received water irrigation to their contents. The cans were secured to the lids with straps so that they would not be dislodged by wind action yet could be easily removed if the lid was required to be opened. The tap at the base of each can was connected to the irrigation inlet pipe of each lysimeter by means of a flexible piece of PVC tubing. The tubing fitted snugly enough over the tap to ensure a gas-sealed system. The irrigation inlet pipe to the lysimeter was placed in a rubber bung in the lid of the lysimeter and connected to a perspex liquid distributor. This distributor consisted of a horizontal lattice of perforated perspex pipes positioned 100mm below the lid to provide even distribution of the water or leachate applied to the lysimeter.

The head tanks were filled with water by a hose pipe attached to a tap located near the experimental set-up. The tanks had volume graduations marked on them and the required volume of water to be applied to the refuse daily was drained from the tanks batch-wise over a 5 to 10 minute period daily with the volume applied.

3.1.4 Leachate traps

Leachate traps consisting of 150mm diameter perspex "dishes" with a reinforced flexible draining tube attached were installed for the purpose of obtaining leachate samples from different spatial positions in the refuse. The traps were positioned centrally in the lysimeters with the draining tubes at a 45^{o} angle between the trap and the tube exit hole in the side wall of the lysimeter. This was done so that when the trap subsided due to the consolidation of the refuse, there would still be a sufficient gradient on the draining tube to enable leachate to drain out. However, the excessive compaction of the refuse resulted in the traps subsiding below their wall outlet hole so that leachate could not drain from the traps. When this happened the holes in the sides of the lysimeters for the draining tubes were sealed off and the intention of obtaining leachate from different levels in the refuse was abandoned.

3.2 CONTENTS OF LYSIMETERS

Each lysimeter contained approximately 500kg (when freshly placed) of refuse. Units 2, 3, 4, 5 and 6 also contained 200l of sludge co-disposed with the refuse.

3.2.1 Refuse constituents

The refuse placed in the lysimeters comprised selected constituents in order to obtain standard refuse. The constituents of the standard refuse were chosen after a consideration of the make-up of typical urban refuse both at present, and for the future. Present-day constituents of normal municipal refuse from two different population groups in South Africa are given in Table 3.1 below.

Table 3.1 Present day constituents of normal municipal refuse from Johannesburg and Soweto.

Constituents	Average % by mass	
	Johannesburg	Soweto
Paper/cardboard	34	4
Plastic	7	1
Glass	10	2
Metals	6	1
Putrescibles	30	15
Ash	2	45
Unclassified (cloth, rubber etc.)	11	32

Considering the above breakdowns of refuse constituents the standard refuse was chosen to represent constituents somewhere in between the two. The reasons for this were as follows:

(1) Future landfills will contain refuse with more reduced percentages of paper, glass and metals than would be indicated by the Johannesburg breakdown. This is because communities are moving into a new era of waste-recycling whereby paper, plastics, glass and metals will be removed as legislation is developed to allow for laws enforcing such a practise. The breakdown of the Soweto refuse gives an indication of the resulting percentages of these materials if recycling were to be effected. This is mainly because the Soweto communities place greater value on the various materials than do the Johannesburg communities and effectively recycle these by removing the paper, glass etc. from the refuse. The remaining percentages of these materials then gives an indication of what the unrecoverable fractions would be.

(2) The ash content was retained at the low 2% value for the standard refuse as the high Sowetan value is unique to this particular community which burns a lot of its refuse for heating and cooking purposes. As electrification of these areas progresses so the ash content of the refuse will decrease.

The breakdown of refuse constituents used in the standard refuse for this investigation was as shown in Table 3.2 below.

Table 3.2 Breakdown of refuse constituents used in standard refuse.

Constituents	Average % by mass
Organic	60
Paper/cardboard	15
Cloth	20
Plastic	3
Ash	2

It was not necessary to macerate the refuse as the paper and plastic which are considered to be the biggest hindrances to biodegradation in landfills due to clogging, were in a shredded form.

3.2.2 Origin of refuse

The constituents were obtained from different sources as follows: (i) organic matter: vegetable waste from the Epping vegetable market, (ii) coal ash: waste from the Pinelands power station, (iii) shredded plastic bags: obtained from Nampak Recycling (Pty) Ltd., (iv) grade 3 waste paper: shredded and also obtained from Nampak Recycling (Pty) Ltd and (v) cloth off-cuts: waste material from clothing manufacturers.

3.2.3 Refuse placement

The 5 refuse constituent materials were placed in the 6 lysimeters as follows: with a 50l plastic dirt bin on an industrial beam scale, each of the 5 components were added to the bin so that a bin full of refuse contained the 5 constituent materials in the constituent fractions established above. The contents of the bin were then emptied into the lysimeter and compacted. The bin contained approximately 25kg of mixed refuse and 20 bins full were required to fill a lysimeter. The operation of placing the refuse in the lysimeters is shown in Figure 3.2.

Fig 3.2 Picture showing method of placing refuse in the lysimeters. Also shown is the method by which the lysimeters were insulated.

The large number of full bins required per lysimeter (full) ensured that the refuse was well mixed and relatively homogeneous in each lysimeter. Before the refuse was placed in each lysimeter, 25kg of 25mm stone gravel was placed in the bottom cone to act as a filter for the leachate. Also, a 4m long, 25mm diameter perforated PVC pipe was placed down the centre of each lysimeter around which the refuse was compacted. The purpose of this pipe was to facilitate movement of gas produced by the degrading refuse to the top of the lysimeter.

As each lysimeter had a volume of placed refuse of about 1,0 m^3, the density of the compacted refuse was about 500 kg/m^3. However, it should be noted that after water and/or sludge addition, the volumes of which were measured, the refuse had compacted and subsided considerably in the lysimeter. Consequently more mixed refuse was added to fill the space created by the compaction and the final density of the refuse, including the water/sludge mass retained by the refuse was about 700 kg/m^3 at a moisture content of 57%. Although this density is comparable to that obtained in fresh refuse landfills, the moisture content is much higher than in fresh placed landfills so that a significant part of the mass of the refuse is water retention rather than very compact drier refuse.

In the fourth lysimeter (unit 4), where lime was co-disposed with the refuse/sludge mixture, the lime was distributed equally throughout the lysimeter with the refuse.

3.2.4 Origin and placement of sludge

Anaerobically digested sludge was obtained from one of the anaerobic digesters at the Mitchell's Plain sewage treatment works. The MLSS concentration of the sludge was about 5% and 200l (i.e. a dry solids mass of 10 kg SS) was added to 5 of the 6 lysimeters (units 2 to 6). In one of these units (unit 2) all the sludge was placed on the top of the compacted refuse. In the remaining 4 units (units 3 to 6) the 200l sludge was placed with the refuse in four 50l lots at 1/4, 1/2, 3/4 and full levels. The liquid added with the sludge was taken into account in the water balance calculations to determine the moisture content of the refuse/sludge mixture.

3.2.5 Moisture content of refuse (unit 1) and refuse/sludge mixture (units 2 to 6).

From the literature review it was established that the moisture content of the refuse plays an important role in enhancing the degradation of the waste. Also because field capacity, which is generally accepted as a 65% moisture content in the waste based on wet weight, represents the ideal moisture content for the rapid break-down of refuse, the moisture content of the refuse/sludge mixture in all the lysimeters was increased to field capacity (65%) by water addition. To do this required estimating the moisture content of the refuse placed in the lysimeters.

To determine the moisture content of the freshly placed refuse the mass reduction in the refuse was estimated by drying a sample of the organic material constituent at 105°C for 24h. It was not necessary to include the other 4 constituents because they were dry when placed. The moisture content of the organic matter was 80% by wet mass and taking into account the masses of the other 4 dry constituents, the moisture content of the mixed refuse was about 48%.

3.2.5.1 Calculation of extra water requirement to reach field capacity

In unit 1, which contained no sludge co-disposed with the refuse, the extra water required to elevate the moisture content in the refuse from 48% to field capacity (65%) was calculated from the following equation:

Final mass of water = 0,65 x (total mass of refuse + total mass of water added).

i.e.: $W + 0{,}48 \times R = 0{,}65 \times (W + R)$ ....(1).
or $W = 0{,}486R$
where W = volume of extra water required and
R = mass of refuse

Therefore, for unit 1 which contained 495kg of refuse, 240l of water was required to elevate the moisture content of this refuse to 65% (see Table 3.3).

The calculation for the additional water requirement for the remaining lysimeters (units 2 to 6) had to take into account the moisture added due to the sewage sludge co-disposed with the refuse as well as the extra solids added due to the sludge i.e.:

Final mass of water = 0,65 x (total mass of refuse + mass of sludge + total mass of water added)

i.e.: $W + 0{,}48 \times R + 190 = 0{,}65 \times (W + 200 + R)$ .... (2).
or $W = 0{,}486R - 171$
where W and R are the same variables as in the previous equation and the value 200 represents the total mass of sludge added.

This extra water was added to the refuse after the second amount of refuse was placed in the lysimeters; after the initial refuse and sludge placement in units 2 to 5 the refuse compacted and settled with the higher moisure content due to the sludge addition. Extra refuse was then added to each of these units to fill the lysimeters (final refuse masses shown in Table 3.3) with the intention of adding the extra water requirements calculated using equation 2 at this stage. However there was a high flux of liquids through the refuse after the sludge addition to units 2 to 5 which indicated that the moisture holding capacity of the refuse was not as high as expected. The reason for this could be that the estimation of the initial moisture content of the freshly placed refuse was too low (48%). Therefore to avoid a higher flux of liquids through the refuse, 25l less water than was considered necessary to bring the refuse to field capacity (see equation 2 above) was placed in the units after the second refuse placement. For example, in unit 2 for which it was calculated that an extra 54l of water was required for the refuse to reach field capacity (65%), only 29l of water was added. This was also the case for the other 4 lysimeters, i.e. units 3, 4, 5 and 6 (see Table 3.3). The moisture content of the refuse in these units after these reduced water additions had been made was still considered to be 65% (by wet mass) for the purpose of this investigation.

For the first 2 weeks of operation of the lysimeters (weeks 1 and 2 after refuse placement) all the liquids extracted from the lysimeters were returned to the refuse at the top of the lysimeters. This was done to sufficiently wet the whole mass of refuse in each lysimeter. From week 3 onwards leachate was extracted from the lysimeters to maintain the water balance as described in the following section.

Table 3.3 Summary of lysimeter constituents and operating conditions.

Parameter	Lysimeter 1	2	3	4	5	6
Refuse added (kg)	495	462	512	462	528	445
Water added (l)	240	29	53	29	61	21
Sludge added (l)	—	200	200	200	200	200
Initial moisture content (% by wet weight)	65	65	65	65	65	65
Density (kg/m^3)	714	691	743	670	789	666
Water irrigation	YES	—	YES	YES	YES	—
Leachate recycle	—	—	—	YES[1]	YES[1]	YES
Lime in refuse (kg)	—	—	—	8,00	—	—
Lime added to recycled leachate (kg)	—	—	—	—	4,65	—
NaOH dosed to refuse (g)	—	—	—	943	974	—
$NaHCO_3$ dosed to refuse (kg)	—	—	—	—	4,00	—

[1] Units 4 and 5 were operated with leachate recycling during NaOH dosing to the recycled leachate from week 11 to 20.

3.2.6 Water balance to maintain a constant refuse moisture content.

To be able to maintain the moisture content of the refuse at 65%, i.e. field capacity, it was necessary to replace liquids lost from the refuse (through leachate extraction) with an equal volume of tap water or recycled leachate (where applicable). However it was found that during the wetting of the refuse in the first 2 weeks after refuse placement (see previous section) increasingly more leachate was being produced from all the lysimeters. From this it was realized that the moisture holding capacity of the refuse was not 65% but a lower value. Therefore for the next 3 weeks in units 5 and 6 and for the next 8 weeks in units 1,3 and 4 leachate was extracted from each lysimeter but not replaced with tap water. By recording the volume of liquid drained from the refuse over these periods it was estimated that the moisture holding capacity of the refuse was 57%. Liquid replacement was then commenced again, but now the moisture content remained constant at 57% rather than 65%. Had this not been done, then the high flow of liquid through the refuse would have caused "flushing" of the leachate out of the refuse. Moisture lost from the refuse as water vapour in the gas produced and moisture gained from the biochemical and biological reactions taking place during the degradation of the refuse were regarded as negligible in the water balance.

The above procedure was developed specifically to keep the moisture content of the refuse constant so that the influence of a variable moisture content could be positively eliminated when investigating the effect of leachate recycling and sludge addition on the acceleration of the onset and progress of methanogenesis.

3.3 MONITORING AND TESTING

3.3.1 Leachate extraction and sampling

On a weekly basis, leachate extractions from the lysimeters were made by placing a 5l bucket beneath the gate valve of a lysimeter and opening the valve to allow the leachate to flow freely out of the lysimeter into the bucket. The valve was opened a sufficient amount to allow all the leachate present in the lysimeter to drain into the bucket in a short period of time without the valve admitting large quantities of air into the lysimeter. 100 ml grab samples of leachate were taken from the leachate extracted from each of the six lysimeters and stored in 200 ml plastic jars with sealable lids. The lid was placed on the jar immediately after sampling to prevent excessive CO_2 exchange between the sample and the atmosphere. The quantity of leachate remaining in the bucket was measured using a measuring flask and recorded. This procedure was carried out on all six lysimeters except for unit 6 which produced more than 5l of leachate and therefore a separate 20l PVC bucket was placed in a hole in the ground next to the 5l PVC bucket so that the extra leachate could be siphoned from this bucket into the larger bucket. The six samples of leachate so obtained were taken to the laboratory immediately after the sixth sample was extracted and the pH of each of the samples was measured using a pH probe connected to a Radiometer bench-type pH meter.

After measuring the pH of the leachate samples, the recycling or disposal (where applicable) of the leachate volume produced by the lysimeters as well as the temperature and gas production measurements were carried out before the leachate samples were prepared and analyzed for the selected chemical characteristics.

3.3.2 Liquid replacement to maintain a constant refuse moisture content.

To maintain a constant moisture content in the refuse in all the units (except unit 2 which was allowed to drain freely) either water was irrigated to the refuse or leachate was recycled.

3.3.2.1 Water irrigation

With water replacement by irrigation a volume of water equal to the volume of leachate extracted from a lysimeter was irrigated on to the refuse in the lysimeter at the time of leachate extraction each week throughout the investigation. The water additions were made by draining the required volume of water out of the header tank placed on the lids of the lysimeters. The intention of the water additions was to replace liquids lost by leachate extractions so that the moisture content of the refuse would be kept constant. However it was found that the quantity of leachate produced each week increased with time which indicated a decreasing moisture content in the refuse. This was to be expected as the mass of refuse decreased as it degraded and therefore at the same moisture content the refuse could retain only a progressively smaller volume of liquid. The compaction of the refuse exacerbated this effect. To avoid replacing too much water in this situation, when the volume of leachate produced exceeded about 3l this leachate was discarded and no water addition made to the refuse. The total volume of liquids remaining in the refuse therefore decreased when leachate production exceeded 3l/week which with the decreasing mass of refuse, maintained an approximately constant moisture content (~ 57%). If this had not been done, the continuously increasing water fluxes through the refuse would have washed out much of the dissolved organic matter from the lysimeter.

3.3.2.2 Leachate recycling

For the lysimeters with leachate recycling, the volume of leachate less the 100 ml sample, that was extracted from the units each week, was recycled back into the lysimeter. The leachate was transferred manually to the top of the lysimeter and allowed to flow under gravity through a syphon pipe into the lysimeter. Initially a positive displacement type pump was used to transfer the leachate from the leachate collection bucket at the base of a lysimeter to the top of the lysimeter. However the manual method of recycling the leachate was preferred due to its simplicity.

3.3.3 Gas production detection, volume measurement and percentage composition.

Two types of gas meter were available for gas production detection and volume measurement.

A prototype gas meter was developed and built in the Department of Civil Engineering at U C T for the purpose of measuring small gas flow rates (< 1l/day to 300l/day). The meter was a positive displacement type and operated by means of a float which activated an electronic counter each time it oscillated a certain distance about its neutral position (see Figure 3.3). A drawback of this meter was that it did not operate well under a reverse (suction) pressure.

Fig 3.3 Picture of the prototype gas meter used in the investigation.

The other gas meter was a commercial bucket-type positive displacement meter which only became available at week 37. This meter was capable of measuring a reverse gas flow and could measure flow rates of between about 10l/day and 3000l/day.

The gas meters were connected to the gas exit pipe in the lid of a lysimeter by a reinforced flexible rubber hose. A water trap was connected to the gas line at a position 1m from the gas exit pipe in the lysimeter's lid.

3.3.3.1 Gas production detection

Despite the provision of insulation on the lysimeter lids and walls, the detection of gas evolution from the lysimeters proved to be problematic due to the contraction and expansion of the gas in the headspaces in the lysimeters with the ambient temperature variation. The ideal situation was to monitor the gas production from a lysimeter over a period of 24 hours or more to determine whether there was any net gas production. However, this was not possible for 2 reasons: (i) the prototype gas meter used initially could not operate under a reverse gas flow (as occurred when the gas in the lysimeter headspace contracted with cooler temperatures), and (ii) the commercial gas meter (which could operate with a suction pressure) was used to measure the gas production during methanogenesis in unit 4 and therefore was not available to monitor whether or not gas was being produced from the other units during this time.

The prototype gas meter was used to monitor the commencement of gas production from the lysimeters when the ambient temperature was decreasing in the afternoon. For a temperature decrease from 25 to 22^{o}C over 2 hours the headspace gas volume contracted about 3l and if the gas meter showed a positive gas production (i.e. the meter was functioning normally) then it was accepted that at least 3l of gas was produced, indicating that gas production had commenced. The 3l volume was considered a reasonable datum, it being about 10% of the estimated daily gas production during methanogenesis.

3.3.3.2 Gas volume measurement

Once methanogenesis had commenced (in unit 4), the volume of gas produced per day from this lysimeter was measured at the same time that the lysimeter temperature measurements were made. Two gas meters were used for measuring the gas production rate from unit 4, initially the prototype gas meter, then later a commercial-type gas meter.

(1) Prototype Gas Meter (weeks 32-36)

To exclude gas expansion and contraction effects on the gas flow measurement, the gas evolution rate from unit 4 had to be determined over a period of time when the temperature of the headspace in the lysimeter remained fairly constant. If the temperature of the headspace was increasing or decreasing the volume of gas in the headspace (0,28m^3 at STP) would concomitantly increase or decrease respectively with temperature and therefore affect the true rate of gas evolution from the unit. Therefore the volume of gas produced from this lysimeter was measured over a period of 2 hours between 12 and 2 pm on the same day that the temperatures in the lysimeters were measured. The number of oscillations of the float in the gas meter over the 2hr period was read from the totaliser on the meter and converted to a volume of gas for a 24 hr period. The temperature of the gas in the meter was measured by means of an electronic thermometer connected to a thermocouple placed in the meter.

(2) Commercial Gas Meter (Week 37 onwards)

A commercial gas meter became available at week 37 and at this time the prototype gas meter was replaced by the commercial gas meter for the gas volume measurements in unit 4. The commercial positive displacement-type gas meter was considered to be more suitable than the prototype gas meter due to its ability to cater for reverse gas flows so that the meter could be left to operate continuously. The volume of gas measured by the meter was read from the totaliser on this meter at the same time each day (2.00 pm) and converted to a daily flow rate. The temperature of the gas indicated on a mercury thermometer in the meter was also read and recorded at this time.

3.3.3.3 Composition of gas produced

The composition of the gas produced from unit 4 during methanogenesis was determined by measuring the percentage of CO_2 in the gas. It was assumed that the balance of the constituents of the gas was CH_4. The percentage of CO_2 in the gas was determined using a device that dissolved the CO_2 from a sample of the gas into a solution of NaOH. The dissolution of the CO_2 caused a pressure differential that was indicated by the height to which liquid in a standpipe in the device rose to. Thus the height of this liquid gave a direct indication of the percentage of CO_2 in a sample of the gas.

3.3.4 Temperature measurement

The ambient temperature, the temperature of the headspace in a lysimeter and the temperatures of the refuse in units 1, 3 and 4 were measured at about 4.00 pm every second to third day. The measurements were made by connecting a Gondo portable electronic thermometer to each of 5 type-K, exposed junction thermocouples, one placed in each of the units 1, 2 (for the headspace temperature), 3 and 4 and one thermocouple used externally for ambient temperature measurements. The gas temperatures in the gas meters were also recorded at the same time that gas measurements were made as already mentioned in the above section.

3.3.5 Summary of measurements made on each lysimeter

Unit 1: leachate extracted and sampled. Volume of leachate measured and equal volume of water irrigated to refuse. Leachate discarded. Temperature of refuse measured.

Unit 2: leachate extracted and sampled. Volume of leachate measured. Leachate discarded. Temperature of headspace measured.

Unit 3: leachate extracted and sampled. Volume of leachate measured and equal volume of water irrigated to refuse. Leachate discarded. Temperature of refuse measured.

Unit 4: leachate extracted and sampled. Volume of leachate measured and equal volume of water irrigated to refuse. Leachate discarded. (This unit was operated with leachate recycling during dosing of NaOH to the refuse from week 11 to 20). Temperature of refuse measured.

Unit 5: leachate extracted and sampled. Volume of leachate measured and equal volume of water irrigated to refuse. Leachate discarded. (This unit was initially operated in the same manner as unit 6 but with buffer addition to the recycled leachate). Unit 5 was also operated with leachate recycling during dosing of NaOH to the refuse from week 11 to 20.

Unit 6: leachate extracted and sampled. Volume of leachate measured and all leachate returned to top of unit.

3.3.6 Testing of leachate samples

After the pH values of the leachate samples were determined a few drops of mercuric chloride solution were added to each sample to halt bacterial activity. The samples were then filtered through a Whatman's No.1 filter and returned to their original plastic jars after these had been thoroughly rinsed with tap water. The filtrates were then stored at $5^{o}C$ and diluted where necessary for testing as shown in Table 3.4 below in accordance with Standard Methods (1985). The $H_2CO_3^*$ alkalinity, SCFA concentrations and Ct concentrations in the filtrates were determined by means of a 5-point titration method (Moosbrugger, 1991).

Table 3.4 Tests Conducted on filtered samples of leachate in accordance with Standard Methods (1985).

	TEST	DILUTION	FREQUENCY
1	pH		weekly
2	COD	1:80	weekly
3	Conductivity		fortnightly[1]
4	SO_4^{2-}	1:40	fortnightly[1]
5	NH_4^+	1:40	fortnightly[1]
6	TKN	1:40	fortnightly[1]
7	PO_4^{3-}	1:4	fortnightly[1]
8	$H_2CO_3Alk^{*}$[2]	1:11	fortnightly[1]
9	SFCA[2]	1:11	fortnightly[1]
10	Ct[2]	1:11	fortnightly[1]

[1] These tests were carried out on a weekly basis from week 15 to 28 i.e. during the pH elevation period in unit 4.

[2] Determined using a 5-point titration method (Moosbrugger, 1991).

3.4 OPERATION OF LYSIMETERS

Different operating conditions were imposed on the 6 lysimeters to examine the effects of sludge addition, leachate recycling and buffer addition on the onset and progress of methanogenesis. A summary of the different operating conditions is given in Table 3.3 (previously).

As described earlier, although the 6 lysimeters were filled with slightly different masses of refuse (ranging from 445 to 512kg at natural moisture content) the constituents of the refuse were the same in each lysimeter.

To all the lysimeters except Unit 1, 200l of liquid anaerobically digested sewage sludge at about 5% solids was added, the unit 1 serving as a control. This allowed a comparison to be made between the behaviour of the lysimeters with and without sludge addition.

With the sludge, about 190l of liquid also was added, and this needed to be taken into account when calculating the water addition to bring the refuse to 65% moisture content. Consequently unit 1 without sludge addition, 240l of water was added whereas in the other 5 only between 21 and 53l of water needed to be added; the differences in water addition arose from the differences in refuse mass contents of the lysimeters to yield a moisture content (on total mass basis) of 65% in all lysimeters (see Table 3.3).

As mentioned earlier, during the first 2 weeks it was found that progressively more leachate was produced weekly in the lysimeters. From this it was realized that the moisture carrying capacity of the refuse i.e. absorbancy was less than the established 65% moisture content and hence from week 3 to 5 in units 5 and 6 and from week 3 to 10 in units 1, 3, and 4 leachate was extracted and no liquid replacements were made. The moisture content of the refuse in these units after these periods was estimated to be about 57% and liquid replacement to each unit was again commenced. Excepting for unit 2 which was allowed to continue to drain freely, all the lysimeters were maintained at 57% moisture content through leachate and/or water replacement.

3.4.1 The effect of moisture content

Since sludge addition to refuse increases the moisture content of the refuse, the effect of moisture content in isolation was examined by comparing the response of units 2 and 3. In both these units, sludge was added but in one unit (unit 2) the leachate that drained from it was not replaced with the result that the moisture content of the refuse in it progressively declined (from 57% to 47% 52 weeks later). Although both units received sludge it should be mentioned that the sludge was placed differently; in unit 2 it was all poured over the top of the refuse filled lysimeter whereas in unit 3 it was placed in 50l volumes as the lysimeter was filled with refuse to 1/4, 1/2, 3/4 and full levels. Due to the very liquid nature of the sludge, it percolated very quickly throughout the refuse volume in unit 2 and the differences in sludge placement were not regarded as significaant after the first 3 weeks of operation at 65% moisture content when liquid fluxes through the refuse were quite high.

3.4.2 Sludge as a source of alkalinity, inoculum and nutrients

Although maintained at the same moisture content (57%) unit 1 contained refuse only and unit 3 a refuse-sludge mixture. This allowed the effects of the sludge as a source of alkalinity, methanogen inoculum and nutrients addition to be assessed.

3.4.3 Leachate recycling

The effects of leachate recycling on refuse degradation were evaluated by comparing unit 6, which was operated with leachate recycling and unit 3 which was operated with water replacement. Both units contained a mixture of refuse and sludge and were maintained at a 57% moisture content throughout the investigation period (~52 weeks).

3.4.4 Buffer addition to refuse-sludge mixture

To investigate the effect of chemical buffer addition at refuse placement, lime was mixed with the refuse at placement in unit 4. The amount of lime ($Ca(OH)_2$) placed in the refuse in unit 4 was determined as follows: from the literature, the average concentration of SCFA in leachate from a landfill in its acid phase of degradation is about 15000mg/l as HAc. The buffering of these SCFA by $Ca(OH)_2$ can be represented by the following stoichemetric equation for acetic acid and lime:

$$2CH_3COOH + Ca(OH)_2 \rightarrow (CH_3COO)_2Ca + 2H_2O$$

Therefore one mole of $Ca(OH)_2$ is required to buffer 2 moles of acetic acid. i.e. for 15000mg/l of acetic aicd, the mass of lime required is15/60 x 1/2 x 74,1 = 9,3g/l of $Ca(OH)_2$

where the values 60 and 74,1 are the molecular masses of CH_3COOH and $Ca(OH)_2$ respectively. As there was approximately 240l of liquids as moisture in the lysimeter (unit 4), the total mass of lime required was:

240 x 93 = 2,2kg.

Only 67% of the powdered lime added was useful as $Ca(OH)_2$ so that at least 3,3kg of commercial powdered lime needed to be added to the refuse. In actuality, 5 kg of lime was mixed with the refuse in unit 4 at the time of refuse placement so that additional buffering capacity was available in the event that high SCFA acid concentrations were generated. During the monitoring of the $H_2CO_3^*$ alkalinity of the leachate from unit 4, it was found that by week 7, most of the lime placed in the refuse had dissolved and washed out of the refuse and so losing the buffer capacity of the placed lime. Consequently at week 7 an additional amount of 3kg of lime was added in the water irrigated to the refuse. Therefore a total of 8 kg of lime was added to unit 4 during the investigation period. Unit 3 which also contained a refuse and sludge mixture and was maintained at a moisture content of 57% by water replacement for leachate extracted served as the control unit with which to compare unit 4 to allow the effectiveness of the lime as a buffer in the refuse-sludge mixture to be assessed.

3.4.5 Buffer addition to recycled leachate

As described above, lime was added as a buffer at refuse placement in unit 4. In a separate experiment with unit 5, lime was also added by dosing the recycled leachate. Over the first 11 weeks a total of 4,65kg of lime was added to the leachate recycled to unit 5. The amount of lime dosed to this unit during this period depended on the amount of lime that could be dissolved in the volumes of leachate that were recycled.

Unit 6 which received recycled leachate with no buffer addition was used as a control for unit 5.

3.4.6 Elevation of pH with NaOH dosing (units 4 and 5)

NaOH was dosed to the refuse in units 4 and 5 in recycled leachate from week 11 to 20 in an attempt to elevate the pH in these units to a value of about pH 7. Recycled leachate was used as a dosing medium for the NaOH for the following reason: if water had been used as a dosing medium, large quantities of water would have been required to dose a sufficient quantity of NaOH - a situation causing a high water flux through the refuse and regarded as undesirable. A high concentration of NaOH in water elevates the pH of the water to values in excess of 11 and therefore to keep the pH of the dosing liquid below 9 to avoid inhibition of the microorganisms in the refuse the NaOH was dosed into the recycled leachate.

The amount of NaOH that could be dosed to the refuse in a volume of leachate extracted from the lysimeter was determined as follows: a 1N solution of NaOH was pipetted into a 100ml stirred sample of the leachate until the leachate had a pH of about 9. The corresponding mass of NaOH required for the volume of leachate recycled was then calculated and dissoved into the recycled leachate in units 4 and 5.

After 9 weeks, i.e. from week 11 to 20, a total mass of 943kg of NaOH had been dosed to the refuse in unit 4 and 974kg of NaOH to the refuse of unit 5. The $H_2CO_3^*$ alkalinity and pH values in the leachate from these 2 units however had not increased by the desired amount with these operations: it was sought to elevate the $H_2CO_3^*$ alkalinity and pH to values around 2000mg/l as $CaCO_3$ and 7 respectively. However units 4 and 5 had $H_2CO_3^*$ alkalinity and pH values of about 500mg/l and 6,3 and 200mg/l and 6,2 respectively at the end of the dosing period (week 20). The continued suppression of the $H_2CO_3^*$ alkalinity and pH values in these units was thought to be caused by the presence of high SCFA concentrations. Therefore the refuse in unit 4 was subjected to a high flux of water between week 20 and 28 with leachate recycling so that the SCFA concentration in the refuse would be diluted and washed out. The high flux of water was achieved by irrigating the refuse with 20l of water each week when leachate was extracted and all the leachate produced was discarded. This was done until 100l of water had been irrigated to the refuse and about 100l of leachate had been produced and discarded. Unit 5 was subjected to a similar high flux of water but from week 28 to 34. During the application of a high water flux to this unit a total of 4kg of $NaHCO_3$ was dosed to the refuse in the water added. The amount of $NaHCO_3$ dosed in this fashion depended on the quantity of this buffer that could be dissolved into the volume of water irrigated to the refuse. After the high flux of water units 4 and 5 were operated in the same manner as units 1 and 3 i.e. the amount of leachate produced each week was replaced by irrigating an equivalent amount of water over the top of the refuse.

The results of the different operative conditions on the 6 lysimeters described above are discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

The effect that (i) co-disposal of anaerobic sewage sludge and (ii) leachate recycling had on the degradation process that took place in the refuse, as reflected by the chemical constituents in the leachates produced from the lysimeters, is reported and discussed in this chapter. The effectiveness of the various buffers and alkalis added to the refuse and recycled leachate in an attempt to maintain near neutral pHs in the liquid fraction of the refuse is also discussed. In the discussion references are made to graphs showing the variations of the various chemical constituents measured in the leachates from the lysimeters over the period of the investigation. Only the data that show trends that are relevant to the evaluation of sludge addition and leachate recycling on the degradation process taking place in the refuse are presented in the graphs in this chapter. A full set of all the results obtained in this investigation is presented in appendices A and B.

Before the effect of sewage sludge co-disposal and leachate recycling can be meaningfully discussed it is necessary to give some background information regarding the moisture content and temperature of the refuse. These are important parameters because they define the environment in which the refuse degradation reactions take place. The moisture content in particular is relevant in this investigation because from the literature review it was found that the beneficial effect of sludge addition on leachate recycling could not be isolated because of the moisture content increases these practises simultaneously produced. In this investigation care was taken to keep the moisture content constant to isolate the effects of sludge addition and leachate recycling, and how this was done is briefly described below.

4.2 MOISTURE CONTENT OF REFUSE

The net cumulative liquid loss from the six lysimeters over the duration of the 50 week investigation is plotted in Figure 4.1. In Figure 4.1 a horizontal line implies no net liquid loss from the refuse and therefore represents a situation of constant moisture content in the refuse.

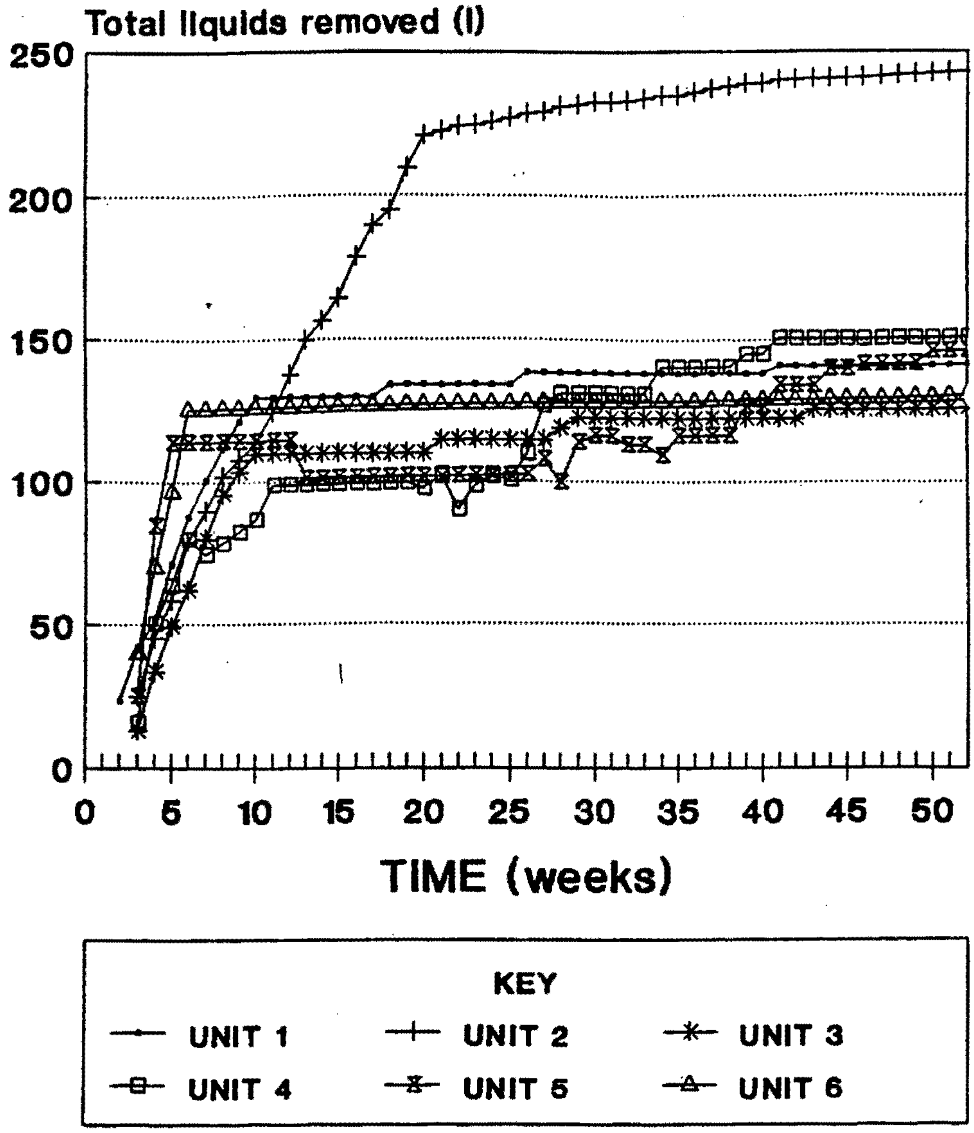

Fig 4.1 Net cummulative volume of liquid removed from each of the 6 lysimeters during the investigation (50 weeks).

It was mentioned in chapter 3 that all six lysimeters were started with a moisture content of 65%. This was estimated from an assumed moisture absorbance capacity of the refuse and it was the intention to maintain the moisture content as constant as possible by replacing over the top of the refuse, a volume of liquid equal to that which drained from the bottom of a lysimeter. For the first 2 weeks after start-up all the liquids that drained from the bottom were replaced. This was done to properly wet the refuse so as to achieve this absorbance capacity. Thereafter for the next 3 weeks (weeks 3-5, Fig 4.1) in units 5 and 6 and for the next 8 weeks (weeks 3 to 10, Fig 4.1) in units 1, 3 and 4 no drained liquids were replaced on any of the six lysimeters. This was done to allow drainage of all non-absorbed water and from Figure 4.1 it can be seen that about 100-120l drained from each lysimeter. During this time the moisture content decreased from 65% to about 57% in the lysimeters (see chapter 3 for equations). After 2 weeks of not replacing any drained liquid it was accepted that the moisture retained in the lysimeters represented the maximum absorbance capacity of the refuse and consequently, from this time (week 5), the drained liquid volume was replaced to all the lysimeters except unit 2 (as a control against which to check the effect of liquid replacement). The start-up strategy outlined above was specifically adopted to avoid excessive moisture contents in the refuse which would cause short-circuiting and intersticial flow rather than capillary flow within the refuse itself.

The cummulative volume of liquids removed from unit 4 at week 50 was greater than that from any of the other lysimeters (except unit 2) due to the greater amount of degradation that had taken place in the refuse in this unit. The extra refuse degradation was due to methanogenesis which occurred only in unit 4. The headspaces above the refuse in the lysimeters measured at week 50 are given in Table 4.1 below. From this table it can be seen that unit 4 had the greatest headspace which confirms that the refuse in this unit underwent the greatest amount of degradation.

Table 4.1 Heights of headspaces (m) in lysimeters at week 50.

	Lysimeter					
	1	2	3	4	5	6
Headspace (m)	0.8	0.92	0.8	1.14	0.8	1.0

4.3 TEMPERATURE VARIATIONS IN LYSIMETERS

The ambient temperature, the headspace temperature in unit 2 and the refuse temperature of units 1, 3 and 4 were recorded on a daily basis. The results of the measurements over the 50 week investigation are given in 3 consecutive graphs, Figure 4.2 (week 3-19), Figure 4.3 (week 20-36) and Figure 4.4 (week 37-53). From the overall trends in these graphs it can be seen that in general the headspace temperature and refuse temperature followed the ambient temperatures. This investigation period covered an entire year and commenced in the springtime. Hence for the first 10 weeks the temperatures were generally increasing from around 10 to 23 ^{o}C. During summer the temperatures remained generally constant at about 24^{o}C and with the onset of autumn (week 30) started to decline to 15 ^{o}C (week 39). During winter the temperatures generally remained at around 15^{o}C and at the end of winter (week 50) this investigation terminated.

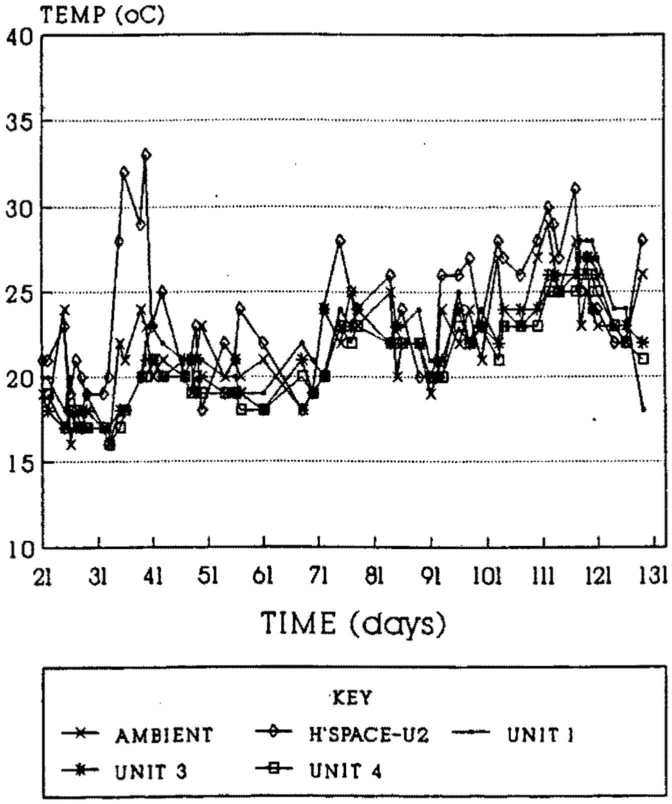

Fig 4.2 Ambient, headspace and refuse temperatures (units 1, 3 and 4) from week 3 to 19 (days 21 to 133).

It is very difficult to get a comparative impression of the temperatures in Figures 4.2 to 4.4. Consequently summer and winter periods, during which time the temperatures remained generally the same, were identified and the temperature recorded averaged. The results of these averages are given in Table 4.2. From Table 4.2, it can be seen that in summer the headspace temperature was 2^{o}C above ambient (24^{o}C). The higher headspace temperatures relative to the ambient temperatures in summer were due to heating of the headspace by direct sunlight which was stronger in summer than in winter. The temperatures of the refuse in units 1, 3 and 4 were approximately the same and in winter 1^{o}C below ambient whereas in summer the same as ambient.

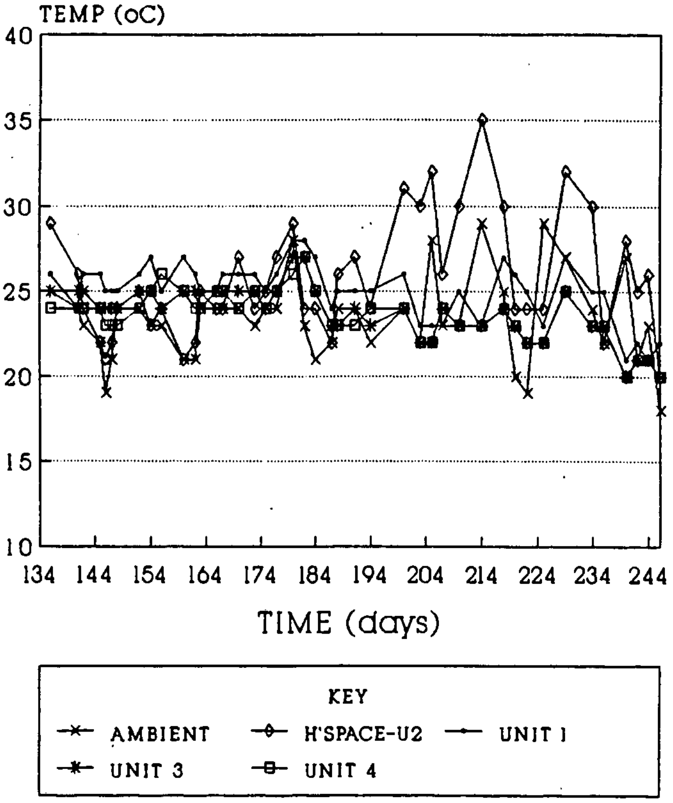

Fig 4.3 Ambient, headspace and refuse temperatures (units 1, 3 and 4) from week 20 to 36.(days 134 to 246)

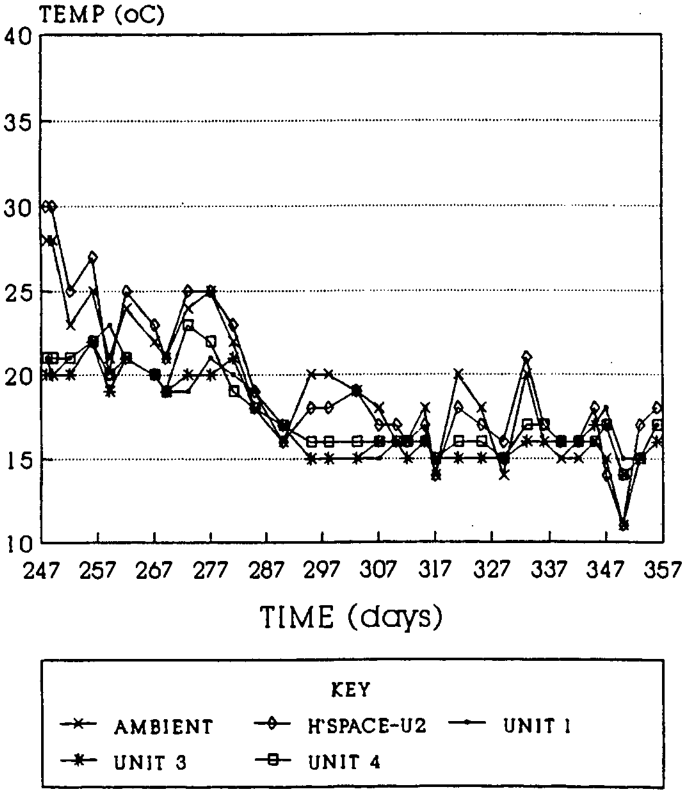

Fig 4.4 Ambient, headspace and refuse temperatures (units 1, 3 and 4) from week 37 to 53 (days 247 to 357)

Table 4.2 Average ambient, headspace and refuse temperatures in winter and summer.

	Temperatures (^{o}C)				
Season	Ambient	Headspace	Unit 1	Unit 2	Unit 3
Winter	17	17	16	16	16
Summer	24	26	25	24	24

It was mentioned in Chapter 3 that the units were completely insulated with 40mm glass fibre wool and wrapped with 0,5mm PVC sheeting for protection against rain. From the temperature data this measure appeared to have the desired effect i.e. to damp out the very rapid temperature variations, leaving the seasonal temperature variations to have the dominant effect.

From Figures 4.2 to 4.4, the following additional points may be of interest:

(1) Prior to the tops of the lysimeters being insulated with glass fibre wool and PVC in the same manner that the sides of the lysimeters were insulated, the headspace temperatures increased markedly due to heating from direct sunlight. This is shown in Figure 4.2 where large differences occurred between the external temperatures and headspace temperatures from days 31 to 41.

(2) The low temperatures during winter (~day 287 i.e. week 41 onwards) resulted in a marked reduction in the gas production rates from unit 4. This was due to the lower temperatures inhibiting the bacterial acitivity in the refuse resulting in less CH_4 and CO_2 production occurring (see section 4.9.3 on gas production from unit 4).

4.4 ANAEROBIC SLUDGE CO-DISPOSAL

The co-disposal of anaerobic sewage sludge with refuse is considered to accelerate the onset of methanogenesis in the refuse as already mentioned in chapter 1. The sludge is considered to add (i) moisture, (ii) alkalinity and (iii) nutrients and (iv) to provide an inoculum of methanogenic bacteria to the refuse. The effect that the addition of moisture, alkalinity and nutrients, as a result of sludge addition had on the refuse degradation process is now discussed.

4.4.1 Moisture increase due to sludge addition

Figure 4.5 shows the variation of the SCFA and COD concentrations in the leachates from units 2 and 3. Unit 2 was operated so that the refuse had a low moisture content (MC) of 48% whereas the refuse in unit 3 had a moisture content of about 57%. From Figure 4.5 it can be seen that the COD concentrations in the leachate from unit 3 (57% MC) were approximately 2000 to 5000mg/l greater than the COD concentrations in the leachate from unit 2 (48% MC) throughout the duration of the investigation. Therefore greater degradation of the refuse occurred in unit 3 as a result of the higher moisture content in this unit. The pHs of the leachates produced from units 2 and 3 were constantly less than 6,0 after decreasing to this value only 2 weeks after refuse placement. Therefore the refuse in these units was mostly in its acid-phase of decomposition for the duration of the investigation period of 50 weeks. It can be concluded then that any extra moisture that is added to refuse with sludge co-disposal facilitates greater degradation of the refuse in the acid-phase, leading to high leachate COD and SCFA concentrations.

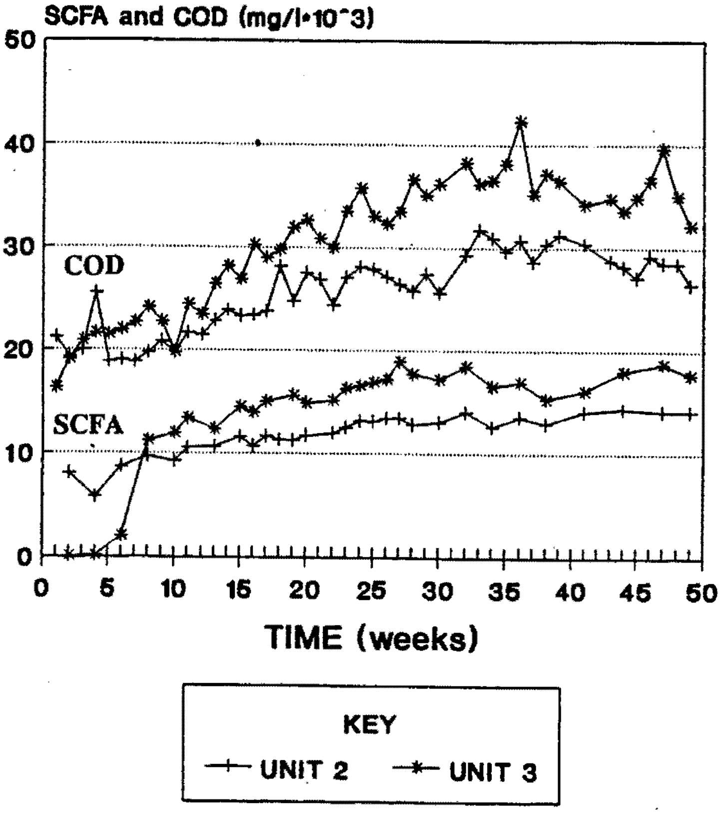

Fig 4.5 SCFA and COD concentrations in leachate from unit 2 (sludge addition to top of refuse only and lower refuse (MC:47%)) and unit 3 (sludge addition throughout refuse (MC:57%).

4.4.2 SCFA increases due to sludge addition

From Figure 4.6, it can be seen that from around week 8, the SCFA in the leachates from unit 3 (with sludge addition) were between 2000 and 5000 mg/l as HAc higher than the SCFA in the leachate of unit 1 (no sludge addition). From starting at the same values, the differences progressively increased to about 5000mg/l (as HAc) by week 27 after which the difference remained approximately constant.

With regard to the COD concentrations in the leachates, these tend to be roughly the same for the first 25 weeks, both increasing from 20 000 mg/l to 30 000mg/l. Thereafter the leachate COD concentrations from unit 3 (with sludge addition) increased slightly above that of unit 1 (no sludge addition), but curiously this difference is only about half of the difference in the SCFA concentration. Therefore the addition of anaerobic sludge to refuse resulted in enhanced degradation during the acid phase (pH < 6,0). The higher SCFA concentrations in the leachate of the refuse caused the pH of unit 3 (with sludge) to decrease to 5,5. Therefore any alkalinity addition sought to be obtained by sludge addition is completely outweighed by the higher SCFA concentration generated due to the sludge, leading to a net lower leachate pH (i.e. 5,5 with sludge addition, 6,0 without sludge addition).

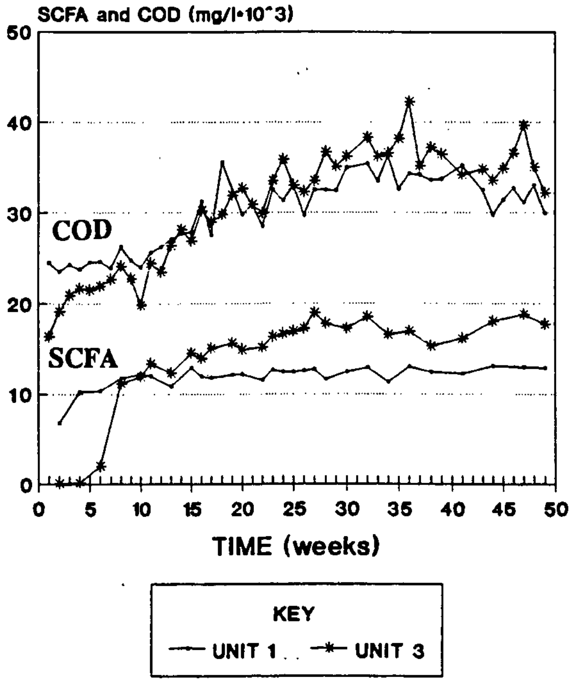

Fig 4.6 SCFA and COD concentrations in leachate from unit 1 (control with no sludge addition) and unit 3 (sludge addition).

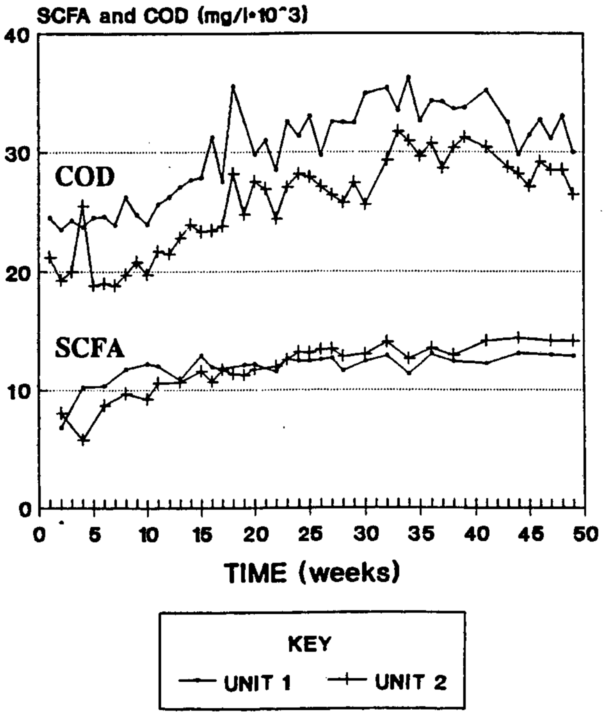

Fig 4.7 SCFA and COD concentrations in leachate from unit 1 (control with no sludge addition (MC:57%)) and unit 2 (sludge addition to top of refuse only and low MC:47%).

It is interesting to note that sludge addition increased the SCFA concentrations in the leachate even under lower refuse moisture contents (48% versus 57%). This can be seen in Figure 4.7, which shows the SCFA concentrations in units 1 (no sludge addition) and 2 (sludge addition, 48% moisture content) to be virtually the same throughout the 50 week investigation. The lower COD concentrations in the leachate from unit 2 probably arise as a result of the lower moisture content.

4.4.3 $H_2CO_3^*$ alkalinity increase due to sludge addition

The variation of the $H_2CO_3^*$ alkalinity in the leachate from units 1, 2 and 3 is shown plotted against time in weeks in Figure 4.8. From this graph it can be seen that unit 1 (refuse only) had an $H_2CO_3^*$ alkalinity in the leachate of about 200mg/l (as $CaCO_3$) for the duration of the investigation. In contrast, unit 3 (refuse and sludge) had for the first 8 weeks 2000 to 2500mg/l leachate alkalinities, but thereafter these fell to similarly low values as unit 1. Therefore the anaerobic sludge added between 1800 and 2300mg/l $H_2CO_3^*$ alkalinity (as $CaCO_3$) to the liquid fraction of the refuse. Unit 2 had a higher leachate $H_2CO_3^*$ alkalinity (~500mg/l) than unit 1 for the first 5 weeks only which can also be attributed to the sludge addition to this unit. However the sludge was added to the top of the refuse in this unit compared to unit 3 in which the sludge was distributed throughout the unit. Therefore the sludge in unit 2 took longer to percolate through the refuse in this unit which accounts for the lower initial $H_2CO_3^*$ alkalinities relative to those in unit 3.

The rapid decreases in $H_2CO_3^*$ alkalinity in unit 3 occurred at about the same time (week 8) that the SCFA concentrations in this unit increased rapidly (Fig 4.6 (previously)). The SCFA concentrations increased to about 10000mg/l (as acetic acid) at this time and clearly the alkalinity present as a result of the sludge addition (~2000mg/l) was not sufficient to buffer these high acid concentrations. As a result of the high acid concentrations the pH of the leachates from units 2 and 3 decreased to below pH 6,0 and remained at around pH 5,5 for the duration of the investigation. (Fig 4.9).

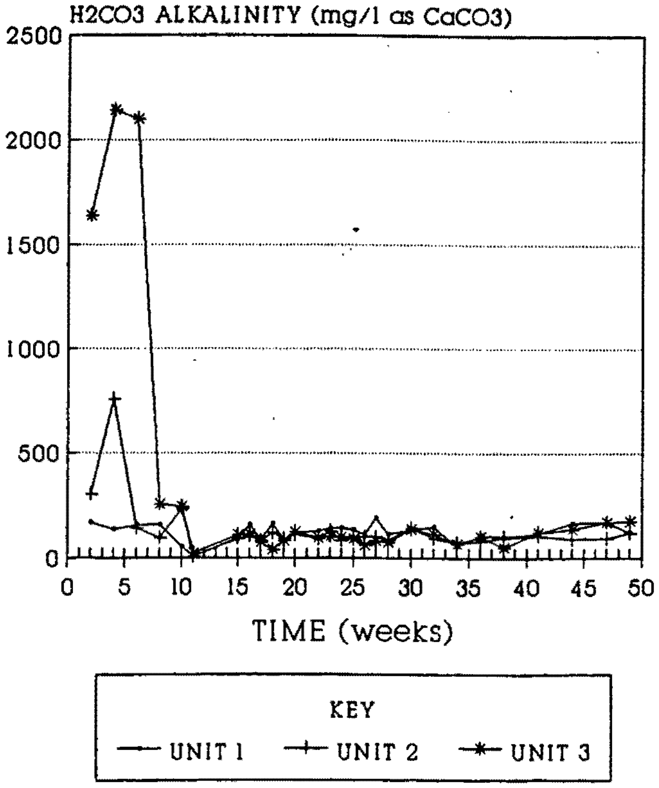

Fig 4.8 $H_2CO_3^*$ alkalinity in leachate from unit 1 (control with no sludge addition (MC:57%)), unit 2 (sludge addition to top of refuse only and low MC:47%) and unit 3 (sludge addition throughout refuse (MC:57%).

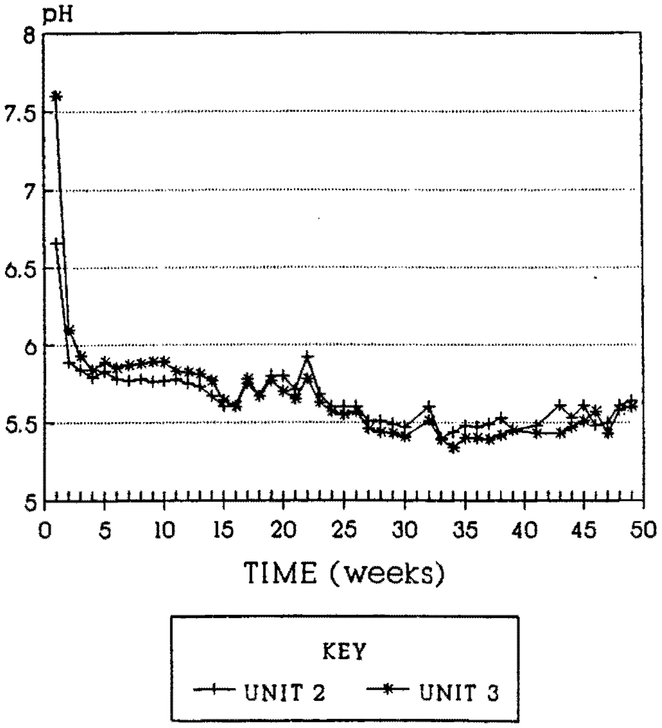

Fig 4.9 pH in leachate from unit 2 (sludge addition to top of refuse only and low MC:47%) and unit 3 (sludge addition throughout refuse MC:57%).

4.4.4 Nutrient increases due to sludge addition

The addition of nutrients to the refuse as a result of sludge addition is assessed by comparing the concentrations of phosphates (PO_4^{3-})and saline ammonia (NH_4^+)[1] that occurred in the leachates from units 1 (refuse only) and 3 (refuse and sludge).

4.4.4.1 Phosphates (PO_4^{3-})

Figure 4.10 shows the variation of the PO_4^{3-} concentrations in the leachates from units 1 and 3 with time. From this graph it can be seen that unit 3 (with sludge) contained PO_4^{3-} concentrations that were initially 100mg/l greater than the PO_4^{3-} concentrations in unit 1 (without sludge). These higher concentrations are as a result of PO_4^{3-} added to the refuse through the addition of anaerobic sludge. The concentrations of PO_4^{3-} in both these units then decreased to about 30mg/l at around week 7.

From these results it cannot be said whether or not the extra PO_4^{3-} added was beneficial to the refuse degradation because the elevated PO_4^{3-} concentrations lasted only 7 weeks and methanogenesis had not occurred even after 50 weeks. The PO_4^{3-} concentrations in units 1 and 3 did at no time decrease to zero and therefore PO_4^{3-}s were unlikely to be limiting. The unlikelihood that PO_4^{3-} was limiting is supported by the observation that the PO_4^{3-} concentrations in the unit which was in its methanogenic phase were about the same as those in the leachates from the units not yet in their methanogenic phase. (i.e. ~50mg/l).

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[1] The test used to determine the NH_4^+ concentrations in the leachate actually measures both the free and saline ammonia (NH_3 and NH_4^+) concentrations. However, at the pH values normally encountered in the leachates (< 7) the NH_4^+ is the predominant form and therefore only this will be referred to.

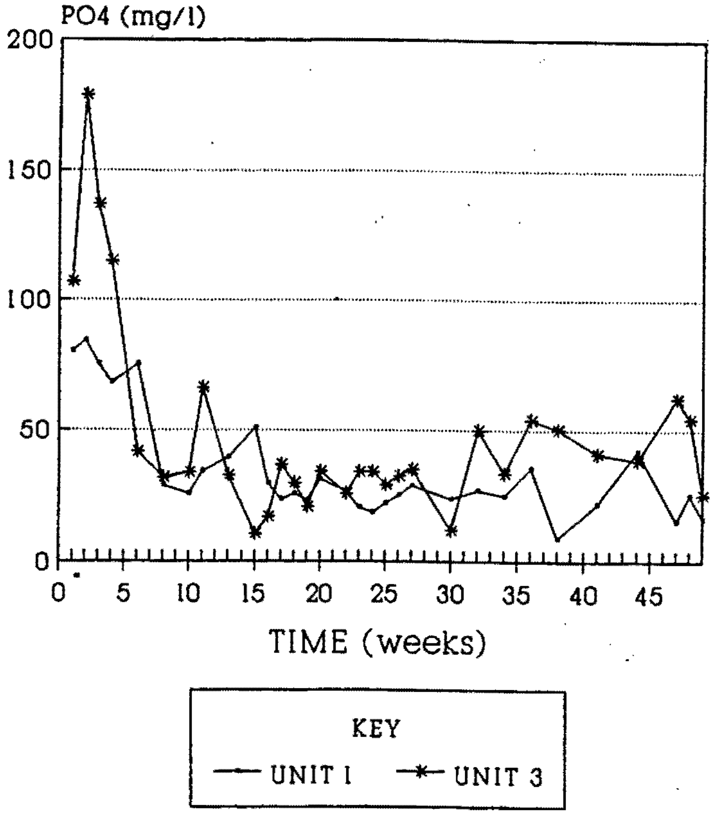


Fig 4.10 PO_4^{3-} concentrations in leachate from unit 1 (control with no sludge addition) and unit 3 (sludge addition).

4.4.4.2 Saline ammonia (NH_4^+)

The variations of the concentrations of NH_4^+ with time in the leachates from units 1 and 3 are shown in Figure 4.11. This graph shows that the NH_4^+ concentrations in the leachates from both units 1 and 3 for the first 12 weeks are approximately equal, indicating that sludge addition to unit 3 apparently initially did not contribute to the NH_4^+ concentration in the leachate. However, from the $H_2CO_3^*$ alkalinity increase (Fig 4.8 (previously)), higher NH_4^+ concentrations were expected in the leachate from unit 3, the $H_2CO_3^*$ alkalinity increase arising from ammonification of sludge proteanaceous material to NH_4^+. Examining the $H_2CO_3^*$ alkalinity and NH_4^+ data it can be seen that some of the NH_4^+ concentrations from unit 3 were higher than those in unit 1 during the time that the $H_2CO_3^*$ alkalinity from unit 3 was higher than unit 1 (weeks 1,3,7 and 8). Consequently, although difficult to discern, there are indications in the NH_4^+ data that the NH_4^+ concentrations from unit 3 were higher than those from unit 1 during the weeks 1 to 8, causing the higher $H_2CO_3^*$ alkalinity concentration from unit 3 compared to unit 1 during this period. After about 12 weeks the NH_4^+ concentrations in the leachate of unit 3, to which sludge was added, increased by more than 60% above that from unit 1. The extra NH_4^+ concentrations during this period are attributed to the hydrolysis of the sludge in this unit producing NH_3 which then formed NH_4^+ at the low pH. From week 25 onwards the difference progressively decreased until by week 45 the NH_4^+ concentrations from units 1 and 3 were similar again.

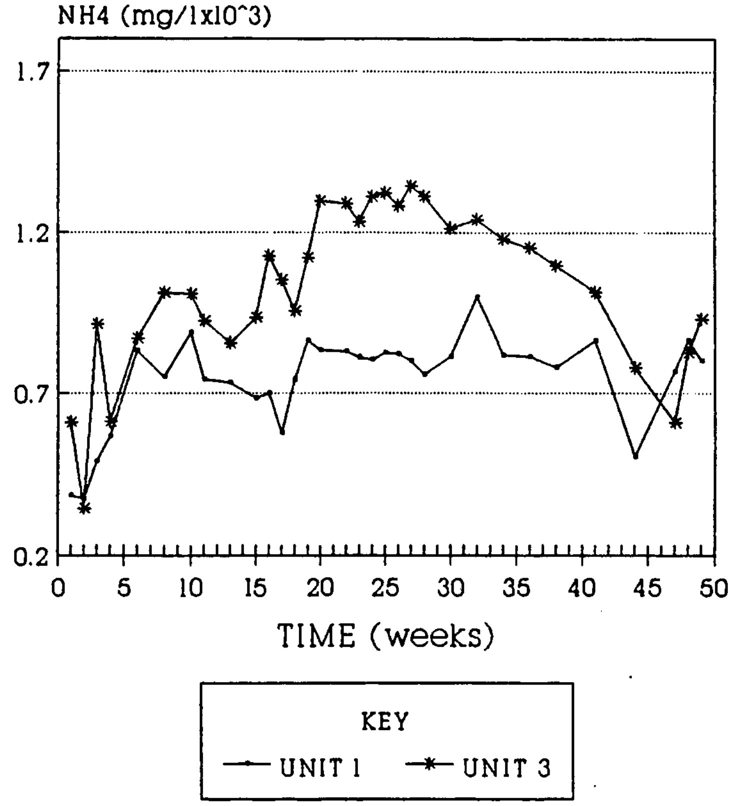


Fig 4.11 NH_4^+ concentrations in leachate from unit 1 (control with no sludge addition) and unit 3 (sludge addition).

Comparing the NH_4^+ concentrations with the PO_4^{3-} concentrations, it would appear that the nitrogen in the sludge has a far longer term influence. This is probably due to the nitrogenous material in sludge requiring hydrolysis and ammonification before becoming part of the leachate NH_4^+ concentration. This could not be checked with the $H_2CO_3^*$ alkalinity measurements because the $H_2CO_3^*$ alkalinity increase from ammonification was completely overwhelmed by the SCFA production.

4.4.5 Effect of sludge addition on sulphate reduction.

Initially, up to week 10, the SO_4^{2-} concentrations in the leachates from units 1 (no sludge addition) and 3 (sludge addition) increased to a maximum of around 800mg

SO_4^{2-} /l (Fig 4.12). These increases probably arose from dissolution of sulphates in the organic and inorganic solid phase. From weeks 10 to 17, the SO_4^{2-} concentrations decreased in both units probably as a consequence of the activity of sulphate reducing organisms under the anaerobic conditions. In unit 3, (sludge addition) the SO_4^{2-} concentration reduced to about 150mg SO_4^{2-}/l but in unit 1 (no sludge addition) it reduced to only 400mg SO_4^{2-}/l. The reason for this difference is not clear. It seems unlikely to be attributed to sludge addition *per se*; it is not unreasonable to expect that once sulphate reducing organism activity commences, the SO_4^{2-} concentration be reduced to low values in both units whether or not sludge was added. Nevertheless the SO_4^{2-} concentration remained consistently around 400mg/l for the 50 week investigation. Differences in SO_4^{2-} concentrations in the leachates from units 4, 5 and 6 were also observed, where those in the former two were very low (~0 mgSO_4^{2-}/l) but those in the latter one were high (~400mgSO_4^{2-}/l). Also for these differences no plausible explanation could be found.

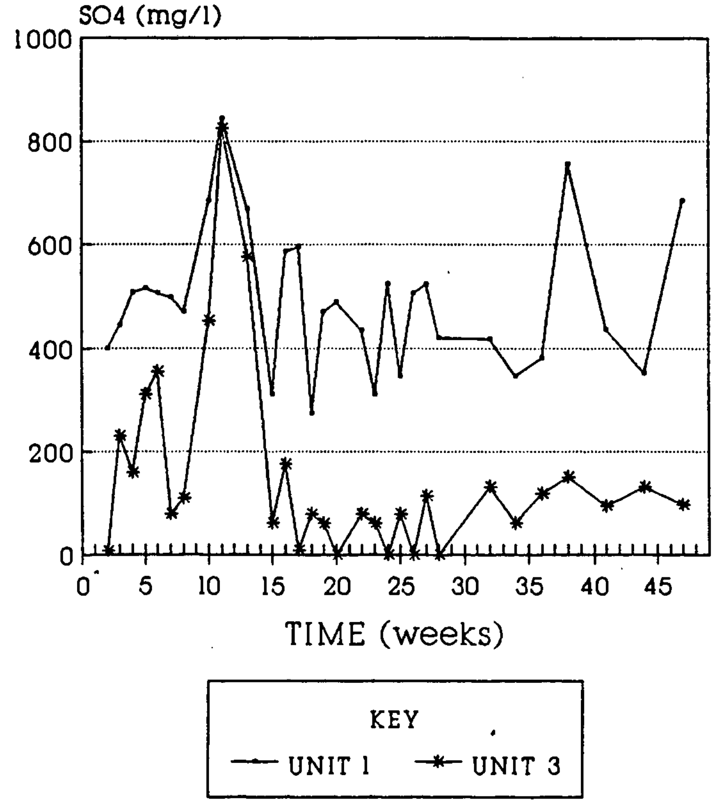


Fig 4.12 SO_4^{2-} concentrations in leachate from unit 1 (control with no sludge addition) and unit 3 (sludge addition).

4.5 LEACHATE RECYCLING

The effect that leachate recycling had on the refuse degradation process was determined by comparing the chemical composition of the leachates from units 3 and 6. These units contained the same constituents (refuse and anaerobic sewage sludge) at approximately the same moisture content (57%). However unit 6 was operated with leachate recycling while unit 3 (the control) had water irrigated onto the refuse to replace lost leachate.

Comparing the two systems, leachate recycling was found to have the following effects on the leachate constituents:

(1) the SCFA and COD concentrations in the leachate were increased by about 10%

(2) the pH of the leachate was lower - 5,2 (compared to 5,5) and remained at this low level.

(3) reduced sulphate reduction took place.

Each of these effects is discussed below.

4.5.1 SCFA and COD increases due to leachate recycling.

Figure 4.13 shows the variation of the leachate SCFA and COD concentrations with time from units 3 and 6 over the 50 week investigation period. From this graph it can be seen that both the SCFA and COD concentrations in the leachate from unit 6 (with recycling) were constantly 2000 to 3000 mg/l greater than those in unit 3 (without recycling). The higher concentrations of SCFA and COD in unit 6 are due to the accumulation of these concentrations from recycling. Little degradation of these substances took place in the refuse because the units were in the acid phase and not the methanogenic phase.

The SCFA and COD concentrations in the leachate from unit 3 are lower than unit 6 because these are diluted as a result of leachate extractions and water addition to the refuse in this unit. In unit 6 the higher SCFA concentration caused the pH to be depressed to 5,2, whereas in unit 3, with the slightly lower SCFA concentrations, (by 2500mg acetic acid) the pH remained at around 5,5 (Fig 4.14).

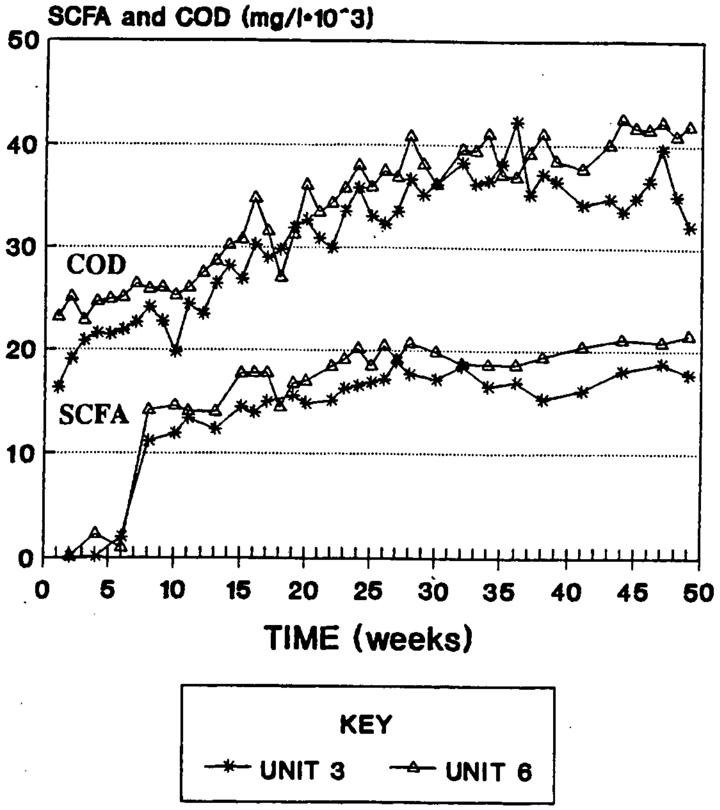


Fig 4.13 SCFA and COD concentrations in leachate from unit 3 (control) and unit 6 (leachate recycling).

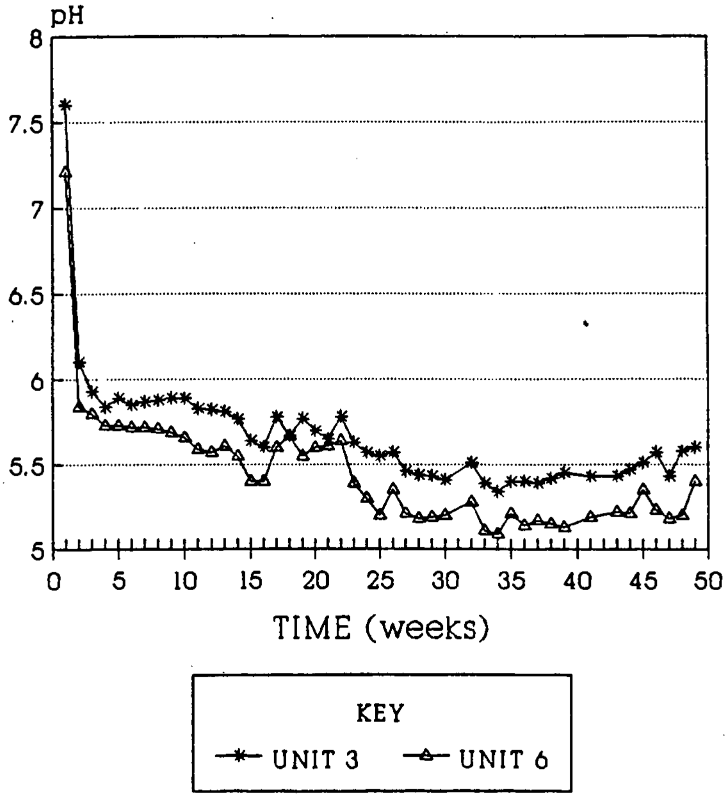


Fig 4.14 pH in leachate from unit 3 (control) and unit 6 (leachate recycling).

4.5.2 Effect of leachate recycling on $H_2CO_3^*$ alkalinity

The $H_2CO_3^*$ alkalinity of the leachates from units 3 and 6 increased from about 2000mg/l as $CaCO_3$ at week 2 to a maximum of about 3000mg/l as $CaCO_3$ at week 7 (Fig 4.15). The $H_2CO_3^*$ alkalinities then decreased to about 200mg/l as $CaCO_3$ at week 8 and thereafter remained at about 50mg/l for the duration of the investigation. The initial high $H_2CO_3^*$ alkalinities were due to the alkalinity contribution of the anaerobic sludge added to the refuse at the time of refuse placement in units 3 and 6. From Figure 4.15 it can be seen that the $H_2CO_3^*$ alkalinities were reduced to very low values (~50mg/l) by the high SCFA acid concentrations generated.

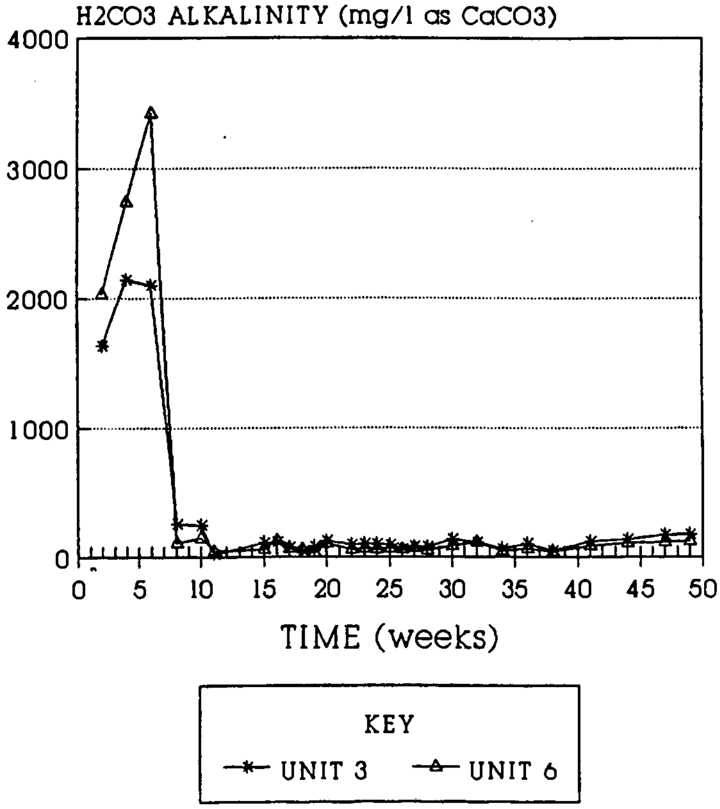
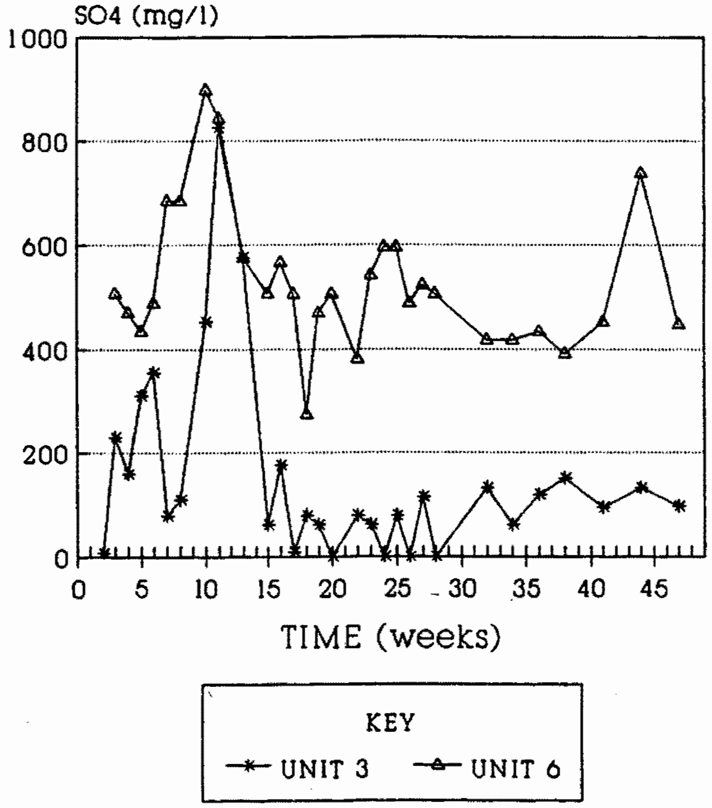


Fig 4.15 $H_2CO_3^*$ alkalinity in leachates from units 3 (control) and 6 (leachate recycling).

From the above results it can be seen that if the objective of leachate recycling is to obtain near neutral pH values in the leachate to accelerate the onset of methanogenesis, then leachate recycling onto acid phase refuse is clearly counter-productive.

4.5.3 Effect of leachate recycling on sulphate reduction.

The SO_4^{2-} concentrations in the leachates from units 3 and 6 increased to a maximum value at about week 11 (~ 500mg/l). Thereafter the SO_4^{2-} concentration in both units decreased. In unit 3 the SO_4^{2-} concentrations decreased to 50-100mg/l, however in unit 6 the SO_4^{2-} reduction did not take place to the same extent as occurred in unit 3 and the SO_4^{2-} concentrations remained at about 450mg/l (Fig 4.16). This effect also occurred in the leachate from unit 1 and there does not appear to be any particular reason for the inhibition of sulphate reducers in these units at this time. Although the pH in unit 6 was low (~ 5,2) the sulphate reducing bacteria are not inhibited at this low pH.



<u>Fig 4.16</u> SO_4^{2-} concentrations in leachate from unit 3 (control) and unit 6 (leachate recycling).

4.6 EFFECTIVENESS OF LIME ($Ca(OH)_2$) ADDITION

The effectiveness of lime addition to refuse (unit 4) and to recycled leachate (unit 5) in maintaining the pH of the leachate at near neutral values to assist the onset of methanogenesis is discussed in this section. The chemical constituents of the leachates from units 4 and 5 are compared with those in the leachate from unit 3 (the control with no lime addition) for the period week 1 to week 11. Lime was added to the refuse-sewage sludge mixture in two ways:

(1) admixed in powdered form with the refuse at placement (unit 4) and
(2) dosed into the leachate which was recycled (unit 5).

4.6.1 Lime mixed with refuse at placement (unit 4)

8 kg of lime was mixed with the refuse (~500kg)in unit 4 at the time of refuse placement. The lime proved to be unsuccessful in buffering the pH in the refuse against decreasing below a value of 7 for the following reasons:

(1) most of the lime appeared to be "washed-out" of the refuse in the leachate produced, thereby diminishing its effectiveness. Lime was too soluble and with the large flux of liquids through the refuse in the first 3 weeks of operation of unit 4 the lime was "washed-out" of the refuse with the leachate. From Figure 4.17 it can be seen that the $H_2CO_3^*$ alkalinity of the leachate from unit 4 was initially higher than the $H_2CO_3^*$ alkalinity in unit 3 (the control) due to the lime present in unit 4's leachate at this time. The leachate from unit 4 was also very opaque in appearance which was not found in any of the leachates from the other lysimeters. The opaqueness was attributed to the presence of lime in the leachate.

(2) the SCFA concentrations in the leachate from unit 4 increased rapidly shortly after the refuse and lime placement (Fig 4.18). The $H_2CO_3^*$ alkalinity gained in unit 4 as a result of the lime in the unit was lost with the generation of these high SCFA concentrations and consequently the pH of the leachate fell to about 6. Therefore the 8kg of lime in unit 4 was insufficient to buffer against the high SCFA concentrations generated.

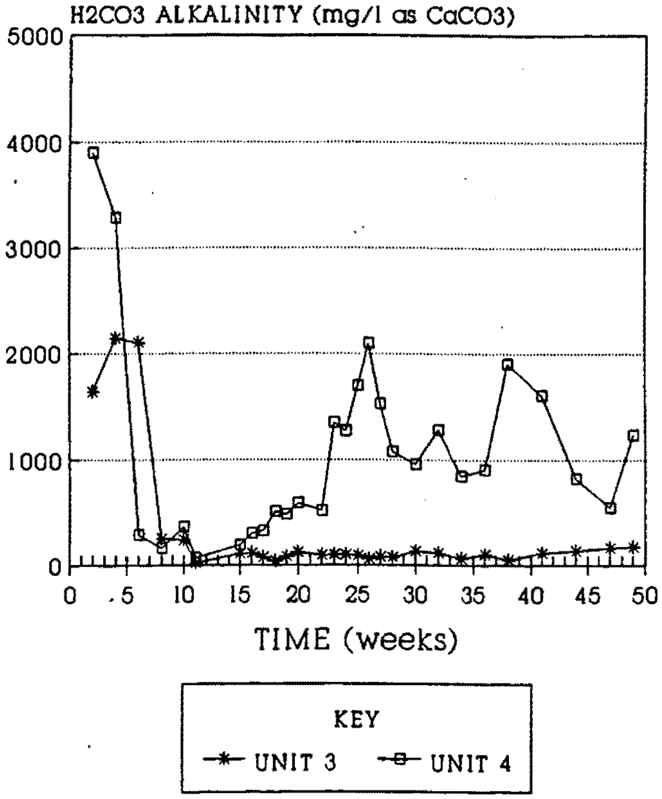


Fig 4.17 $H_2CO_3^*$ alkalinity in leachate from unit 3 (control with no lime addition) and unit 4 (8kg of lime mixed with refuse at start-up).

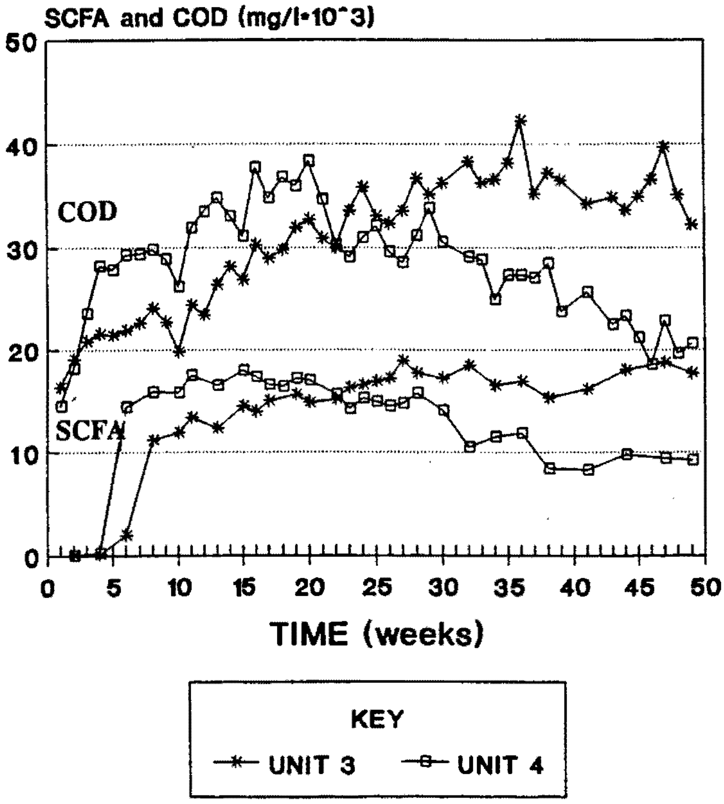


Fig 4.18 SCFA and COD concentrations in leachate from unit 3 (control with no lime addition) and unit 4 (8kg of lime mixed with refuse at start-up).

4.6.2 Lime added to recycled leachate (unit 5)

4.65 kg of lime in total was added to the recycled leachate in unit 5 between week 6 and week 11. From Fig 4.19 it can be seen that once the pH of the leachate from unit 5 had decreased to about 5,9 (week 3) the pH remained constant until week 11 when lime addition was terminated. In contrast, the pH of the leachate from unit 6 which also received leachate recycling but no lime addition decreased over this period to a value of 5,6 (Fig 4.14 previously). Therefore it appears that the lime addition to the recycled leachate controlled the pH of the leachate at 5,9. At a much greater lime dosage the pH of the leachate could no doubt have been controlled at 7,0 to promote methanogenesis, but the required dosage of lime for this could not be dissolved in the recycled leachate.

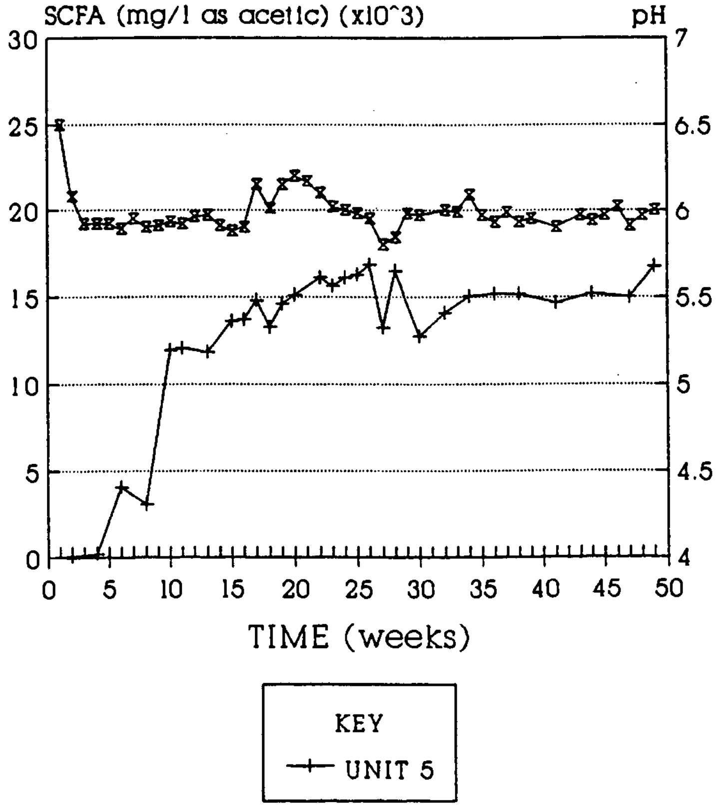


Fig 4.19 SCFA concentrations and pH in leachate from unit 5 (4.65kg lime added between weeks 6 and 11).

4.6.3 Conclusions on lime addition

Lime addition to refuse was not successful in maintaining the leachate pH near 7 because:

(1) too little lime was mixed in with the refuse; even though the quantity of lime required to neutralize the estimated concentration of acids generated in the leachate was added, the lime was sufficient only for about 5 weeks.
(2) if dosed by leachate recycling or water addition lime is too insoluble to dose sufficient quantities to keep the pH of the leachate near 7.

For it to have been successful, much more lime would have been required to be sufficient for the complete duration of the acid phase (estimated to be around 6 months at pH > 6,8)

4.7 ARTIFICIAL ELEVATION OF pH WITH NaOH (UNITS 4 AND 5)

From week 11 to week 20 NaOH was added to the refuse in units 4 (943g NaOH total) and 5 (974g NaOH total) by dosing the leachate with NaOH which was then recycled onto the refuse. The NaOH dosing was considered to be necessary once it was discovered that the lime addition to these units proved to be unsuccessful as a buffer in maintaining a near neutral pH in the leachate. As already mentioned in chapter 3, the recycled leachate was used as a dosing medium for the NaOH so that sufficient quantities of the strong base could be dosed to the refuse while preventing the pH of the recycled pH from increasing above a value of 9. If water were to have been used as a dosing medium, large volumes of water would have been required to prevent the pH of the water-NaOH mixture from increasing to values that are harmful to microorganisms($\sim >9$). The high water flux through the refuse was not desired as this would disturb the liquid balance in the refuse and possibly flush out leachate unnecessarily (this assumption was found to be invalid at a later stage-see section on high water flux through refuse).

The addition of NaOH to refuse in recycled leachate was found to have the following effects on units 4 and 5;

(1) The pH and $H_2CO_3^*$ alkalinity values in the leachate produced from unit 4 increased marginally, the pH from 5,8 to 6,3 and the $H_2CO_3^*$ alkalinity from about

100 to 500mg/l as $CaCO_3$ (Fig 4.20, week 10 to 20). Although the pH in the leachate from unit 5 increased from 5,8 to 6,2 during this period, the $H_2CO_3^*$ alkalinity increased from about 100mg/l to only 200mg/l as $CaCO_3$.

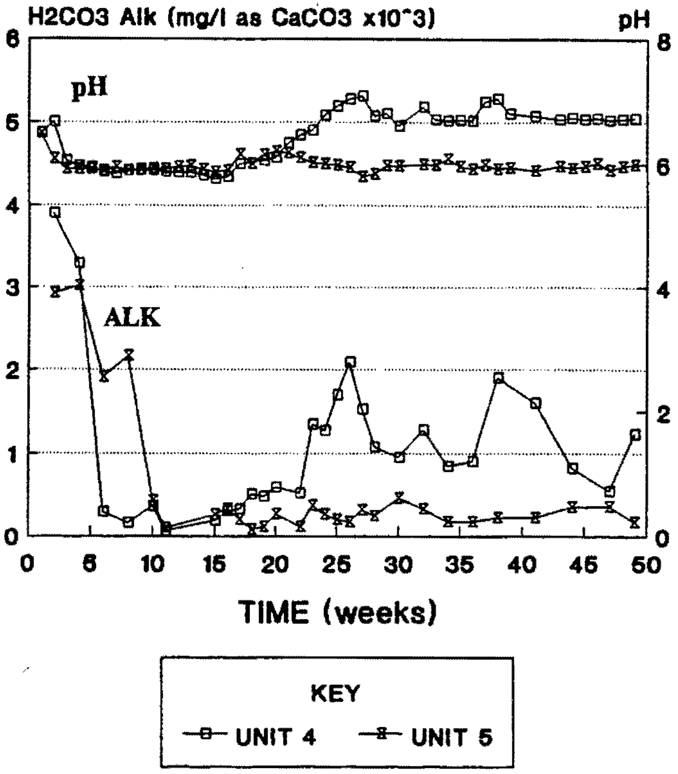


Fig 4.20 $H_2CO_3^*$ alkalinity and pH in leachates from units 4 and 5. NaOH was dosed to these units from week 11 to 20.

(2) The SCFA concentrations in the leachate from unit 4, which previously did not receive any recycled leachate remained approximately the same during NaOH dosing. However the COD concentrations in the leachate from this unit increased from about 33000mg/l to about 37000mg/l during the same period (Fig 4.21 - week 10 to 20). In unit 5 which was previously operated with leachate recycling the SCFA concentrations increased from about 12500mg/l to about 16000mg/l as $CaCO_3$ and the COD concentrations increased from about 26000mg/l to about 36000mg/l during NaOH dosing.

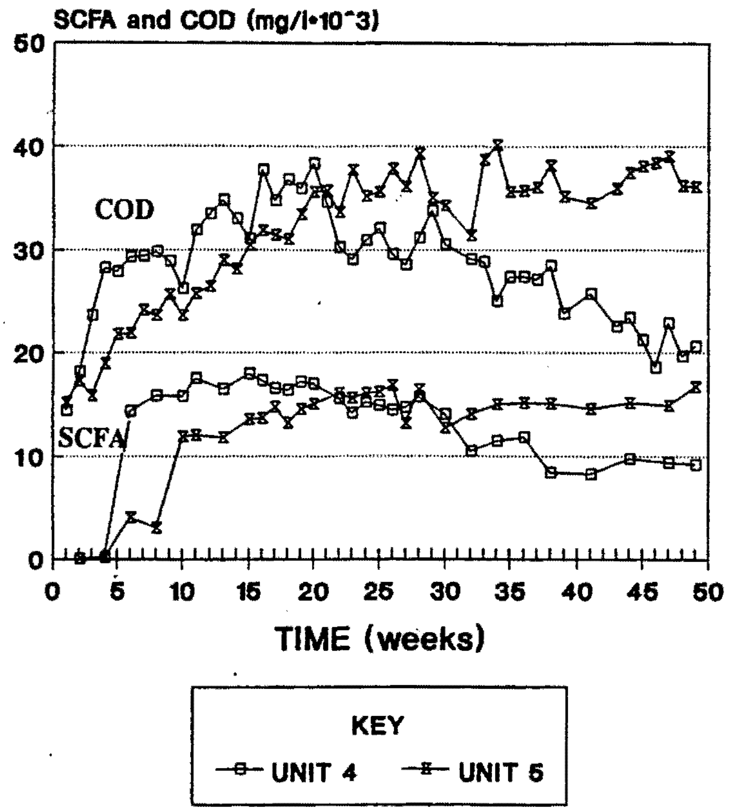


Fig 4.21 SCFA and COD concentrations in leachates from units 4 and 5. NaOH was dosed to these units from week 11 to 20.

4.8 EFFECT OF HIGH WATER FLUX THROUGH REFUSE (UNITS 4 AND 5)

4.8.1 Unit 4

The NaOH dosing to units 4 and 5 (weeks 11 to 20) did not elevate the pH and $H_2CO_3^*$ alkalinity of the leachate very rapidly due to the presence of high SCFA concentrations. Therefore from week 20 to 28 the refuse in unit 4 was subjected to a high flux of water and the leachate produced was discarded so that the concentration of SCFA in unit 4 could be reduced. Unit 5 in contrast was operated with leachate recycling for the same period (week 20 to 28). The intention was to reduce the SCFA concentrations in unit 4 by dilution with the high water flux and then afterwards continue with the NaOH dosing to unit 4 in the same manner as was done earlier once the SCFA concentration had been reduced sufficiently. In this way a suitable $H_2CO_3^*$ alkalinity (~2000mg/l) and pH (~7) could be established for the onset of methanogenesis. Unit 5 with leachate recycling was used as a control against which to compare the effect of the high water flux through unit 4. It was found, however, that the high flux of water alone (over the 8 week period ~100l water was added and ~ 100l leachate was extracted i.e. 12l/week compared to the usual 2-4l/week) was sufficient for elevating the alkalinity and pH of the leachate in unit 4 to the intended $H_2CO_3^*$ alkalinity and pH values (2000mg/l and 7) (see Figure 4.20 (previously) - week 20 to 28). In contrast, the $H_2CO_3^*$ alkalinity and pH values in the leachate from unit 5 (with leachate recycling) remained at about 200mg/l and 6 respectively for the same period (week 20 to 28, Fig 4.20). The increases in $H_2CO_3^*$ alkalinity and pH in the leachate from unit 4 during the high water flux are attributed to the combination of two effects:

(1) the reduction in SCFA concentration due to the flushing-out and removal of leachate (see Fig 4.21 above - week 20 to 28) and

(2) the washing-down of NaOH (added earlier during weeks 11-20) through the refuse mass. At the end of the NaOH dosing period (week 20) 200g of the total amount of 943g of NaOH was dosed to the refuse in recycled leachate and this large dosage of NaOH in all likelihood was the cause for the rapid $H_2CO_3^*$ alkalinity and pH increases that occurred in unit 4 from weeks 22 to 26.

The effect of the high water flux in unit 4 can also be seen in the concentrations of NH_4^+ in the leachate from unit 4 which showed a decrease from about 750mg/l to about 600mg/l due to dilution during the water fluxing period (Fig 4.22- week 20 to 28). The water flux in unit 4 was terminated at week 28 once the $H_2CO_3^*$ alkalinity and pH in the leachate from this unit had started to decrease and had values of about 1000mg/l as $CaCO_3$ and 6,7 respectively.

4.8.2 Unit 5

Due to the success of the high flux of water through unit 4 (albeit immediately after NaOH dosing) in elevating the pH and $H_2CO_3^*$ alkalinity in the leachate from this unit, a high flux of water was also imposed on unit 5 from week 27 to 34. NaOH was also dosed to unit 5 in recycled leachate from week 11 to 20 in the same manner as unit 4. However unlike unit 4 which received a high water flux for 8 weeks (week 20 to 28) immediately after the NaOH dosing to this unit (4), unit 5 was operated with a leachate recycle during this period. The high water flux imposed on unit 5 then took place after the leachate recycling to this unit. During the high water flux period 4kg of $NaHCO_3$ buffer was also dosed to the refuse in unit 5 in the water added. This was because the $H_2CO_3^*$ alkalinity and pH values in unit 5 had been suppressed by the leachate recycling that had been carried out on this unit in the previous weeks. From Figure

4.21 (previously) it can be seen that during the high water flux period in unit 5 (week 27 to 34) the SCFA and COD concentrations decreased due to the dilutory effect of the large water addition (~100l) together with the large volumes of leachate (~100l) extracted. A similar effect can be seen in the NH_4^+ concentrations in the leachate from unit 5 during this period (Fig 4.22 (above) - week 27 to 34). The $H_2CO_3^*$ alkalinity and pH values in the leachate from unit 5, however did not increase significantly during the high water flux and $NaHCO_3$ dosing period and remained at fairly constant values of about 200mg/l as $CaCO_3$ and 6 respectively (Fig 4.20 (above) - week 27 to 34).

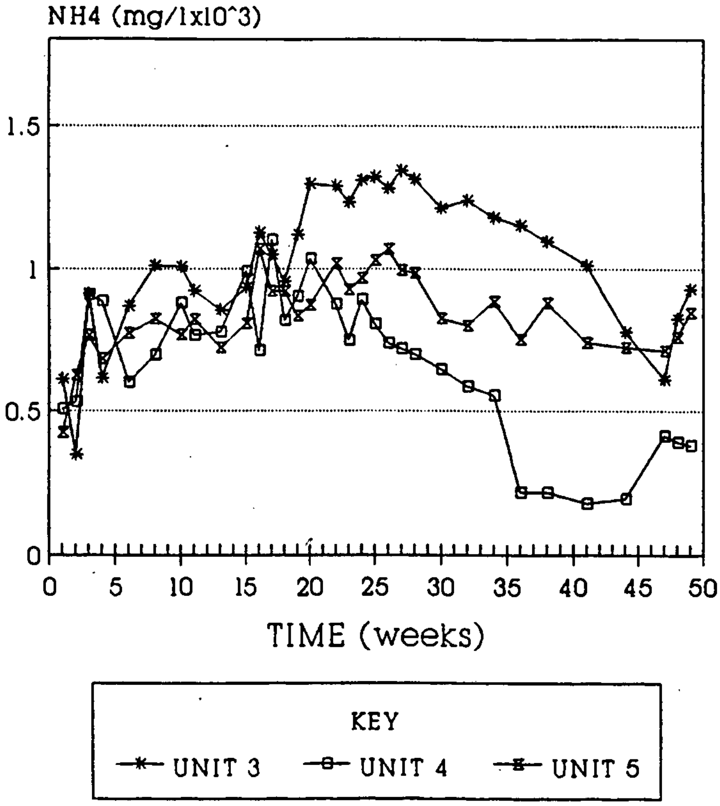


Fig 4.22 NH_4^+ concentrations in leachates from units 3, 4 and 5 showing the effect of the high water flux in units 4 and 5 from weeks 20 to 28 and 27 to 34 respectively in which NH_4^+ concentrations in these units decreased during these periods.

Unlike unit 4, where the high water flux and NaOH dosing caused the $H_2CO_3^*$ alkalinity and pH to increase, in unit 5 this did not happen. This is in all likelihood due to the leachate recycling practised in unit 5 during weeks 20 to 27 which was not practised in unit 4.

4.9 ONSET OF METHANOGENESIS IN UNIT 4

Evidence that indicated that methanogenesis had commenced in unit 4 at week 32 was:

(1) the high rate of gas production measured in this unit from week 32 onwards.
(2) the significant reduction in SCFA concentration in the leachate from about 15000mg/l at week 30 to about 8000mg/l at week 37.
(3) the alkalinity increase from about 1000mg/l as $CaCO_3$ at week 30 to 2000mg/l as $CaCO_3$ at week 36.

The above observations are consistent with those which would be expected when methanogenesis is taking place. With methanogenesis, SCFA is converted to methane and CO_2 gas causing the SCFA concentration to decrease and the gas production to increase; the reduction in SCFA concentration causes the alkalinity to increase.

Unfortunately, the gas composition could not be measured at the time of methanogenesis commencement because the instrument required to do this was unavailable; if with gas composition measurements CH_4 is detected, then methanogenesis in the refuse is confirmed. However, despite the absence of such direct confirmation of methanogenesis, the evidence listed above is regarded as sufficient to indicate that methanogenesis had commenced. This conclusion is confirmed from evidence reported by Farquhar and Rovers (1973) (see Figs 2.1a, b and c) which show that phase 3, i.e. the methanogenic phase, commences when the SCFA concentration (VFT in Fig 2.1b) decreases and the alkalinity (HCO_3^- concentration in Fig 2.1c) increases, at which time methane production commences and increases with time (CH_4 in Fig 2.1a). Note that Fig 2.1a gives the gas composition, not the gas production rate - the presence of CH_4 in the gas from the beginning of phase 3 indicates that methanogenesis has commenced. Gas composition measurements were conducted from week 44 and from this time until the end of the investigation at week 51 the average CH_4 composition was 53% by dry volume (see Appendix A, page A.22-23). This also confirms that methanogenesis must have commenced in unit 4 several weeks prior to week 44 since according to Farquhar and Rovers (1973) there is an appreciable time lag between the onset of methanogenesis and when the methane concentration in the gas is about 50% (see Fig 2.1b).

4.9.1 Effect of methanogenesis on SCFA and COD concentrations

From Figure 4.23 it can be seen that at about the same time that methane production was measured from unit 4 (week 32), the SCFA and COD concentrations in the leachate started to decrease. Although generally rates of CH_4 production accompanied the greatest reductions in SCFA and COD concentrations (week 32 to 35, and 36 to 39) this was not necessarily always the case. This is because the units were operated as plug-flow systems and therefore pockets of leachate extracted from a unit were not necessarily truly representative of the contents of the whole unit. The trend however is that the SCFA and COD concentrations decreased as the organic acids were used up in the production of CH_4 and CO_2 during methanogenesis.

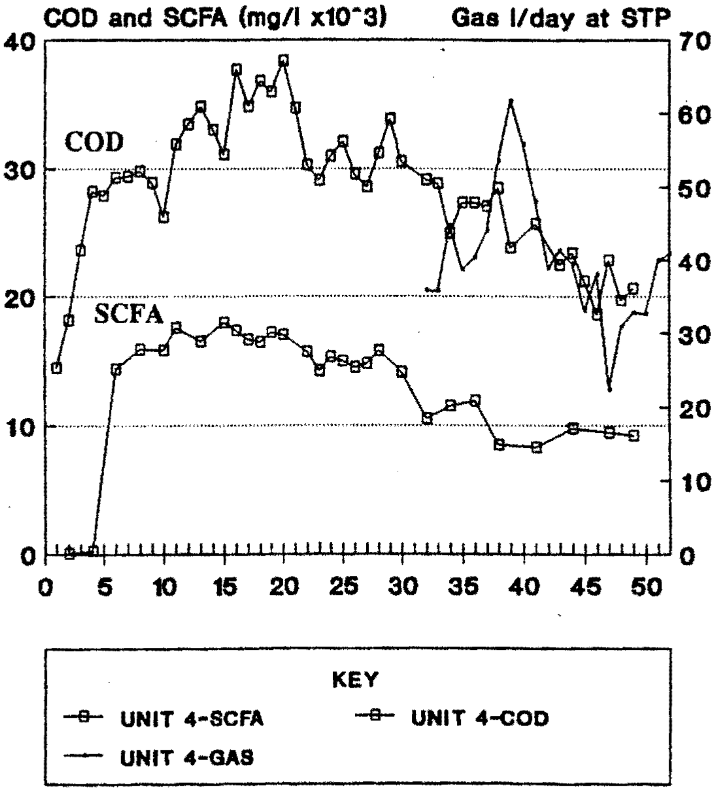
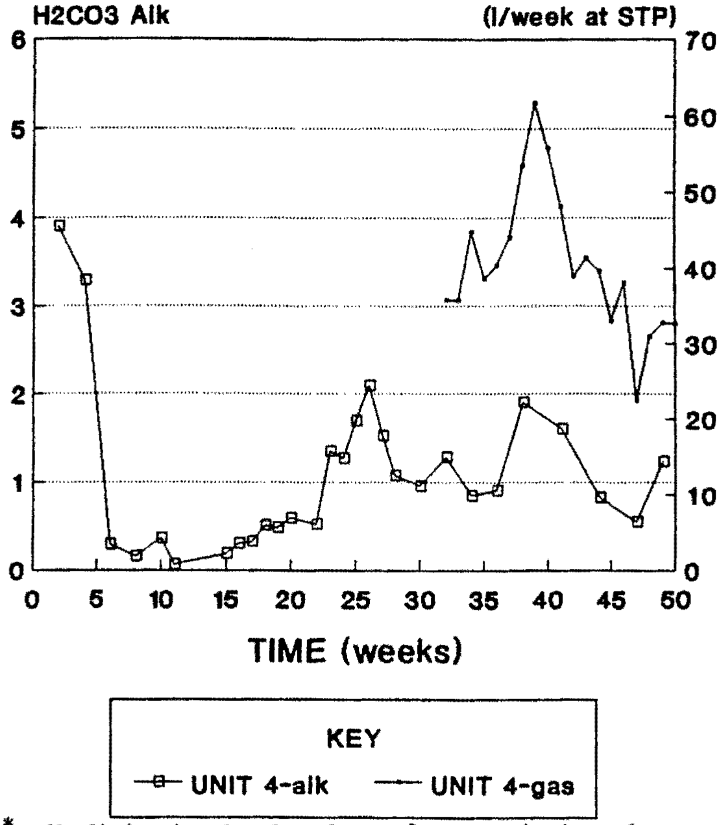


Fig 4.23 SCFA and COD concentrations in leachate from unit 4 and average volumes of gas produced per week during methanogenesis in this unit.

It is not possible to calculate the CH_4 producing potential of the refuse from the decrease in SCFA concentrations over the period that methanogenesis was taking place in unit 4. This is because it is not known how much the SCFA concentrations increased in the unit as a result of refuse degradation during this period since the extra SCFA generated were also utilised in the production of CH_4. Fig 4.21 (previously) shows that the SCFA concentrations in unit 4 increased slightly on occasions during methanogenesis in this unit which indicates that high SCFA concentrations were still being generated at this time.

4.9.2 Effect of methanogenesis on $H_2CO_3^*$ alkalinity and pH

The $H_2CO_3^*$ alkalinity of the leachate from unit 4 increased and decreased with the rate of gas production per week from this unit as shown in Figure 4.24.



<u>Fig 4.24</u> $H_2CO_3^*$ alkalinity in the leachate from unit 4 and average volume of gas produced per week during methanogenesis in this unit.

The $H_2CO_3^*$ alkalinity during this period also increased with decreases in SCFA in unit 4 (Fig 4.25). Therefore it appears that an increase in alkalinity in the refuse brings about an increase in the CH_4 production rate and concomitantly a decrease in the SCFA concentrations.

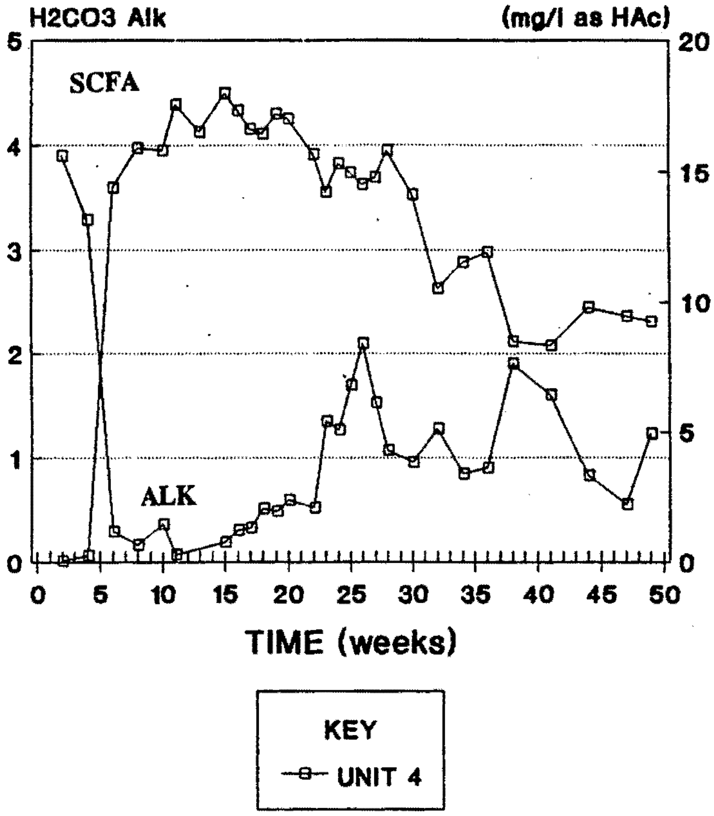


Fig 4.25 $H_2CO_3^*$ alkalinity and SCFA concentrations in the leachate from unit 4.

4.9.3 Decrease in NH_4^+ concentrations during methanogenesis

The large decrease in the NH_4^+ concentrations during methanogenesis in unit 4 (weeks 34 to 45 in Fig 4.22 (presented previously)) is extraordinary and cannot be accounted for. This large decrease in NH_4^+ concentrations at this time was also reflected in the TKN concentrations during the same period. Gradual decreases in nitrogen concentrations in unit 4 can be accounted for by the wash-out of the constituents from the refuse with the water additions and leachate extractions. It is possible that channeling of water through the refuse caused large dilutions of the leachate constituents, however all the constituents would have been affected (i.e. PO_4^{3-} also) which is not evident.

4.9.3 Effect of temperature on methanogenesis

Figure 4.26 shows the variation of the volume of gas produced per week from unit 4 with the temperature of the refuse in this unit. From this graph it can be seen that the average rate of CH_4 production decreased at about week 40 and remained at a lower rate relative to the rate before week 40. This lower gas production rate coincided with the lower refuse temperatures during this period and therefore the low winter temperatures inhibited the methanogenic bacteria.

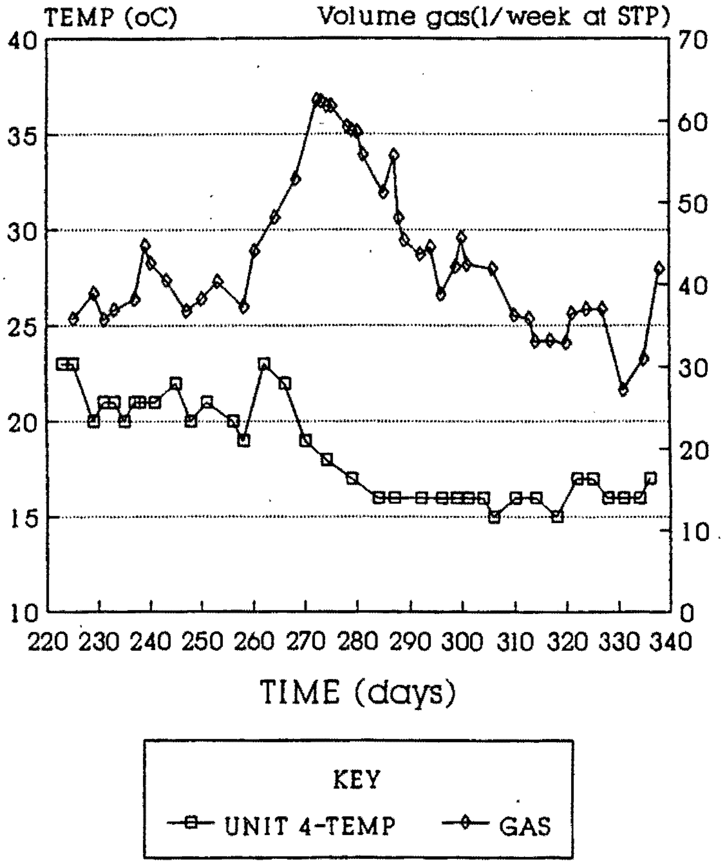


Fig 4.26 Average volume of gas produced per week during methanogenesis in unit 4 and temperatures of refuse in this unit during this period (week 31 to 50).

CHAPTER 5

CONCLUSIONS

The objectives of this investigation were to investigate at pilot scale whether (1) the co-disposal of anaerobic sewage sludge with refuse and (2) leachate recycling enhanced degradation of the refuse and accelerated the onset of methanogenic conditions in the refuse. Although these two parameters were found to affect the degradation of the refuse in its acid phase (see below) it cannot be said at this early stage how the parameters affect methanogenesis. This is because only one lysimeter commenced methanogenesis during the investigation period; one wherein pH control was practiced via chemical dosing. In the lysimeters with leachate recycle and sludge addition only, methanogenesis did not commence during the investigation period (1 year).

From the lysimeter studies the following conclusions were formed:

(1) Moisture addition to refuse as a result of sludge co-disposal enhanced the degradation of refuse in its acid phase.

(2) The co-disposal of sludge increased the alkalinity in the liquid fraction of the refuse but the SCFA concentrations generated were also increased with the result that the leachate pH dropped to below 6,0 after 8 weeks; indeed it appeared that the alkalinity generated by the sludge was insufficient to buffer the additional acids generated by the sludge.

(3) The sludge added PO_4^{3-} and NH_4^+ to the refuse. The PO_4^{3-} added (~ 100mg/l) were reduced to about 30mg/l after 5 weeks whereas the NH_4^+ added had a longer lasting effect. This was due to the hydrolysis of the sludge releasing NH_4^+ into solution (~ 500mg/l) over a period of about 40 weeks. The alkalinity gained by this hydrolysis was completerly neutralized by the high SCFA concentrations generating resulting in a low leachate pH (~ 5,5).

(4) Leachate recycling resulted in 10% higher SCFA and COD concentrations in the leachate than occurred in the leachate from refuse without leachate recycling. The higher concentrations result from the accumulation of COD and SCFA in the liquid fraction of the refuse due to the leachate recycling.

(5) The high SCFA concentrations due to leachate recycling caused the pH of the leachate to decrease to a value around 5,2. Therefore recycling of leachate from acid phase refuse back to this refuse for the purpose of accelerating the onset of methanogenesis in the refuse is counter-productive. It is recommended therefore that leachate from acid phase refuse should be recycled rather to refuse in its methanogenic stage of decomposition. In this way the SCFA concentrations in the leachate would be reduced by the methanogenic activity in the refuse.

(6) The mixing of lime ($Ca(OH)_2$) with refuse for the purpose of buffering the pH of the refuse to promote the onset of methanogenesis was unsuccessful. This was because not enough lime (8kg) was mixed with the refuse to be effective for the approximately 6 months it takes for methanogenic conditions to commence (the 8kg of lime only lasted for about 5 weeks by which time most of it was dissolved and flushed out with the leachate.

(7) Dosing of lime to refuse in either recycled leachate or irrigated water was not successful as not enough lime could be dissolved in these volumes to buffer against the high SCFA concentrations present.

(8) NaOH dosing to the refuse in recycled leachate followed by a high flux of water through the refuse successfully elevated the $H_2CO_3^*$ alkalinity and pH of the leachate to the sought after levels for methanogenesis to take place (~ 2000mg/l as $CaCO_3$ and 7 respectively). Methanogenesis and CH_4 production from this unit commenced about 7 weeks after these $H_2CO_3^*$ alkalinity and pH values had been obtained.

(9) The rate of methane production from the refuse was temperature dependant and decreased by about half; during autumn when methanogenesis commenced and gas production reached a maximum of 60 l/day the refuse temperature was around 21°C; later in winter when the refuse temperature had decreased to 16°C, the gas production declined to about 30 l/day.

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APPENDIX A

TABLES OF ALL THE MEASURED PARAMETERS DURING THE 50 WEEK INVESTIGATION

Table A.1a Volumes of liquid added to, extracted from and cummulative volumes of liquid extracted from units 1, 2 and 3 during the 50 week investigation.

WEEK	UNIT1			UNIT 2		UNIT 3		
	ADD	EXT*	CUMM	EXT*	CUMM	ADD	EXT*	CUMM
0								
1								
2		23.5	23.5					
3		18.2	41.7	25.2	25.2		13.1	13.1
4		9.7	51.4	20.1	45.3		20.5	33.6
5		19.5	70.9	13.2	58.5		15.6	49.2
6		16.8	87.7	20.5	79		12.9	62.1
7		13.1	100.8	10.9	89.9		17.8	79.9
8		10.9	111.7	12.1	102		15.5	95.4
9		9.7	121.4	5.8	107.8		8.3	103.7
10		8.3	129.7	6.2	114		6.2	109.9
11	5.8	5.8	129.7	10.5	124.5	7.5	7.5	109.9
12	2	2	129.7	13.1	137.6	2.6	2.6	109.9
13	2.1	2.1	129.7	12.2	149.8	2.8	2.8	109.9
14	1.5	1.5	129.7	6.7	156.5	3.5	3.5	109.9
15	1.6	1.6	129.7	7.8	164.3	2.1	2.1	109.9
16	1	1	129.7	14.5	178.8	1.1	1.1	109.9
17	1.1	1.1	129.7	11	189.8	1.2	1.2	109.9
18		4.2	133.9	5.2	195	2.1	2.1	109.9
19	2.9	2.9	133.9	14.6	209.6	2.5	2.5	109.9
20	2.5	2.5	133.9	11.1	220.7	1.3	1.3	109.9
21	2.2	2.2	133.9	1.9	222.6		4.8	114.7
22	2.1	2.1	133.9	1.7	224.3	2.1	2.1	114.7
23	1.9	1.9	133.9	0.2	224.5	0.7	0.7	114.7
24	1.8	1.8	133.9	1.1	225.6	2.3	2.3	114.7
25	1	1	133.9	1.4	227	2	2	114.7
26		4.3	138.2	1.5	228.5	1.7	1.7	114.7
27	1.2	1.2	138.2	0.5	229	2.5	2.5	114.7
28	1.5	1.5	138.2	2.1	231.1		4.1	118.8
29	1.7	1.7	138.2	0.7	231.8		3.8	122.6
30	1.9	1.9	138.2	0.8	232.6	1.3	1.3	122.6
31			138.2		232.6			122.6
32	2.1	2.1	138.2	0.5	233.1	2.4	2.4	122.6
33	2.3	2.3	138.2	0.7	233.8	0.7	0.7	122.6
34	2	2	138.2	0.8	234.6	0.3	0.3	122.6
35	1.7	1.7	138.2	0.2	234.8	2.3	2.3	122.6
36	0.5	0.5	138.2	1	235.8	0.2	0.2	122.6
37	0.3	0.3	138.2	1.1	236.9	0.7	0.7	122.6
38	0.5	0.5	138.2	0.9	237.8	0.4	0.4	122.6
39	0.2	0.2	138.2	1.1	238.9	1.3	1.3	122.6

* EXT = Volume of leachate extracted

Table A.1a continued

WEEK	UNIT1			UNIT 2		UNIT 3		
	ADD	EXT*	CUMM	EXT*	CUMM	ADD	EXT*	CUMM
40			138.2		238.9			122.6
41		2.7	140.9	1.2	240.1	1.8	1.8	122.6
42			140.9		240.1			122.6
43	1.3	1.3	140.9	0.3	240.4		3.1	125.7
44	0.2	0.2	140.9	0.2	240.6	1.1	1.1	125.7
45	0.1	0.1	140.9	0.1	240.7	0.4	0.4	125.7
46	0.4	0.4	140.9	0.3	241	0.7	0.7	125.7
47	0.3	0.3	140.9	0.5	241.5	0.1	0.1	125.7
48	0.5	0.5	140.9	0.4	241.9	0.2	0.2	125.7
49	0.7	0.7	140.9	0.3	242.2	0.2	0.2	125.7
50	0.4	0.4	140.9	0.1	242.3	0.3	0.3	125.7
51	0.3	0.3	140.9	0.5	242.8	0.9	0.9	125.7
52	0.5	0.5	140.9	0.3	243.1	0.7	0.7	125.7

* EXT = Volume of leachate extracted

Table A.1b Volumes of liquid added to, extracted from and cummulative volumes of liquid extracted from units 4, 5 and 6 during the 50 week investigation.

WEEK	UNIT 4			UNIT 5			UNIT 6	
	ADD	EXT*	CUMM	ADD	EXT*	CUMM	EXT*	CUMM
0								
1								
2								
3		16.1	16.1		25.3	25.3	40.2	40.2
4		34.5	50.6		59.5	84.8	30	70.2
5		13.2	63.8		29.2	114	26.3	96.5
6		16.2	80			114.1	29.1	125.6
7	20	14.5	74.5			114.2		125.7
8	10	13.9	78.4			114.3		125.8
9		4	82.4			114.4		125.9
10		4.3	86.7			114.5		126
11		12.1	98.8			114.6		126.1
12			98.9			114.7		126.2
13			99	13.7		101.1		126.3
14			99.1			101.2		126.4
15			99.2			101.3		126.5
16			99.3			101.4		126.6
17			99.4			101.5		126.7
18			99.5			101.6		126.8
19			99.6			101.7		126.9
20	20	18	97.6			101.8		127
21		5.1	102.7			101.9		127.1
22	20	7.5	90.2			102		127.2
23	15	23.3	98.5			102.1		127.3
24	6.5	9.7	101.7			102.2		127.4
25	15	14.1	100.8			102.3		127.5
26	10	19.2	110			102.4		127.6
27		16.8	126.8	20	25.4	107.8		127.7
28	10	14.3	131.1	20	11.9	99.7		127.8
29	1.9	1.9	131.1		14.3	114		127.9
30	2.1	2.1	131.1	10	12.1	116.1		128
31			131.1			116.1		128.1
32	4.3	4.3	131.1	20	17.2	113.3		128.2
33	3.7	3.7	131.1	4.5	4.5	113.3		128.3
34		9.4	140.5	10	6.1	109.4		128.4
35	2.9	2.9	140.5		7.1	116.5		128.5
36	0.3	0.3	140.5	3.8	3.8	116.5		128.6
37	1.5	1.5	140.5	3.6	3.6	116.5		128.7
38	3.2	3.2	140.5	4	4	116.5		128.8
39		4.5	145		10.2	126.7		128.9

* EXT = Volume of leachate extracted

Table A.1b continued

WEEK	UNIT 4			UNIT 5			UNIT 6	
	ADD	EXT*	CUMM	ADD	EXT*	CUMM	EXT*	CUMM
40			145			126.7		129
41		5.7	150.7		7.4	134.1		129.1
42			150.7			134.1		129.2
43	1.1	1.1	150.7	4.1	4.1	134.1		129.3
44	2.4	2.4	150.7		5.9	140		129.4
45	0.4	0.4	150.7	3.8	3.8	140		129.5
46	1.1	1.1	150.7		1.6	141.6		129.6
47	0.9	0.9	150.7	3.1	3.1	141.6		129.7
48	0.3	0.3	150.7	2	2	141.6		129.8
49	0.6	0.6	150.7	1.4	1.4	141.6		129.9
50	0.9	0.9	150.7		4.3	145.9		130
51	0.4	0.4	150.7	1.6	1.6	145.9		130.1
52	1.1	1.1	150.7	2.9	2.9	145.9		130.2

* EXT = Volume of leachate extracted

Table A.2 Ambient, headspace and refuse temperatures (units 1, 2 and 3) over the 50 week investigation.

DAY	AMBIENT	H'SPACE	UNIT 1	UNIT 3	UNIT 4
	T (^oC)	T (^oC)	T (^oC)	T (^oC)	T (^oC)
21	19	21	20		
22	18	21	20	18	19
25	24	23	18	17	17
26	16	19	20	18	18
27	18	21	18	17	18
28	18	20	18	17	17
29	17	19	19	18	17
32	17	19	17	17	17
33	16	20	17	16	16
35	22	28	18	18	17
36	21	32	18	18	18
39	24	29	20	20	20
40	23	33	22	21	20
41	20	23	23	21	21
43	21	25	22	20	20
47	20	20	21	21	20
48	19	21	21	21	19
49	21	23	21	19	20
50	23	18	21	20	19
54	20	22	20	19	19
56	21	21	20	19	19
57	20	24	19	19	18
61	21	22	19	18	18
68	18	18	22	21	20
70	19	19	21	19	19
72	24	24	20	20	20
75	22	28	24	23	23
77	25	25	23	23	22
78	23	24	24	24	23
84	25	26	22	22	22
85	20	23	23	23	22
86	22	24	23	22	22
89	22	20	24	22	22
91	19	20	21	20	20
92	20	21	21	20	20
93	24	26	20	21	20
96	22	26	25	24	23
98	24	27	22	22	22
100	21	23	24	23	23

Table A.2 continued.

DAY	AMBIENT	H'SPACE	UNIT 1	UNIT 3	UNIT 4
	T (^{o}C)	T (^{o}C)	T (^{o}C)	T (^{o}C)	T (^{o}C)
103	27	28	22	22	21
104	23	27	24	24	23
107	23	26	23	24	23
110	27	28	24	24	23
112	29	30	25	26	25
113	27	29	26	26	25
114	25	27	26	25	25
117	28	31	26	26	25
118	23	25	28	27	26
119	25	27	28	27	26
120	24	24	28	27	26
121	23	24	27	26	25
124	23	22	24	23	23
126	22	22	24	23	22
129	26	28	18	22	21
136	25	29	26	25	24
141	24	26	24	25	24
142	23	24	26	25	24
145	22	22	26	24	24
146	19	21	25	24	23
147	21	22	25	24	23
148	24	24	25	24	23
152	24	25	26	25	24
154	23	23	27	25	25
156	23	24	25	24	26
160	21	21	27	25	25
162	21	22	26	25	24
163	24	25	25	24	24
166	24	24	25	25	25
167	24	24	26	25	25
170	24	27	26	25	24
173	23	24	26	25	25
175	24	25	25	24	24
177	24	27	26	25	25
180	28	29	28	27	26
182	23	24	28	27	27
184	21	24	27	25	25
187	22	22	24	23	23
188	24	26	25	23	23
191	24	27	25	24	23
194	22	24	25	23	24
200	24	31	26	24	24

Table A.2 continued.

DAY	AMBIENT	H'SPACE	UNIT 1	UNIT 3	UNIT 4
	T (°C)	T (°C)	T (°C)	T (°C)	T (°C)
203	22	30	23	22	22
205	28	32	23	22	22
207	23	26	23	24	24
210	23	30	25	23	23
214	29	35	23	23	23
218	25	30	27	24	24
220	20	24	26	23	23
222	19	24	25	22	22
225	29	24	23	22	22
229	27	32	27	25	25
234	24	30	25	23	23
236	22	22	25	23	23
240	27	28	21	20	20
242	21	25	22	21	21
244	23	26	21	21	21
246	18	20	22	20	20
248	28	30	21	20	21
249	28	30	20	20	21
252	23	25	21	20	21
256	25	27	22	22	22
259	21	20	23	19	20
262	24	25	21	21	21
267	22	23	20	20	20
269	21	21	19	19	19
273	24	25	19	20	23
277	25	25	21	20	22
281	22	23	20	21	19
285	18	19	19	18	18
290	16	16	17	17	17
295	20	18	15	15	16
298	20	18	15	15	16
303	19	19	15	15	16
307	18	17	15	16	16
310	16	17	16	16	16
312	16	16	16	15	16
315	18	17	16	16	16
317	14	14	15	15	15
321	20	18	15	15	16
325	18	17	15	15	16
329	14	16	15	15	15
333	20	21	16	16	17

Table A.3 pHs in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1	UNIT 2	UNIT 3	UNIT 4	UNIT 5	UNIT 6
	pH	pH	pH	pH	pH	pH
1	5.91	6.66	7.6	6.5	6.5	7.21
2	5.66	5.89	6.1	6.68	6.08	5.84
3	5.73	5.84	5.93	6.05	5.92	5.8
4	5.68	5.79	5.84	5.97	5.92	5.73
5	5.73	5.83	5.89	5.95	5.92	5.73
6	5.71	5.78	5.85	5.87	5.89	5.72
7	5.7	5.77	5.87	5.85	5.95	5.72
8	5.74	5.78	5.88	5.89	5.9	5.71
9	5.74	5.76	5.89	5.9	5.91	5.69
10	5.76	5.77	5.89	5.9	5.93	5.66
11	5.77	5.78	5.83	5.88	5.92	5.59
12	5.71	5.75	5.82	5.86	5.96	5.57
13	5.7	5.73	5.81	5.86	5.97	5.61
14	5.68	5.67	5.77	5.82	5.91	5.55
15	5.66	5.6	5.64	5.76	5.88	5.4
16	5.78	5.6	5.6	5.8	5.9	5.4
17	5.85	5.75	5.78	6.0	6.15	5.6
18	5.8	5.67	5.67		6.01	5.67
19	5.93	5.8	5.77	6.06	6.15	5.55
20	5.8	5.8	5.7	6.1	6.2	5.6
21	5.8	5.71	5.65	6.33	6.17	5.61
22	5.94	5.92	5.78	6.46	6.1	5.64
23	5.84	5.68	5.63	6.54	6.02	5.39
24	5.79	5.6	5.57	6.78	6	5.3
25	5.8	5.6	5.55	6.93	5.98	5.2
26	5.83	5.6	5.57	7.04	5.95	5.35
27	5.72	5.51	5.46	7.09	5.8	5.21
28	5.74	5.51	5.44	6.77	5.84	5.18
29	5.69	5.49	5.43	6.81	5.98	5.19
30	5.68	5.47	5.41	6.61	5.97	5.2
32	5.81	5.6	5.51	6.92	6	5.28
33	5.71	5.4	5.39	6.72	5.99	5.11
34	5.71	5.44	5.34	6.7	6.09	5.09
35	5.7	5.48	5.4	6.71	5.97	5.21
36	5.71	5.47	5.4	6.7	5.93	5.14
37	5.72	5.49	5.39	7	5.99	5.17
38	5.73	5.53	5.42	7.05	5.93	5.15
39	5.69	5.45	5.45	6.81	5.95	5.13
41	5.68	5.48	5.43	6.77	5.9	5.19
43	5.72	5.61	5.43	6.72	5.97	5.22
44	5.73	5.53	5.47	6.75	5.94	5.21
45	5.71	5.61	5.51	6.73	5.97	5.35
46	5.67	5.48	5.57	6.74	6.02	5.23
47	5.7	5.5	5.43	6.71	5.91	5.18
48	5.7	5.61	5.58	6.73	5.97	5.2
49	5.69	5.64	5.6	6.74	6	5.4

Table A.4 COD concentrations (mgCOD/l) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 COD	UNIT 2 COD	UNIT 3 COD	UNIT 4 COD	UNIT 5 COD	UNIT 6 COD
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
1	24500	21200	16350	14500	15220	23150
2	23480	19300	19100	18150	17300	25100
3	24290	20000	20890	23640	15870	22830
4	23720	25500	21620	28255	18945	24690
5	24515	18870	21450	27900	21773	24920
6	24612	19026	21940	29307	21860	25098
7	23883	18863	22670	29390	24126	26393
8	26231	19754	24127	29793	23640	25907
9	24720	20810	22760	28910	25620	26040
10	23960	19754	19800	26232	23640	25260
11	25584	21700	24450	31900	25746	26070
12	26210	21470	23450	33450	26400	27460
13	27040	22830	26394	34812	28984	28660
14	27640	23910	28170	32990	28110	30200
15	27850	23316	26879	31089	30440	30765
16	31212	23408	30236	37714	31862	34788
17	27526	23802	28984	34813	31470	31574
18	35541	28158	29793	36800	31060	27041
19	24774	31898	35946	33436	31251	
20	29793	27526	32708	38375	35622	36108
21	30970	26890	30900	34660	35760	33450
22	28473	24417	29933	30258	33664	34314
23	32546	27041	33517	29089	37728	35784
24	31355	28136	35862	30970	35218	38041
25	33031	27860	33031	32075	35617	35940
26	29690	27094	32286	29590	37802	37477
27	32546	26393	33517	28565	36108	36918
28	32514	25754	36699	31180	39274	40884
29	32420	27400	35100	33800	35040	38150
30	34928	25593	36216	30540	34285	36216
32	35411	29295	38308	29130	31387	39596
33	33490	31710	36200	28829	38720	39440
34	36270	30927	36594	24985	40156	41128
35	32600	29640	38190	27365	35660	37190
36	34300	30724	42266	27363	35763	36901
37	34200	28620	35190	27100	36090	39250
38	33619	30355	37210	28490	38189	41126
39	33750	31200	36470	23822	35150	38490
41	35200	30400	34240	25710	34560	37760
43	32470	28700	34810	22500	35910	40060
44	29760	28160	33600	23410	37440	42560
45	31400	27100	34900	21250	38100	41700
46	32700	29150	36520	18605	38400	41560
47	31120	28480	39680	22890	39040	42240
48	33040	28490	35100	19700	36200	40970
49	27100	26449	32200	20640	36127	41933

Table A.5 $H_2CO_3^*$ alkalinities (mg/l as $CaCO_3$) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 ALK	UNIT 2 ALK	UNIT 3 ALK	UNIT 4 ALK	UNIT 5 ALK	UNIT 6 ALK
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
2	169	304	1638	3901	2926	2034
4	136	756	2143	3292	3018	2743
6	156	143	2099	294	1909	3422
8	159	94	255	164	2163	111
10	53	234	243	365	430	146
11	7	5	22	71	102	42
15	91	95	109	192	266	59
16	159	102	115	306	333	130
17	87	82	74	328	203	67
18	163	119	38	512	88	58
19	84	92	83	485	118	33
20	120	111	124	594	267	107
22	127	90	94	521	120	58
23	142	128	102	1348	372	66
24	145	84	99	1272	263	59
25	134	104	91	1697	206	66
26	111	101	62	2095	180	59
27	191	101	82	1527	320	72
28	114	86	75	1077	250	51
30	136	145	137	956	463	89
32	149	92	113	1281	333	117
34	58	71	67	845	177	47
36	107	81	101	906	177	66
38	100	98	52	1904	228	40
41	116	106	121	1604	226	89
44	167	91	138	826	355	108
47	172	94	170	551	362	117
49	121	119	175	1234	177	123

Table A.6 SCFA concentrations (mg/l as HAc) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 SCFA	UNIT 2 SCFA	UNIT 3 SCFA	UNIT 4 SCFA	UNIT 5 SCFA	UNIT 6 SCFA
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
2	6827	8061	6359	71	160	
4	10243	7042	149	253	189	2306
6	10374	8704	2021	14396	4066	997
8	11748	9695	11204	15903	3072	14169
10	12223	9256	11921	15831	11937	14662
11	12008	10587	13389	17553	12082	14087
13	10859	10659	12348	16525	11847	14069
15	12914	11604	14513	17979	13625	17760
16	11933	10701	13948	17328	13735	17811
17	11816	11715	15059	16627	14807	17783
18		11355	11511	16439	13286	14493
19	12124	11261	15585	17204	14618	16817
20	12192	11758	14891	17016	15109	17030
22	11513	11985	15142	15665	16111	18435
23	12647	12533	16286	14217	15637	19136
24	12435	13209	16627	15301	16096	20179
25	12441	13128	16922	14959	16268	18536
26	12559	13407	17205	14502	16843	20475
27	12722	13460	18961	14786	13229	19122
28	11635	12847	17769	15797	16484	20724
30	12408	13033	17213	14110	12751	19870
32	12922	14055	18485	10532	14082	18732
34	11367	12638	16567	11516	15057	18669
36	13017	13539	16932	11914	15180	18629
38	12406	12944	15319	8475	15152	19423
41	12249	14152	16146	8314	14664	20433
44	13097	14403	18040	9770	15198	21081
47	12967	14163	18768	9450	14984	20851
49	12876	14151	17705	9241	16734	21508

Table A.7 Conductivities (mhos) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 COND.	UNIT 2 COND.	UNIT 3 COND.	UNIT 4 COND.	UNIT 5 COND.	UNIT 6 COND.
	(mhos)	(mhos)	(mhos)	(mhos)	(mhos)	(mhos)
1	6.18	6.5	3.95	6.52	6.18	4.46
2	10.1	7.73	7.9	8.64	12.3	7.8
3	7.21	7.73	9.1	9.1	8.59	9.8
4	8.76	9.8	11	11.16	8.6	10.13
5	8.1	7.9	9.61	7.7	8.63	10.3
6	8.64	7.9	8.24	11.33	9.44	10.302
7	9.8	9.96	9.96	11.67	12.36	12.53
8	11.16	9.96	12.02	14.6	12.53	13.05
10	12.02	10.3	12.88	12.28	12.71	13.05
11	12.7	10.6	13.7	16.3	13.1	14.8
13	13.05	10.82	11.7	14.4	13.6	15.5
15	11.9	11.16	10.4	13.21	10.4	12.1
16	13.2	10.8	12.3	14.9	11.53	14
17	12.02	11.33	14.77	17.34	15.11	16.31
18	13.2	11.7	13.6	14	12.3	11.9
19	11.2	10.4	13	15.8	11.2	13.8
20	11.2	10.6	11.2	15.6	13.8	14.1
22	11.7	10.8	13	11.7	14	14.1
23	11.16	10.23	14.51	13.6	14.2	15.8
24	9.7	9.5	11.2	12.8	12.1	13.6
25	10	9.86	11.72	11.53	12.46	14.9
26	10.2	12.55	12.31	14.81	15.3	14.01
27	10.23	8.93	10.97	15.07	12.28	12.46
28	10.8	10.42	13.02	13.02	13.58	14.9
30	10.69	10.85	12.7	12.7	14.1	14.75
32	11	11.63	13	13.3	14.88	15.33
34	12.56	13.95	15.31	15	13.44	14.08
36	16.3	12.2	17.9	11.8	18.4	18.8
38	15.5	14.8	17.1	12.4	17.6	18.8
41	14.2	13.63	15	11.3	14.5	15
44	13.4	12.8	15.14	12.68	16.8	17.9
47	15.8	14.5	16.3	13.2	16.8	18.4
48	14.9	13.6	16	12.6	16.3	17.6
49	11.6	11.4	15.5	14.5	16	18
51	14.2	13.5	15.6	12.64	16.9	18.6
53	15.5	14.36	16.6	14.75	17.34	18.8

Table A.8 NH_4^+ concentrations in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 NH_4^+	UNIT 2 NH_4^+	UNIT 3 NH_4^+	UNIT 4 NH_4^+	UNIT 5 NH_4^+	UNIT 6 NH_4^+
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
1	388	393	610	505	424	699
2	375	482	347	531	623	578
3	491	710	913	908	764	908
4	568	741	613	887	681	797
6	831	732	869	599	771	816
8	751	670	1012	695.3	823	1074
10	887	753	1008	880	766	971
11	742	741	923	765	820	1167
13	731	857	854	776	719.7	1104
15	683.7	805	934	992	805	1128
16	700	757	1127	710	1070	1154
17	578	648	1052	1102	921	1142
18	741	877	955	817.1	921	1375
19	862	940	1121	903	832	1241
20	831	868	1298	1036	871	1356
22	828	908	1290	875	1019	1261
23	809	800	1234	746	926	1246
24	802	878	1312	891	967	1291
25	824	898	1324	804	1030	1258
26	819	883	1282	736	1070	1320
27	799	883	1345	716	994.8	1206
28	756	700	1315	697	985	1261
30	812.2	762.4	1214.4	643.6	824.4	1334.8
32	1000	906	1241	585	799	1114
34	816	906	1181	554	885	1219
36	812	874	1154	218	750	1086
38	778	846	1098	218	880	1103
41	862	717	1014	179	739	1014
44	504	946	778	196	722	991
47	767	678	610	414	711	958
48	862	723	825	392	758	1020
49	801	694	930	381	846	1036

TABLE A.9 TKN concentrations (mgN/l) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 TKN	UNIT 2 TKN	UNIT 3 TKN	UNIT 4 TKN	UNIT 5 TKN	UNIT 6 TKN
	(mg/N/l)	(mg/N/l)	(mg/N/l)	(mg/N/l)	(mg/N/l)	(mgN/l)
2	385.6	506	690	641	622	781
4	630	752	1020	986	812	769
6	876	620	912	936	1076	1042
8	755	810	1140	826	672	1120
10	950	734	998	1005	1081	1022
11	940	808	1006	1132	767	934
13	860	820	972	1391	1137	1185
15	774	919	1165	1250	1052	1482
16	886	804	1314	1227	1284	1202
17	716	858	1212	985	1079	1704
18	1046	814	1117	973	1040	1295
19	905	930	1315	1126	1104	1539
20	1016	1091	1459	1240	946	1485
22	996	997	1357	934	1130	1324
23	1052	1023	1420	1062	1146	1575
24	857	1074	1543	1033	1146	1575
25	1126	1163	1509	986	1180	1477
26	1106	1004	1363	879	1148	1508
27	803	895	1419	773	1062	1370
28	1104	930	1375	881	1210	1171
30	820	1051	1340	819	938	1370
32	1191	1135	1454	694	1072	1454
34	1215	1123	1386	828	1090	1381
36	1090	1170	1252	524	1004	1442
38	910	1094	1296	635	978	1253
41	1036	952	1208	515	817	1136
44	795	857	1243	498	890	1142
47	918	952	862	554	627	1299
49	1066	1098	1366	594	918	1372
51	1098	1221	482	538	493	1366

Table A.10 PO$_4^{3-}$ concentrations (mg/l) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 PO$_4^{3-}$	UNIT 2 PO$_4^{3-}$	UNIT 3 PO$_4^{3-}$	UNIT 4 PO$_4^{3-}$	UNIT 5 PO$_4^{3-}$	UNIT 6 PO$_4^{3-}$
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
1	80	66	107	106	89	84
2	84.3	70.3	179	109	102	170
3	75	73	137	134	111	163
4	68	185.9	115	126	122	106
6	75.1	86	42	28.5	29	28
8	29	9.08	32	38	33	32
10	25.7	35.3	34	33	28	29.8
11	34.4	27.4	66	20	8.6	19.5
13	39.7	14.1	32.9	30.4	47	41
15	50.9	30.8	10.5	11.6	5	29
16	29.9	26	17.2	5.4	34.1	26.5
17	23.7	21.1	37	32.9	27.5	35.8
18	26	27.7	30	30	31.9	32.3
19	23.5	18.6	21	31	22	30
20	31.5	9.31	34.5	15.4	19	44
22	26.84	29.6	25.9	10.36	19	49
23	20.7	24.4	34.2	8.8	12	47
24	18.92	16.54	34.3	16	18.9	43.9
25	22.3	18.4	29.2	16.1	20.8	47.9
26	25.5	22.5	32.8	15.9	30.9	54.8
27	29.1	32.3	35.4	17.8	52.64	69.96
30	24	3.5	12.1	14.3	28.8	65.5
32	27.3	35.1	50	26.4	10	52
34	25	8.3	33.7	25.1	16.4	41.1
36	35.6	15.6	54	28	14.4	30
38	8.88	7.76	50.3	44.4	20	31.1
41	22.2	43.3	41.1	10	33.3	40
44	42.2	10	38.6	7.7	13.3	22.2
47	15.6	5.6	62.2	12.1	11.1	30
48	25.6	26.7	54.4		21.1	33.3
49	16.7	16.7	25.6	8.9	30	37.8

Table A.11 SO$_4^{2-}$ concentrations (mg/l) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 SO$_4^{2-}$	UNIT 2 SO$_4^{2-}$	UNIT 3 SO$_4^{2-}$	UNIT 4 SO$_4^{2-}$	UNIT 5 SO$_4^{2-}$	UNIT 6 SO$_4^{2-}$
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
2	400	364	8.4	8.4	0	
3	444	231	231	418	0	507
4	507	186	160	329	0	471
5	515	44.3	311	195	0	435
6	506		355	390	0	489
7	498	62	80	311	0	684
8	471	133	111	311	0	684
10	684	311	453	649	293	898
11	844	311	826	844	346	844
13	668	312	576	684	64	576
15	311	400	62	293	0	507
16	586	133	177	372	0	567
17	595	133	9	347	0	506
18	275	435	80	524	0	275
19	471	80	62	115	0	471
20	489	258	0	133	0	506
22	435	26	80	0	0	382
23	311	98	62	0	0	542
24	524	115	0	0	0	595
25	346	151	80	0	0	595
26	506	186	0	0	0	489
27	524	204	115	0	0	524
28	420	98	0	0	0	506
32	418	133	133	0	0	418
34	347	151	62	0	0	418
36	382	62	120	0	0	435
38	755	120	151	0	0	392
41	437	186	95	0	0	453
44	352	80	133	0	0	738
47	684	169	98	0	0	449

Table A.12 Ct concentrations (mg/l) in the leachates from the six lysimeters during the 50 week investigation.

WEEK	UNIT 1 Ct	UNIT 2 Ct	UNIT 3 Ct	UNIT 4 Ct	UNIT 5 Ct	UNIT 6 Ct
	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)	(mg/l)
2	551	738	1495	3589	2607	1861
4	531	977	2102	3178	2809	2763
6	589	377	2114	676	1951	3614
8	633	318	518	452	3072	444
10	288	816	792	937	1017	762
11	39	27	118	270	242	321
13	808	937	1824	2503	1891	2471
15	318	438	520	668	645	464
16	634	521	577	887	692	888
17	359	447	422	727	408	558
18	441	484	339	582	470	345
19	323	473	494	1009	271	331
20	419	511	685	731	525	894
22	443	407	573	624	283	485
23	510	644	645	1406	835	676
24	505	438	601	1367	581	603
25	473	531	656	1796	481	678
26	369	605	407	2189	436	648
27	632	578	501	1623	868	737
28	337	531	542	1207	631	594
30	473	770	861	1127	794	837
32	517	528	758	1649	702	1200
34	233	467	560	1369	424	640
36	425	534	779	697	413	788
38	437	609	434	2093	518	576
41	455	631	720	900	459	1036
44	691	552	1042	1179	706	1203
47	697	574	1181	1363	711	1363
49	482	737	1238	1279	332	1487

Table A.13 Volume of gas produced (l/ day), average volume of gas produced (l/week) and % composition of gas from unit 4 during methanogenesis.

DAY	VOL/DAY (l)	AVE VOL/ WEEK(l)	%CH_4
3	35.8	35.80	
4		35.80	
5		35.80	
6		35.80	
7	42	38.90	
8		38.90	
9	29.4	35.73	
10		35.73	
11	39.3	36.90	
12		36.90	
13		36.90	
14		36.90	
15	45.9	38.20	
16		38.20	
17	49	44.73	
18	36.1	42.58	
19		43.67	
20		43.67	
21	30.8	40.45	
22		40.45	
23		38.63	
24		38.63	
25	43.3	36.73	
26		37.05	
27		37.05	
28	40.5	38.20	
29		41.90	
30		41.90	
31	37.2	40.33	
32		40.33	
33		38.85	
34		38.85	
35		38.85	
36	37.3	37.25	
37		37.25	
38	57.6	44.03	
39		47.45	
40		47.45	
41		47.45	

Table A.13 continued

DAY	VOL/DAY (l)	AVE VOL/ WEEK(l)	%CH_4
42	49.5	48.13	
43		48.13	
44		53.55	
45		53.55	
46	56	52.75	
47		52.75	
48		52.75	
49		52.75	
50	68.9	62.45	
51	61.8	62.23	
52	60.2	61.73	
53	61.4	61.66	
54		63.08	
55		63.08	
56	43.5	59.16	
57	56.5	58.72	
58	68.1	58.58	
59	45	55.78	
60		54.90	
61		53.28	
62		53.28	
63	42.4	51.10	
64		53.00	
65	66.9	55.60	
66	38	48.08	
67	34.1	45.35	
68		45.35	
69		45.35	
70	36.7	43.62	
71		43.93	
72	46.9	44.52	
73		38.93	
74	37.2	38.73	
75		40.27	
76		40.27	
77	47.7	42.13	
78	50.8	45.65	
79	29.5	42.42	
80		41.30	
81		41.30	
82		42.67	
83		42.67	
84	39.5	41.88	53

Table A.13 continued

DAY	VOL/DAY (l)	AVE VOL/ WEEK(l)	%CH_4
85		39.93	
86		34.50	
87		39.50	
88	33	36.25	
89		36.25	
90		36.25	
91	35	35.83	52
92	31.2	33.07	
93		33.07	
94		33.07	
95	33.5	33.18	54
96		33.23	
97		33.23	
98	31.5	32.80	
99	49.3	36.38	
100		38.10	
101		38.10	
102	33.6	36.98	48
103		38.13	
104		38.13	
105	33.6	37.00	
106		38.83	
107		33.60	
108		22.40	
109	41.2	27.10	
110		24.93	
111		24.93	
112		24.93	
113	51.5	30.90	55
114		30.90	
115		30.90	
116	32.8	41.83	
117		42.15	
118		42.15	
119	34.7	39.67	57
120		39.67	
121	30.9	32.80	
122		32.80	
123	35.4	33.45	49
124		33.67	
125		33.67	

Table A.13 continued

DAY	VOL/DAY (l)	AVE VOL/ WEEK(l)	%CH_4
126		33.67	
127	29.9	32.07	
128		32.07	
129		32.65	
130		32.65	
131	26.4	28.15	55
132	25	27.10	
133	54.1	33.85	51
134	54.4	37.96	
135		39.98	
136		39.98	
137	47.5	41.48	60
138		41.48	
139		45.25	
140	34.2	47.55	49

APPENDIX B

FIGURES OF THE RESULTS FROM TABLES A.4 TO A.13 IN APPENDIX A

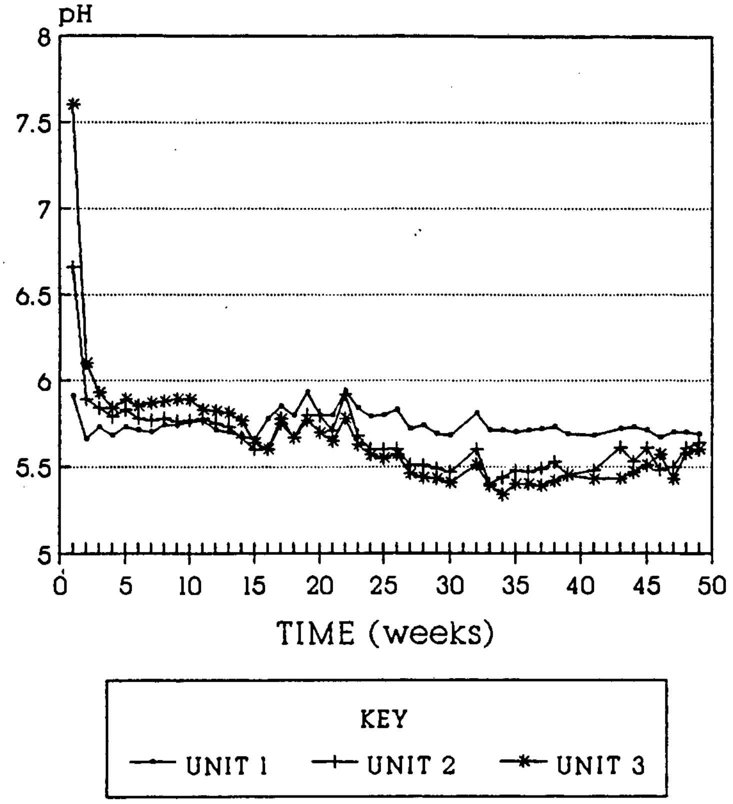

Fig B.1a pH in leachates from units 1, 2 and 3 during the 50 week investigation.

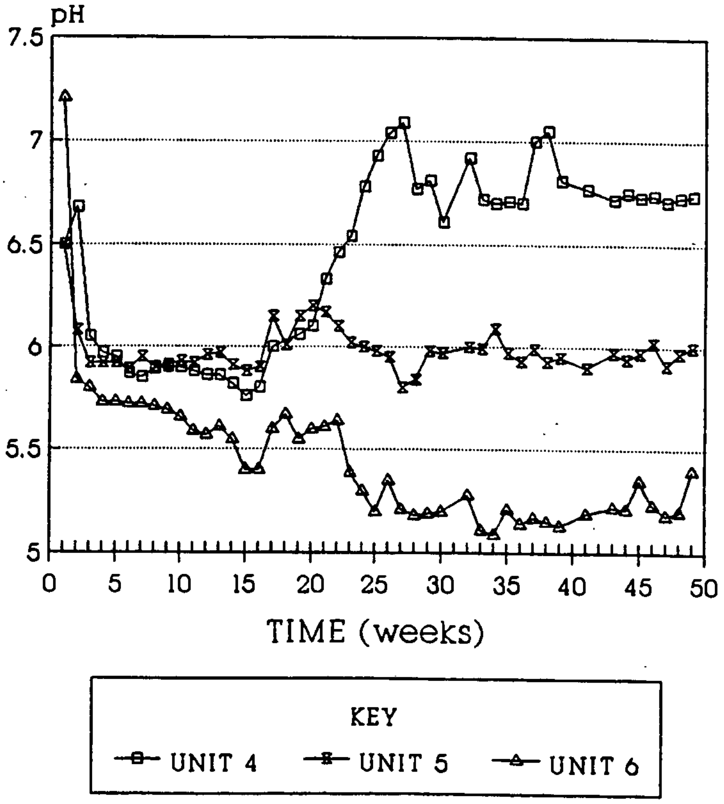

Fig B.1b pH in leachates from units 4, 5 and 6 during the 50 week investigation

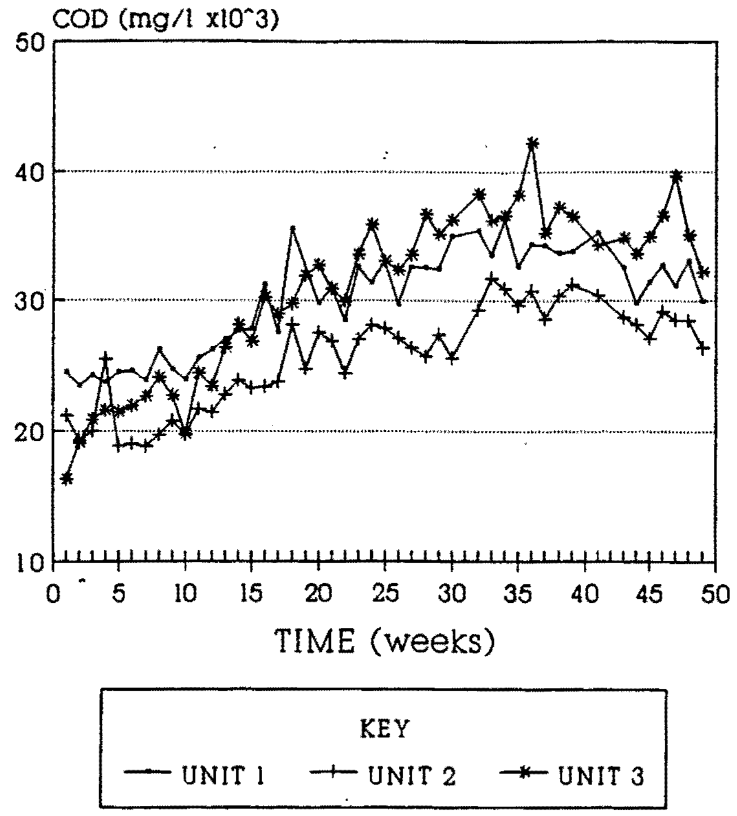

Fig B.2a COD concentrations (mg/l) in leachates from units 1, 2 and 3 during the 50 week investigation.

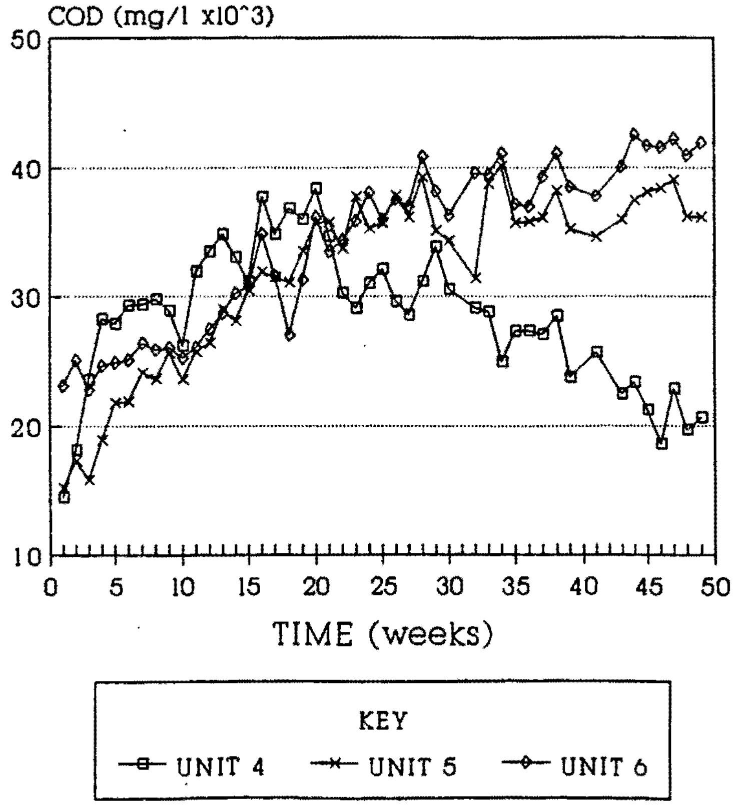

Fig B.2b COD concentrations (mg/l) in leachates from units 4, 5 and 6 during the 50 week investigation

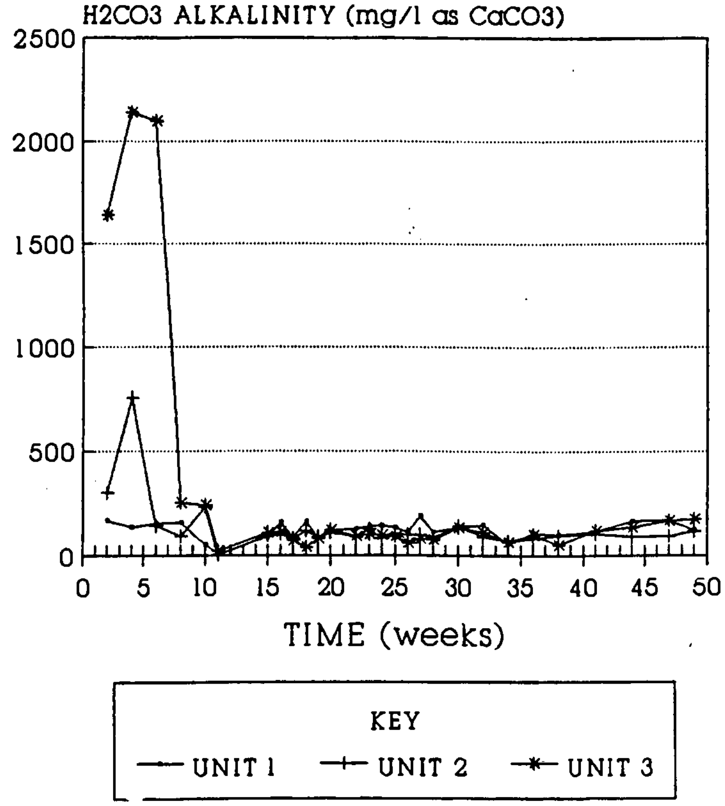

Fig B.3a $H_2CO_3^*$ alkalinity (mg/l as $CaCO_3$) in leachates from units 1, 2 and 3 during the 50 week investigation.

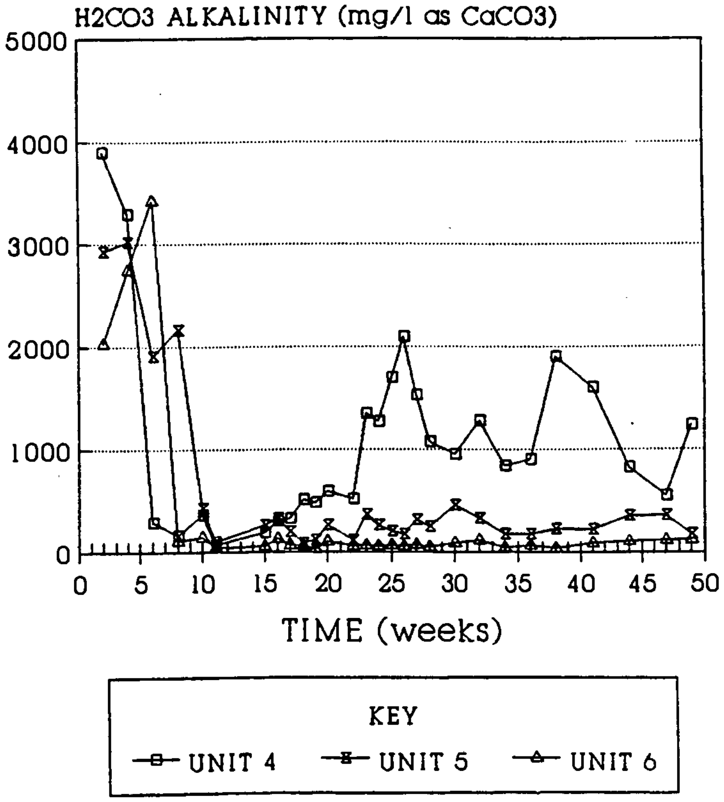

Fig B.3b $H_2CO_3^*$ alkalinity (mg/l as $CaCO_3$) in leachates from units 4, 5 and 6 during the 50 week investigation

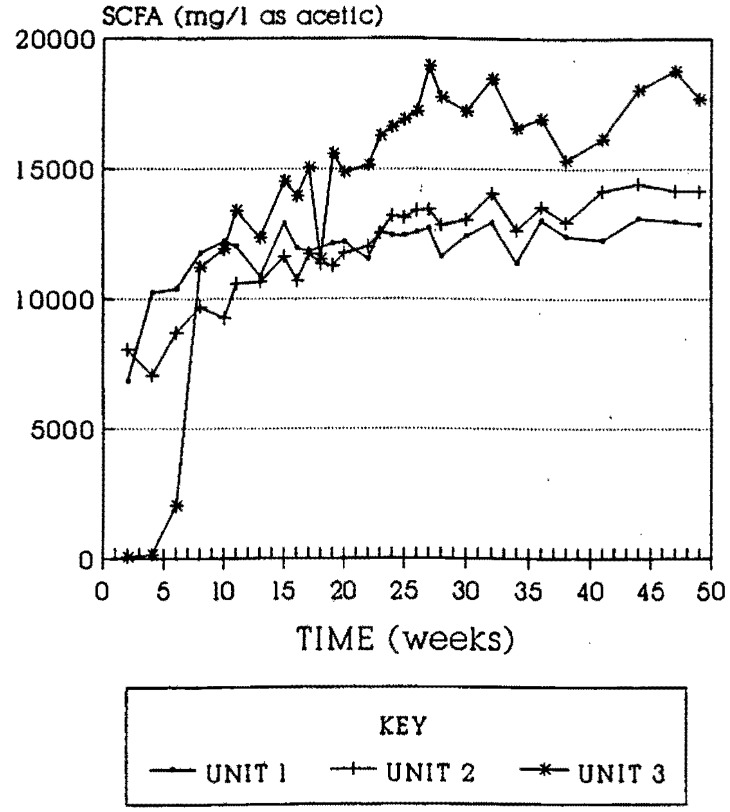

Fig B.4a SCFA concentrations (mg/l as HAc) in leachates from units 1, 2 and 3 during the 50 week investigation.

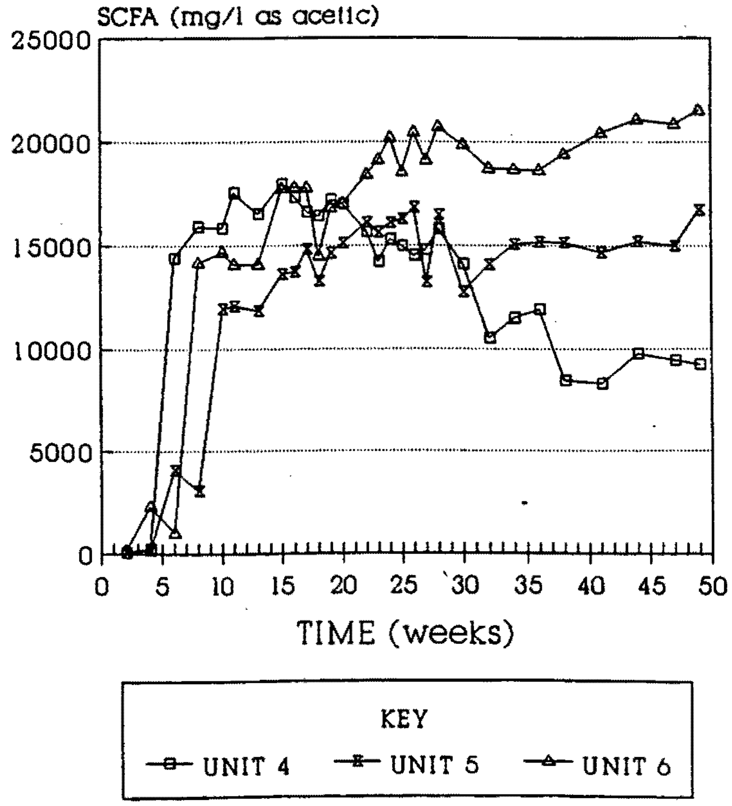

Fig B.4b SCFA concentrations (mg/l as HAc) in leachates from units 4, 5 and 6 during the 50 week investigation.

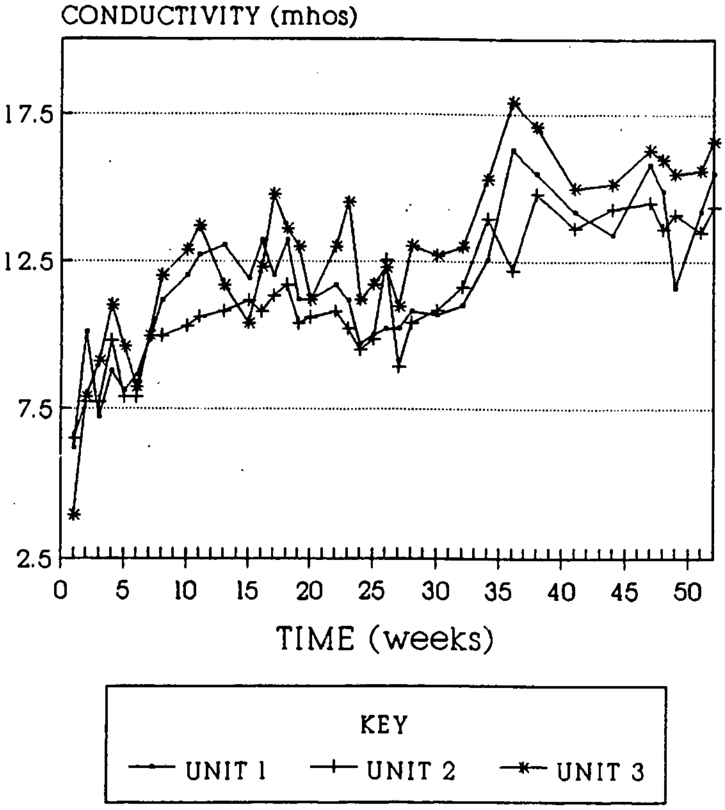

Fig B.5a Conductivities (mhos) in leachates from units 1, 2 and 3 during the 50 week investigation.

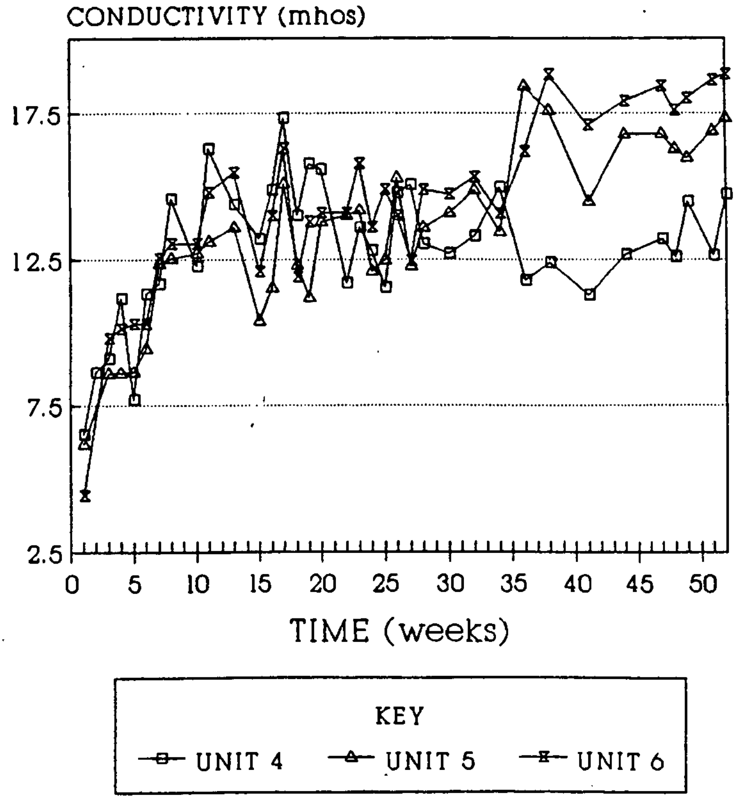

Fig B.5b Conductivities (mhos) in leachates from units 4, 5 and 6 during the 50 week investigation.

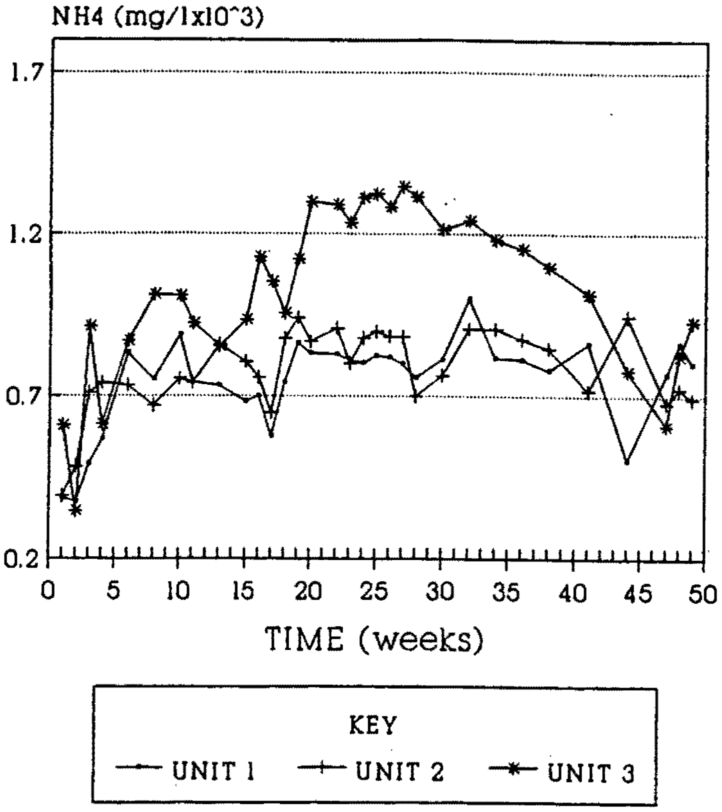

Fig B.6a NH_4^+ concentrations (mg/l) in leachates from units 1, 2 and 3 during the 50 week investigation.

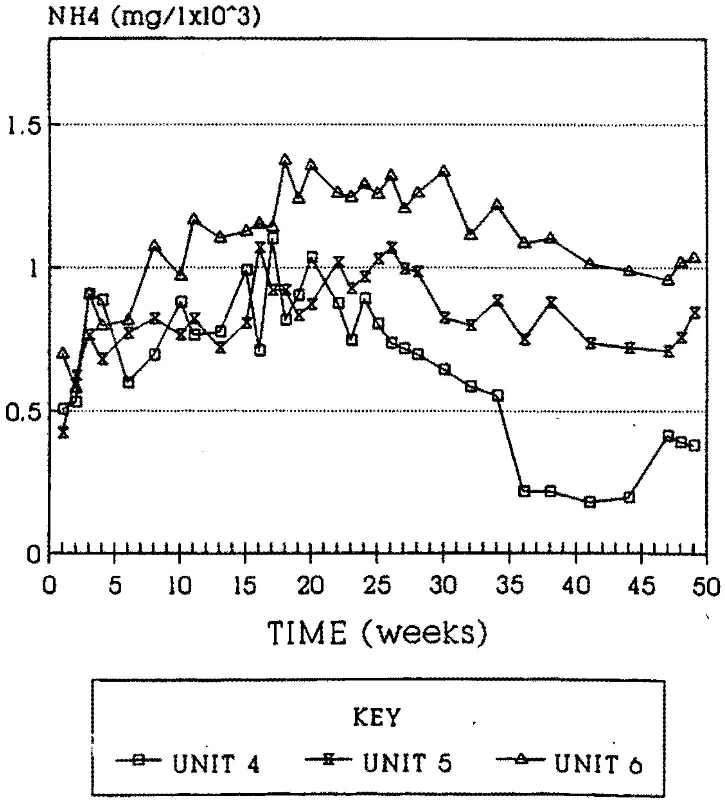

Fig B.6b NH_4^+ concentrations (mg/l) in leachates from units 4, 5 and 6 during the 50 week investigation.

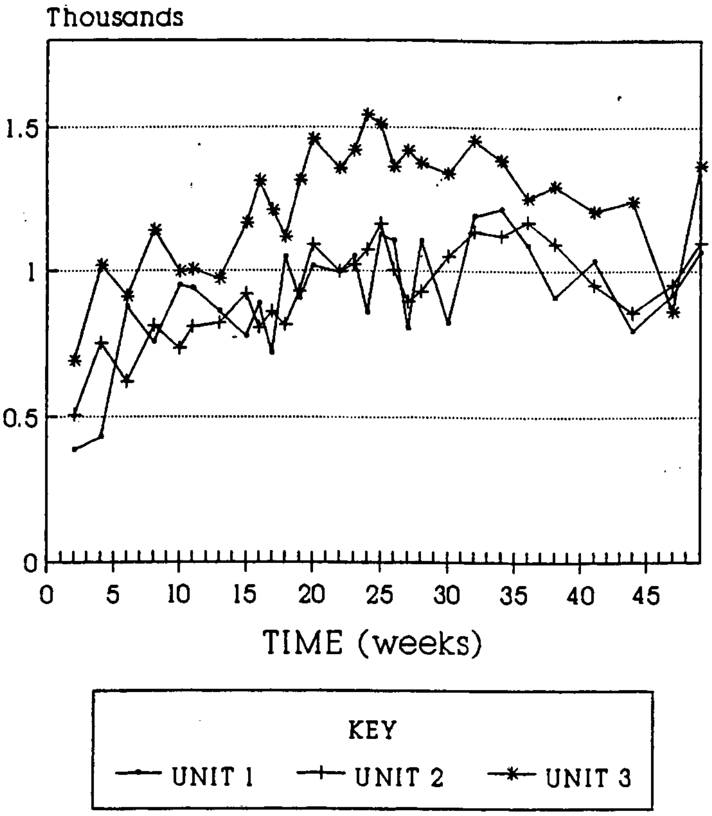

Fig B.7a TKN concentrations (mgN/l) in leachates from units 1, 2 and 3 during the 50 week investigation.

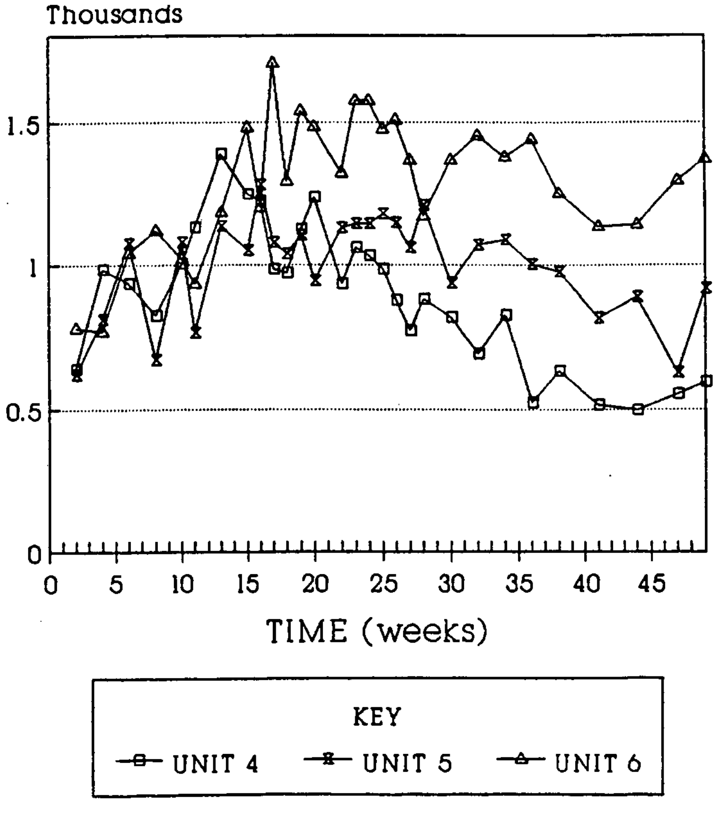

Fig B.7b TKN concentrations (mg/l) in leachates from units 4, 5 and 6 during the 50 week investigation.

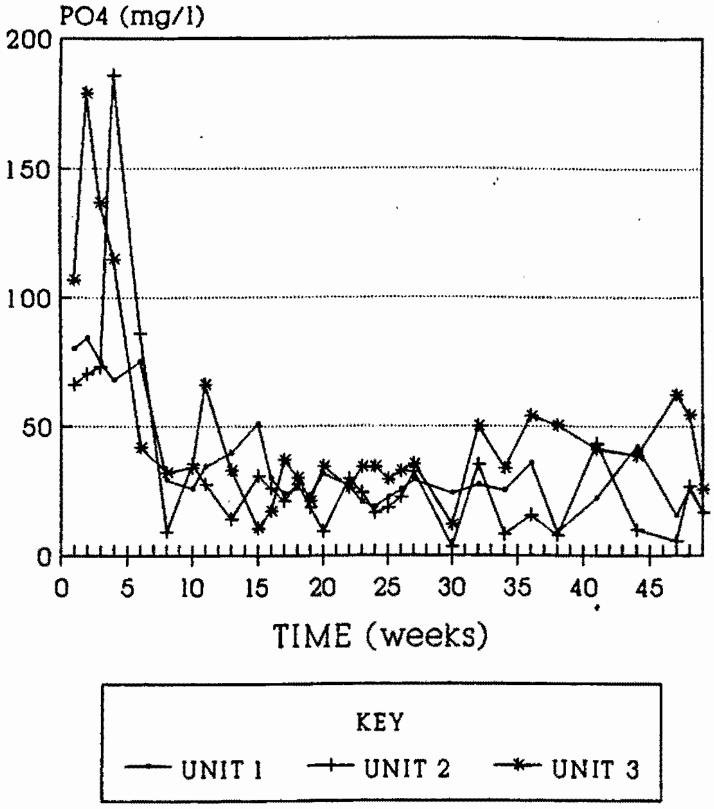

Fig B.8a PO_4^{3-} concentrations (mg/l) in leachates from units 1, 2 and 3 during the 50 week investigation.

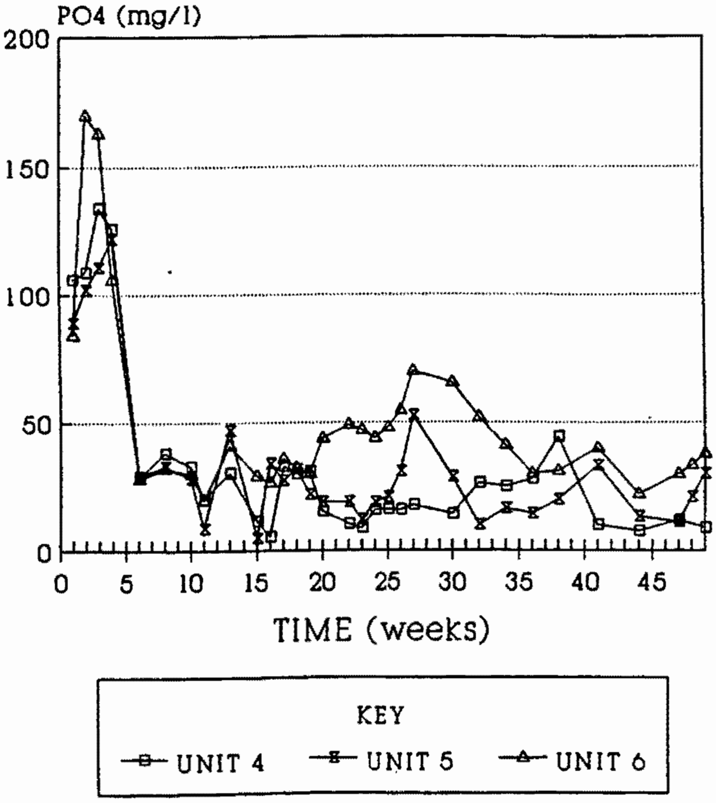

Fig B.8b PO_4^{3-} concentrations (mg/l) in leachates from units 4, 5 and 6 during the 50 week investigation.

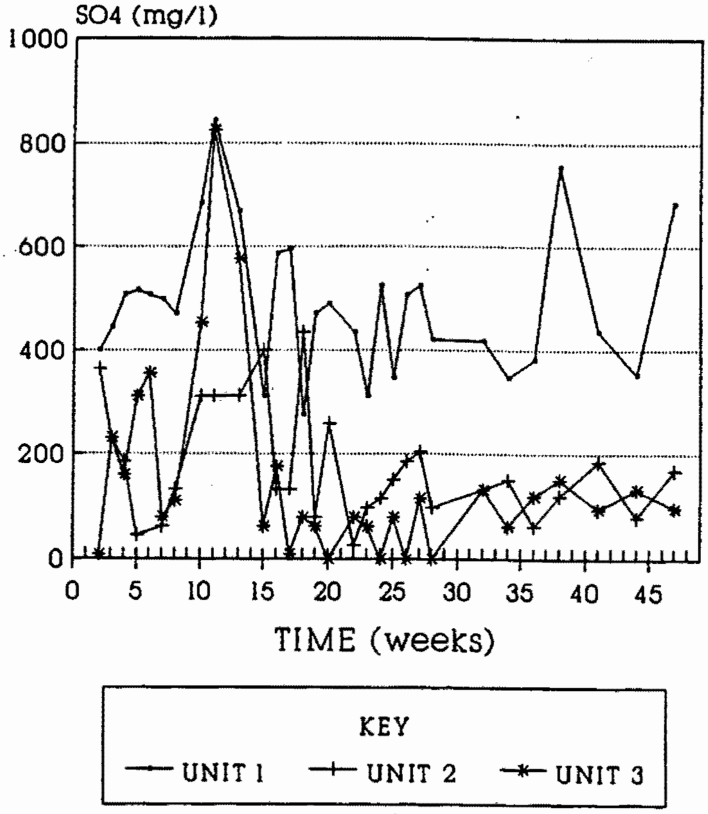

Fig B.9a SO_4^{2-} concentrations (mg/l) in leachates from units 1, 2 and 3 during the 50 week investigation.

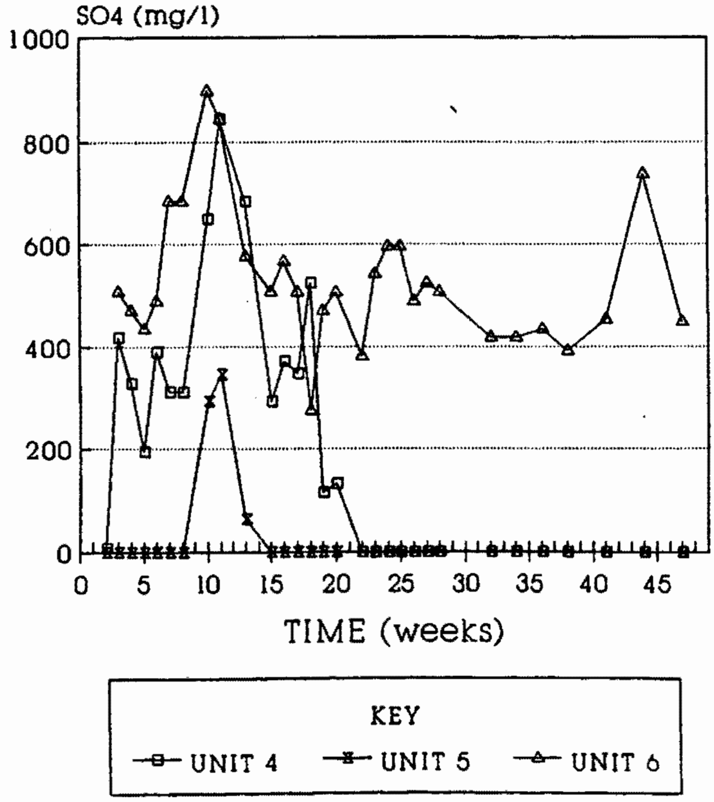

Fig B.9b SO_4^{2-} concentrations (mg/l) in leachates from units 4, 5 and 6 during the 50 week investigation.