MONITORING LEACHATE AND BIOGAS EMISSIONS FROM EXISTING EXPERIMENTAL FIELD CELLS

AB Fourie · JWF Morris

WRC Report No. 995/1/02

Water Research Commission

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Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The work described in this report is a follow-up to an earlier Water Research Commission (WRC) funded project. This earlier project dealt with the construction and commissioning of four field test cells at the Weltevreden landfill. One cell (Cell 1) was filled with refuse from a typical middle class suburb and contained a large proportion of paper and putrescibles. Another cell (Cell 4) was filled with refuse from an informal settlement and consisted primarily of ash and dust, while the remaining two cells (Cells 2 and 3) were filled with blends of these two waste streams. The project ended in December 1998 and by that time only 14 months of data had been collected. These results indicated very little generation of leachate had occurred and in order to maximise the benefit of the money spent on constructing the cells a proposal was submitted to the WRC to continue monitoring the cells for a further two years. This proposal was accepted by the WRC and this report describes the results of this extended period of monitoring.

The intention had been to monitor quantity and quality of both leachate and biogas emissions. A static accumulation chamber was used to attempt to detect biogas emissions through the covers of the test cells but negligible emissions were detected on all testing occasions. The bulk of the useful data collected was thus the leachate data. For the first 2 years of monitoring, the quantities of leachate produced by all four cells were minimal, being less than 3% of the precipitation.

After approximately 930 days however, a significant change in the quantity of leachate generated by Cell 1 occurred. Substantially larger volumes of leachate began to be collected and the total leachate volume from Cell 1 soon overtook the other 3 cells. By the end of the study, Cell 1 had been subjected to about 0.05 pore volumes of flow, while for the remaining cells only about 0.015 pore volumes of flushing had occurred. While the volume of leachate generated by Cell 1 increased dramatically, the generation rates from the remaining 3 cells remained fairly constant. The reasons for the differences in behaviour are attributed to preferential flow occurring within Cell 1, whereas the presence of ash in the other cells tends to prevent this occurring and also improves the moisture retention capacity of the waste. The implication for the practice of landfilling in South Africa is that by blending ash-rich waste with the remainder of the waste stream, the hydraulic characteristics of the waste can be improved, ultimately resulting in reduced leachate volumes.

By the end of the study the quality of the leachate being generated by all cells still showed no sign of reaching an acceptable quality. The concentration of chloride in the leachate from all cells showed a gradual decline in concentration with increasing proportions of pore volumes flushed, but still appeared to be a long way from reaching acceptable concentrations. Chloride, being non-degradable, is often considered to constitute an ideal tracer in ground water and an extremely useful indicator of the changing strength of landfill leachate. In the present study it was estimated that approximately 28 years would be needed to flush the waste in Cell 1 to an acceptable state of degradation. Considering that the height of waste in Cell 1 started off as slightly greater than 1m (and has inevitably decreased with time), it is suggested that a conservative estimate of the time needed to bring a full-scale landfill in a semi-arid climate to an acceptable stage of degradation would be given by assuming that 28 years were needed for every 1m thickness of waste deposited. For many of our urban landfills, that have 20m or more of stored waste, this is clearly an unacceptable condition. We cannot condone the establishment of a source of potential contamination that may be expected to constitute an environmental and health hazard for up to 600 years after closure. Concentrations of ammonia in the leachate from all four cells indicates an even more severe problem. In Cell 1for example, even after 0.05 pore volumes of flushing, the ammonia concentration was still increasing. The estimate of 28 years to achieve acceptable leachate quality that was derived from changes in chloride concentrations measured to date is unlikely to be sufficient to ensure the same goal is achieved for ammonia concentrations.

The primary, and most useful outcome of the work performed in this study is thus to raise concerns about the long-term viability of our current approach to landfilling in semi-arid parts of the country. By encapsulating the waste and maintaining it at a relatively low moisture content, the effect is to retard biological degradation processes and thus effectively retain the polluting potential of the stored waste.

However, the waste cannot be isolated from the ingress of moisture in perpetuity and once moisture begins infiltrating into the stored waste (eg through a damaged or poorly maintained cover system), the process of biological degradation, with associated generation of highly contaminated leachate, will begin again. Current legislation in South Africa requires that a landfill and its surrounding environment (eg adjacent groundwater) be monitored for a period of 30 years after closure, to ensure the environmental and health risks posed by the landfill are not unacceptable. The problem with this approach in a semi-arid climate appears to be that even after this period of aftercare the landfill may in fact be many years from achieving a stable and acceptable state. In short, it may still have a very large proportion of its initial contaminating potential.

The major conclusion to be drawn from this ongoing study is that an urgent re-think is required on current provisions for post-closure monitoring of municipal solid waste landfills in South Africa. In addition, we should be investigating techniques of accelerating the decomposition of refuse within the landfill in order that the contaminating potential of the stored refuse can be reduced to acceptable values within the operational and reasonable post-closure period. If this issue is not addressed now, it is suggested that we will inevitably be forced to revisit it sometime in the future when today's landfills become tomorrow's sources of environmental contamination.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

The pragmatic South African system of graded standards for waste disposal (the Minimum Requirements) already take cognisance of the lower pollution potential posed by small landfills in relation to larger ones, and of the argument that landfills in semi-arid climatic regions will be water deficient and are hence unlikely to produce significant volumes of leachate. In terms of the latter issue, it is accepted by the Minimum Requirements that any landfill has the potential to generate sporadic leachate in excessively wet weather conditions, but that such sporadic leachate generation will not impact adversely on the environment due to the ability of attenuation mechanisms in the receiving media to deal with the escape of small quantities of contaminants (Blight, 1999). Recent research in developed countries on transport mechanisms through landfill barrier systems and leachate attenuation mechanisms, coupled with the recognition that some of the strategies for waste containment (such as the dry tomb landfill) are unwarranted and far too costly (Cit in Blight, 1999), is leading towards moderation of the draconian US and EU regulations and burgeoning interest in approaches to landfill design such as those developed by South Africa.

With regard to the issue of landfill size, studies of waste generation rates (WGRs) show that rich and poor communities of comparable size produce very different quantities of waste. As a result, landfills serving predominantly poor communities will be smaller, grow more slowly, have a longer service life and thus represent a smaller or less rapidly accumulating source of potential pollution than a landfill serving a rich community (Blight, 1996). The Minimum Requirements take account of this by classifying the size of a landfill in terms of the rate of deposition expected at the end of its life.

Waste from poor communities which use coal as their main source of fuel for heating and cooking contains high levels of ash and low levels of putrescible matter. Most research work to date on landfill processes and products, on which international standards of landfilling with regard to design, construction, operation and closure are based, has been carried out on rich waste, that is waste from industrialised countries and communities. Such waste is characterised by high levels of putrescible matter and other organic materials such as paper. It was felt that landfilling of poor waste will produce less concentrated leachate and lower volumes of biogas than rich waste due to its low putrescible content. In addition, and perhaps far more importantly, previous studies (Cit. in Shamrock, 1998) have shown that co-disposal of coal ash with refuse accelerates the biodegradation of the organic fraction of the waste which results in earlier establishment of methanogenic conditions in a landfill, with associated advantages. The properties of the ash component of poor waste which contribute to this are a high pH and acid neutralisation (buffering) capacity which have been shown (Rees, 1980) to aid in the provision of a favourable environment for methanogenic bacteria. In addition, the high bulk density of ash could also significantly improve the hydraulic properties of the waste as a whole. Finally, the high pH could also have the effect of immobilising heavy metals and thus improving leachate quality. However, it is possible that the ash might contain levels of contaminants such as soluble sulphates and other salts in quantities in excess of those found in rich waste (Blight, 1996), and that as such leachate from poor waste could be as much of a cause for concern as it is with rich waste. It is therefore necessary to ascertain at what ratio of ash content to putrescible material landfill degradation of waste

proceeds differently, if indeed any differences are observed at all, and to assess whether such differences are noteworthy should they occur.

It could be argued that the composition of waste in communities that currently burn coal is set to change, as the Government of South Africa has instigated ambitious electrification schemes. In 1996, however, 45 % of South African houses were still not electrified, and this figure was over 73 % for rural homes (NER, 1996). Even amongst communities now connected to the electricity grid, electrical power is often used only for lighting and running appliances such as televisions, while most cooking and heating systems are still fuelled by traditional means (NER, 1996). The production of high ash, low putrescible content waste by many poor communities in South Africa is therefore likely to continue for some time.

An estimated 85 % of MSW generated in South Africa is landfilled (Lumby, 1996), with the remaining 15 % unaccounted for as a result of being generated by rural communities or informal settlements with inadequate waste collection and disposal facilities (Bredenhann, 1998b). This compares with a worldwide average figure of about 80 % in 1990 (Cit. in Lumby, 1996).

In contrast to the situation in developed countries, few alternatives to landfilling are thought to be economically viable in South Africa, although small scale incineration of certain wastes such as those produced by medical institutions is carried out. Some interest in composting has been expressed (Liebenberg, 1998), especially of the large and easily separable component of garden wastes arising from rich communities. Some pilot garden waste composting schemes have been set up with modest success. It has been predicted that 5 of the 9 South African provinces, including Gauteng, will have shortages in available landfill headspace within the next 10 years (Feris, 1999). Whether this will cause an expansion of recycling efforts, at present not at high levels (McLean, 1998), interest in alternative disposal options or, most likely, acquisition of new sites for landfilling remains to be seen. Landfills certainly seem set to dominate waste disposal in South Africa for the foreseeable future.

The generally poor state of solid waste management and disposal in economically developing countries is well documented along with many reasons for short-comings and possible solutions (Savage et al., 1998; Ali et al., 1999). The need for clear direction in terms of administrative and legislative responsibility by their governments and regulators has also been clearly defined (Campbell & Frost, 1997; Hojem, 1997). South Africa has taken important steps towards the development of appropriate, realistic and pragmatic methods of achieving sustainable and reliable environmental protection measures. The potential for exporting the landfill regulatory approach developed here in South Africa to countries with similar waste production characteristics and/or climates, such as other African nations or China, is considerable. Such approaches will surely have more chance of success than the wholescale 'borrowing' of methods recommended by resource rich, industrialised countries.

1.1 Previous study funded by Water Research Commission

When the Department of Water Affairs and Forestry (DWAF) set out in 1990 to formulate a framework of legislation to regulate waste disposal by landfill in South Africa, it recognised that much of the country was

arid or semi-arid and that communities in developing areas tended to have small landfills and could ill-afford the costs associated with the environmentally acceptable waste disposal methods favoured by developed countries in Europe and North America. Establishing appropriate affordable landfill standards for disadvantaged communities which would reflect socio-economic and climatic conditions while still providing acceptable levels of environmental protection was the challenge that presented itself. To address this, the DWAF produced a set of graded standards governing waste disposal. These took the form of Minimum Requirements documents, the first edition of which were released in 1994.

In response to the challenge presented by the philosophy laid out in the Minimum Requirements, and on the back of over 10 years of research into the behaviour of landfills in semi-arid climates (Ball, 1984; Hojem, 1988; Blight, 1992; Vorster, 1994; Roussev, 1996) which had contributed greatly to that philosophy, the Department of Civil Engineering at Wits submitted a research proposal to the Water Research Commission of South Africa in 1994 (Project K5/670). In the proposal, two main aspects of the Minimum Requirements approach were investigated (Blight & Fourie, 2000):

i) The climatic water balance procedure embodied in the Minimum Requirements needed further investigation to justify it, in particular how it would stand up to application at small rural landfill sites where control, compaction and covering were of a low standard.

ii) It was known that the composition of waste generated by poor communities was very different to that generated by rich communities. Would the Minimum Requirements prove adequate and suitable for both waste types?

The three primary topics addressed in the above study that are of relevance to this report were a waste characterization study, construction and monitoring of two small 'mini-landfills' on the campus of the University and construction and monitoring of four large test cells at the Weltevreden landfill. Brief details of these studies are summarized below and more detailed descriptions may be obtained from Blight and Fourie (2000).

1.1.1 Waste composition

Waste composition studies were carried out for two communities, Ratanda and Heidelberg, which have low and higher income communities respectively. The low income community, which relied primarily on coal and wood burning for cooking and heating, was found to produce a large proportion of ash and dust, irrespective of the season. The higher income community of Heidelberg produced waste that was similar to that usually found in developed countries. There was always in excess of 60% of paper plus putrescible (or biodegradable) matter.

Unfortunately when the time came for construction of the field cells, permission could not be obtained to site these cells at the landfill serving the communities of Heidelberg and Ratanda. An alternative site was secured at the Weltevreden landfill which serves Wattville, a poor community, and Benoni, a higher income area (amongst many others). The two new areas fortunately produced waste that was very similar to the

original characterization study at Heidelberg and Ratanda. This waste was thus used to fill both the small 'mini-landfills' and the Weltevreden field cells.

1.1.2 'Mini-landfills'

These small scale field experiments were constructed on the campus of the University of the Witwatersrand and consisted of two 3.3m^3 containers, 3.12m^2 in plan area and 1.06m deep, constructed of vertical double brick walls with concrete floors sloped towards the front of the container. Further details are given in Shamrock (1998). One cell was filled with waste from Wattville and the other with waste from Benoni. There was thus no blending of the two wastes.

Monitoring of leachate from these 'mini-landfills' for three years indicated a definite difference in quality. The high biodegradable content waste from Benoni produced leachate with higher contaminant loads than the low biodegradable content waste from Wattville. The differences at that time were not excessively large. Due to the relatively small volumes of liquid that had passed through these cells at the time, it was considered necessary to continue monitoring for at least another two years.

1.1.3 Large field cells at Weltevreden landfill

Four large field cells were constructed at the Weltevreden landfill. These initial cells had their bases at the level of the natural ground surface. Each cell had a volume of placed refuse of about 35m^3. One cell was filled with Benoni waste only, one with Wattville waste only and the remaining two cells with 64%:36% and 44%:56% blends (on a wet weight basis) of the Benoni and Wattville wastes respectively.

Unfortunately an exceptionally wet year resulted in the leachate collection outlets for the cells (which were in manholes below ground level) becoming flooded shortly after the cells had been completed and filled. The unusually wet weather also caused the groundwater to rise, resulting in the outlets being flooded for nearly two years after the cells were completed. A year later a second tier of four cells was constructed on top of the original cells, with the two tiers of cells separated and isolated from one another with HDPE (high density polyethylene) geomembranes. The same waste compositions were used to fill the upper tier of cells.

Due to the weather induced delays and the need to construct another tier of cells, by the end of the period of this study, only very preliminary data was available from these cells. For example, less than 1mm of equivalent leachate had been generated in any of the four cells.

Having spent a large amount of both time and effort establishing the field test cells at Weltevreden landfill, but having (at that time) very little data a proposal was submitted to Water Research Commission to continue monitoring the cells for a further two years, with a view to obtaining a greater return on the investment already made. This proposal was accepted by the WRC and the work undertaken as part of this project forms the core of the work described in this report.

2 OBJECTIVES OF PRESENT STUDY

As described in the project proposal, the objectives of this project were to:

i) Continue to monitor the emissions from the field test cells (at Weltevreden municipal landfill) in order to obtain full advantage of the money already spent on construction of the cells.

ii) Monitor changes in the moisture content of the waste with time and relate this to ambient climatic conditions

iii) To use these data, together with those already obtained, to refine and improve current landfilling standards to increase affordability for disadvantaged communities

The field cells were completed during 1997 and 'Day zero' was 31 October 1997. All references in this report to time in days uses this date as the datum. The project was approved for a period of two years (1999 & 2000), which would have taken us from Day 427 to Day 1156. At the request of the researchers, the Water Research Commission agreed to extend the monitoring period (but not the budget) to the end of March 2001 (Day 1248). This was done because, as described in the report, significant quantities of leachate began to be generated by one of the field cells during the period of study and it was felt beneficial to extend the monitoring period to near the end of the rainy season.

3 DETAILS OF FIELD CELLS

3.1 Description of original cells and work undertaken on second tier of cells

Field cells at a volumetric scale in between the test cells (less than 3 m^3) and full scale landfills (millions of m^3) were identified as an important component of the initial study in that they could be used to help extrapolate data between scales, and their construction was established as a priority early in the original study. A site for establishment of field cells was found in 1995. This was the then newly-permitted Weltevreden GLB+ Waste Disposal Site in Brakpan, about 35km east of Johannesburg. The site is in a water deficit region, underlain by clay, had available space for the test cells away from the working areas of the landfill and was easily accessible. In addition, a good working relationship between University of the Witwatersrand and the site owners and operators had already been established (Shamrock, 1998). Compositional analysis of the rich and poor waste streams being deposited at the main landfill was carried out in October 1995 and construction of four 240 m^3 cells (one rich waste only, one poor waste only and two mixtures) began in November 1995. Two lifts of 2 m each were originally planned for the cells, the first excavated below existing ground level and the second constructed above ground level. Exceptionally wet weather in the next few months led to multiple problems at the site and this, coupled with the fact that the student carrying out the work left the research group, meant that the cells were abandoned early in 1996 with only the bottom lift completed. Details of the construction are given in Shamrock (1998).

The field cell program was revived in July 1996. Despite repeated attempts to resurrect the bottom lift of the cells, they eventually had to be permanently abandoned as too much damage to their leachate collection systems had been done. Most problems were associated with drainage since the leachate collection sumps were approximately 2 m below the original ground level and situated in a 1.5 m deep gully. A (supposed)

perched water table adjacent to the cells was above the height of the leachate collection sumps and they could not be kept clear of water without continuous pumping, which was not a realistic option. Site operations, layout changes and construction work were also beginning to make it impossible to maintain the integrity of the collection sumps. In addition, summer was fast approaching and with it the likelihood of further disruptions due to weather.

It was therefore decided in October 1996 that the original top lift alone would now comprise the field cells, at half the original design height and volume, and these would be completely isolated from the bottom lift. A gas venting system would be installed to prevent pressure build up below the top cell liners. The leachate collection pipes would daylight well above the waterlogged gully. Any reference to the Weltevreden field cells in this report is a reference to these upper-lift cells.

3.2 Field cell construction

Construction work on the field cells commenced in October 1996. Heavy rainfall from November 1996 – April 1997, caused in all probability by the El Niño / La Niña phenomenon of 1997-98 (NASA, 1999), resulted in the cells being abandoned again, just as they were being prepared for installation of a geomembrane liner. Work up to this point is thus detailed under Phase I below. Phase II includes all subsequent work carried out once access to the cells was possible again in May 1997.

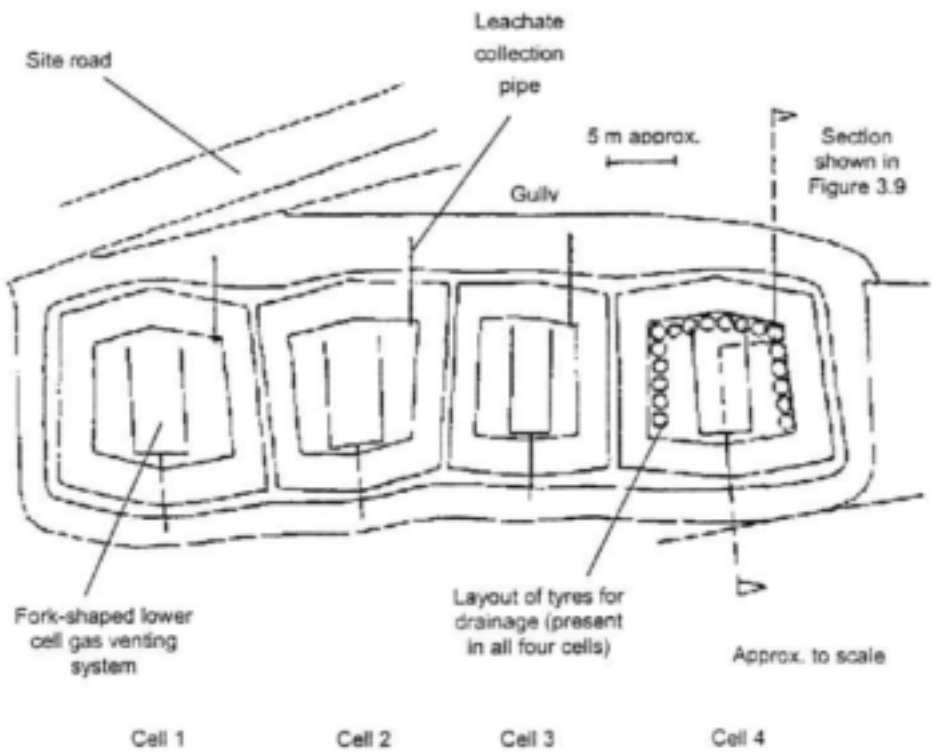

Figure 3.1 Layout of the field cells
(sketch based on site survey carried out by Morris, 2001)

3.2.1 Phase I

Half metre high starter berms for the intended second lift of the original cells had been left in place. These were extended up to 2 m vertical height using local clayey material excavated during extension of the main landfill. A three tonne back-actor was used for construction and compaction of the berms. The berm slopes were kept to the maximum possible so as to maximise the available cell volume. A sloping trench was cut through the down-slope berms at the corner of each cell and an HDPE 50 mm diameter pipe laid down for leachate collection. The trench was then back-filled. Once the berms had been completed, the cells were fully surveyed and a quote for lining with a geomembrane obtained. A ramp up to the top of each cell was constructed to enable independent deposition of any necessary construction materials and, eventually, waste into each cell.

3.2.2 Bottom cell gas vents.

A system of gas vents for collection of any biogas produced by the lower cells (ie those from the original study) was designed and installed. These consisted of perforated LDPE 50 mm diameter pipes laid in the centre of a 100 mm × 100 mm trench filled with 13 mm gravel. The pipes were perforated with staggered 10 mm holes (average 4 per 250 mm length of pipe at random radial positions). The trench was arranged in a two-pronged fork shape with the 'handle' being bent up and sent up through the up-slope cell wall so that it daylighted horizontally approximately 400 mm below the top of the cell. Plastic angles were used for corner joints. A mesh cover was fixed to each pipe end to prevent possible blocking of the pipe by entrapped rodents. The horizontal layout is shown in Figure 3.1 while the vertical arrangement is depicted in Figure 3.2. Details of the position of the trench in relation to the features at the top and bottom of the lower and upper cells respectively is shown in Figure A1 of Appendix A.

After completion of the gas vents, a 300 mm × 300 mm anchor trench for the liner was dug around the top of the outer berms. Work began on bringing the inner side slopes and base of the cells up to grade for installation of the liner. Before this could be completed, the site had to be abandoned due to heavy rain causing severe ponding within the cells (the base slope had not been properly established at this stage).

3.2.3 Phase II

After six months, the cells were accessible once again. A large amount of weed growth had taken root and this was cut back using a brush-cutter and the roots burnt or dug out. Overall damage to the cells was minimal except that the leachate drainage pipes had become covered and had to be exposed. Some damage to the side slopes had occurred. Sandy material from ongoing earthworks at another location on site was brought in to establish an appropriate base slope (diagonally down towards the leachate drainage pipe) and to repair and smooth the sides. The anchor trench was repaired where necessary. The exacting standards required for lining (no particle size greater than 3 mm in contact with the liner) were met. A flange plate connected to a plastic 90° angle was constructed and fitted to each leachate drainage pipe for connection to the liner.

3.2.4 Lining.

A 750 μm Driline© LDPE liner was fitted to the cells by lining sub-contractors. Since the angle changes at the slope-trench interface were steep, geotextile sub-liners were applied there and across the internal walls as load spreaders such that a minimum free length of 500 mm was available (see Figure A2 of Appendix A). The liner was anchored around the external walls of the cells in the anchor trench but laid over the internal cell walls. The liner was anchored in place in the trench with sandbags before back-filling with soil. Details of the completed anchor trench arrangement are shown in Figure A2.

The liner was supplied in seam-free widths of 9.0 m. Joins were made by the method of continuous extrusion fusion welding which applies extrudate along the overlap to provide a totally integrated and homogenous weld. The weld integrity was tested by means of a spark test.

The liner was attached to each flanged leachate drainage pipe as detailed in Figure A1 of Appendix A. A small section of liner material was connected to the flange and then welded to the main liner section. A double layer of wire mesh with 10 mm diamond holes was laid over the flange and an old large tyre placed around the flange. Tyres with numerous holes in their sides were selected so as to ensure adequate lateral drainage of leachate would be able to proceed. 13 mm gravel was then placed over the mesh up to the level of the top edge of the tyre. This layout is shown in the top section of Figure A1. The gravel was placed so as to ensure that adequate drainage at the flange connection would be maintained whilst preventing damage occurring to it during waste placement and compaction.

3.2.5 Drainage layer.

A number of potential materials for provision of a liner protection and drainage layer directly above the liner were considered. The material selected had to be inert and low-cost. Due to the already reduced cell height, the completed layer had to be relatively thin while still providing adequate liner protection. Options considered were whole tyres (abundantly available at the site but too thick when placed as a layer and the liner exposure at their centres posed a potential problem), chipped rubber (too expensive), foam rubber chips (too expensive and compressible), gravel or building rubble (available on site, but of low quality which posed a risk of damage to the liner), chipped garden refuse (available on site but not inert and of unknown behaviour as drainage material), plastic beads from recycled plastic (difficult to obtain and expensive), non-sharp wastes such as paper pulp (unknown drainage properties) and river sand (not cheap, but of known properties). The latter was eventually selected as drainage material.

A drainage layer design in which whole tyres were placed in a U-shape along the base of the down-slope and side walls of the cells was drawn up. The U-shape incorporated the tyre over the leachate collection pipe connection. The river sand was then placed in a 10 cm layer on the base of the cells and on the side walls, with the tyres providing support for the sand layer on the steep sides. Figure 3.2 shows a cross section through the drainage layer. The horizontal arrangement of the tyres is shown in the cell layout drawing (Figure 3.1).

3.2.6 Waste filling.

The cells were now ready to be filled with waste. Waste collection vehicles coming to the main landfill were redirected to deposit their waste load in the cells as appropriate. The composition of waste in each cell was varied with Cell 1 comprising entirely rich waste, Cell 4 entirely poor waste and Cells 2 and 3 mixtures between the two. The waste deposition schedule for each of the cells is given in Table B1 of Appendix B. The origin (rich or poor community) of the waste in each truck load was noted before deposition of the load in a cell and the mass of each load determined from site weighbridge records. In this way, the final waste mass and composition in each cell could be calculated. Waste was pushed around and compacted in the cells by means of a 3 tonne back-actor. Immediately after each cell was full, it was covered with clayey soil which was also compacted by the back-actor. Completion of Cells 3 and 4 took longer than Cells 1 and 2 due to the low volumes of poor waste being delivered to the site. Cover was therefore installed at Cell 1 quite a few days before Cell 4 was finally completed and covered. Sending trucks over the top of the completed cells aided in cover compaction. The interface between the completed upper and lower cells is depicted in Figure A3 of Appendix A.

3.2.7 Soil cover.

Due to the small mass of the back-actor (3 tonnes) in comparison to the immense mass of the landfill site trash compactor (30 tonnes), only limited compaction of the waste in the cells could be achieved before placing of the cover. The site trash compactor was not used for compaction of waste in the cells due to fears of the damage it would cause to the cell structure. The additional mass of cover soil placed over the waste then led to additional compaction taking place. This led to a positive feedback loop where application of more cover resulted in more waste compaction which in turn resulted in more cover being required to bring the top surface of the cell up to the height of the cell walls and so on. As a result, the depth of cover in relation to the final depth of waste is greater than originally anticipated, but the additional compaction provided by the thick cover layers has resulted in waste densities in the cells being at or near that obtained in full scale landfills.

A small ditch and berm (10 cm deep and 5 cm high respectively) were built into the soil cover around the external perimeter of the cell group as shown in Figure 3.2 (cross section). This was to prevent surface run-off of rainwater.

3.2.8 Monitoring instruments.

A range of monitoring instruments and facilities were installed in each cell in March 1998, 5 months after completion of the cell construction:

i) Gypsum blocks (top, middle and bottom of the waste) for reading moisture content.

ii) Resistance cell (bottom of waste only) for reading temperature and moisture content.

iii) 25 mm diameter PVC pipe (to bottom of waste) with slotted end for thermocouple readings.

iv) 50 mm diameter aluminium tube (to bottom of waste) for density and moisture content readings with neutron probe.

The instruments were installed in the plan centre of a cell by cutting a hole down through the entire depth of the cell (cover and waste) with a mechanical digger (back-actor). Once near the level of the sand drainage layer, mechanical digging was halted and the hole extended down to the top of the sand layer by hand digging. PVC electrical conduit cut to an appropriate length was used to ensure the gypsum blocks and resistance cells were installed at the correct level. The five pipes were then installed in a cluster and the hole backfilled with waste which was compacted to its original height. A thin layer of soil was then placed over the waste. A plastic bucket with holes cut in the base was inserted over the top of the pipes. The bucket lid was then fitted and the remaining cover soil replaced and compacted around the bucket so that the lid was now 20 – 30 cm below the surface of the soil. A throw-away piece of plastic pipe was used to mark the position of the bucket. Burial of the instruments in this manner was necessary to prevent theft. The soil over the bucket had to be dug away prior to instrument reading. Figure A4 of Appendix A depicts the set-up.

Figure 3.2 depicts a cross section thorough a completed cell at the position shown on the layout drawing (Figure 3.1).

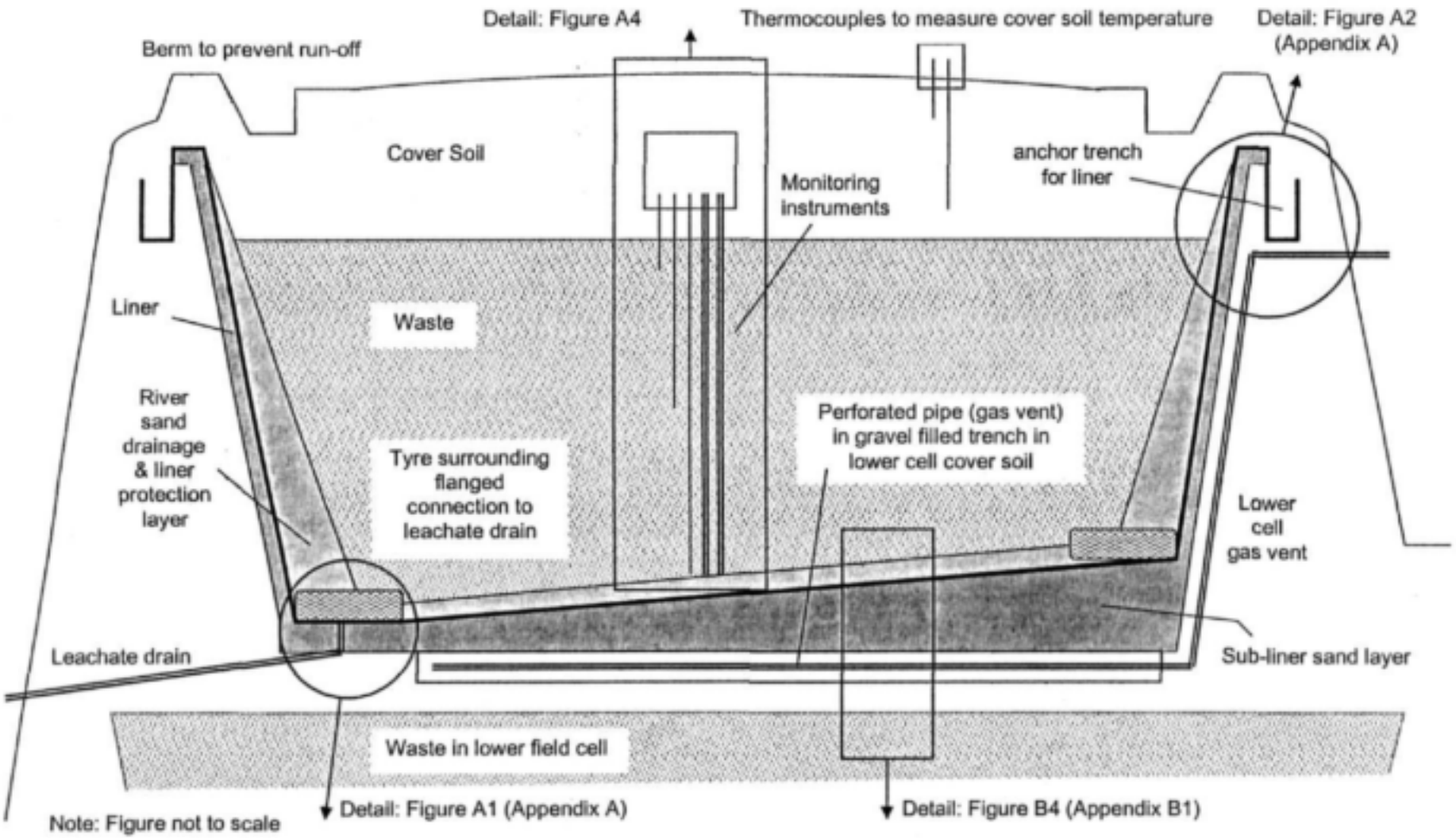

Figure 3.2 Cross section through completed field cell

3.3 Properties of the field cells

3.3.1 Calculation of cell depths, areas and volumes

A detailed survey of the field cells was carried out both during phase I and phase II of the construction. Both surveys were carried out by means of a theodolite and measuring tape. The results of these surveys were used in the determination of top and basal cell areas. Each cell comprises an inverted truncated pyramid with an irregular hexagonal base. The top and bottom surfaces of each cell were assumed to be horizontal and planar and as such are similar polygons. In fact, the basal surface plane is inclined at a 1 in 90 slope along the leading diagonal to the leachate collection sump. However, it is assumed that ignoring this incline would have a negligible effect on volume calculations as the net difference in included cross sectional area would be the small triangular section X as shown in Figure 3.3.

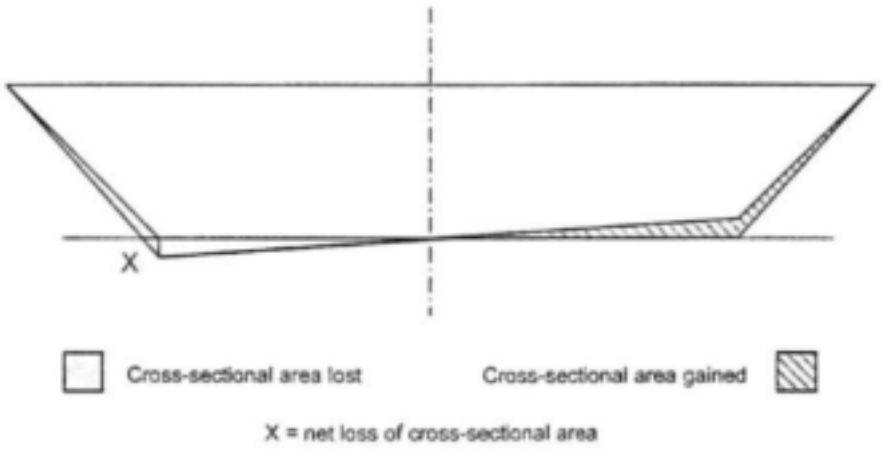

Figure 3.3 Net change in volume calculation caused by assuming the top & bottom surfaces of the field cells are planar

As stated above, the top and bottom surfaces of the cells are irregular hexagons. Each hexagon, top and bottom, was divided in two along its principal axis as shown in Figure 3.4. The half including the leachate drain was termed L (leachate drain) while the opposite half was termed N (no leachate drain). In this way, the notation for each cell section was built up into a 3-character label as follows: first 1 to 4 for cell number, second T or B for top or bottom, and finally L or N. Thus, for example, the bottom section containing the leachate drain in Cell 3 was termed 3BL. The dimensions d, a, b, t and x, as shown in Figure 3.4 for each of the cell sections, are known. Dimensions j, k and y can then be calculated and the area A_L or A_N of each cell section L or N obtained from:

$$A = xy + \tfrac{1}{2}tk + \tfrac{1}{2}xj + \tfrac{1}{2}y(t-x)$$

The total area of each cell surface is therefore the sum of both section areas:

$$A_{Total} = A_L + A_N$$

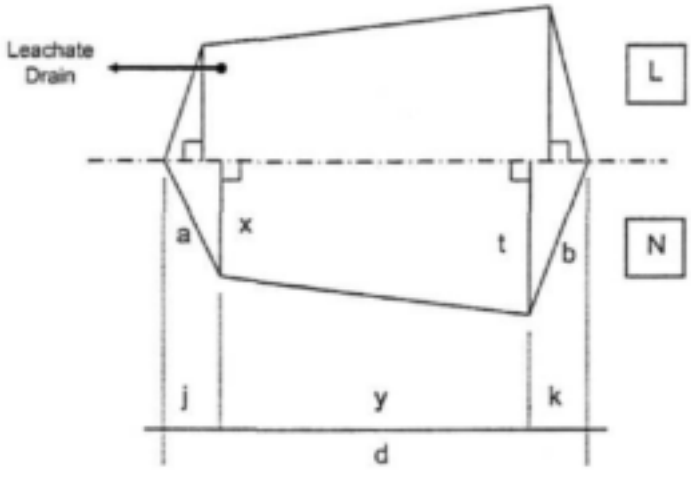

Figure 3.4 Dimensions & notation used to calculate the areas of the top & bottom surfaces of each field cell

The above dimensions and resultant calculated areas for each cell section and surface are shown in Table B2 of Appendix B.

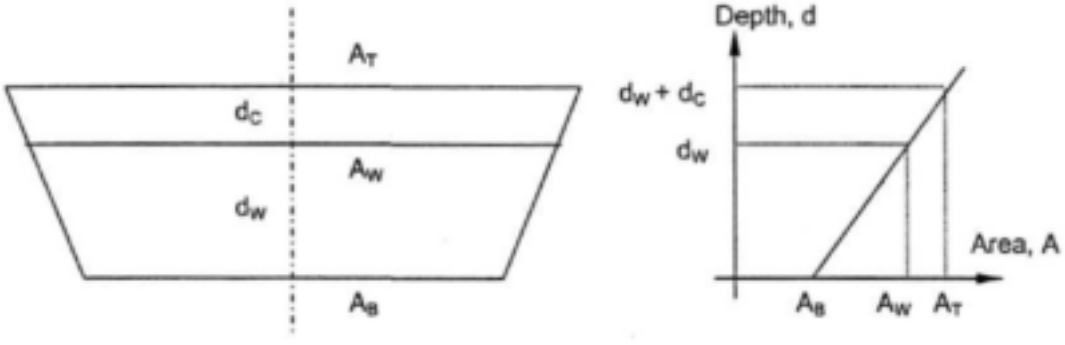

Figure 3.5 Relationship between depths & surface areas in the field cells

During construction of the test cells, waste was evenly placed and compacted in each cell up to a level about 20 cm from the top surface. Further compaction of the waste during placement of cover soil meant that the actual depth of waste in each cell was unknown. In order to calculate the volume of waste in each cell, the final depth of cover and waste needed to be determined. This was done during installation of monitoring instruments in the cells in March 1998. The sum of the measured cover and waste depth compared well with the known total cell depth. The depth of cover was verified using a hand auger at different locations on the cell surface on two occasions (an unsuccessful attempt to extract year old waste samples from the cells in October 1998 and the installation of thermocouples in the cell cover in February 1999). Figure 3.5 represents

the soil cover depth d_C and the depth d_W and surface area A_W of waste in a cell in relation to the known bottom (A_B) and top (A_T) cell surface areas.

Assuming a linear variation of A with d, that is assuming that surfaces A_W, A_B and A_T are planar, A_W can be determined from:

$$A_W = \frac{A_T \times d_W}{d_W + d_C}$$

The volume of waste in a cell can therefore be determined from:

$$V = \tfrac{1}{2} d_W (A_B + A_W)$$

The depths, areas and calculated volumes of each cell are shown in Table 3.1 below.

Cell	Depth (m)		Area (m^2)			Volume of waste (m^3)
	Waste	Cover	Top	Bottom	Waste	
	d_W	d_C	A_T	A_B	A_W	V
1	1.15	0.80	220.83	96.05	130.23	130.11
2	1.05	0.70	196.28	85.95	117.77	106.95
3	1.00	0.80	162.40	66.29	90.22	78.26
4	0.90	0.55	214.49	96.35	133.13	103.27

Table 3.1 Depths, areas & volumes of the field cells

3.3.2 Calculation of density, composition & dry mass of waste in the cells

The total wet mass of waste in each field cell was determined from summing the mass of waste deposited by each truck involved with cell filling. This data was supplied by the weighbridge at the landfill site. A record of the origin of each truck was made so as to ascertain the type of waste deposited (rich or poor). Details of daily waste deposition masses and types are shown in Table B1 of Appendix B.

The as-placed bulk density, in terms of [kg wet mass] m^{-3}, of waste in each field cell was calculated as the total wet mass of waste in a cell divided by the total cell volume taken up by waste. The full results are shown in Table B1.

The dry mass of each waste type in a field cell was determined as shown below, where m_{dxt} is the dry mass, w_t is the waste moisture content and m_{bxt} is the wet mass of waste comprising each waste type t (rich or poor) in a cell x respectively.

$$m_{dxt} = \frac{m_{bxt}}{1 + w_t}$$

The total dry mass of waste in each field cell was therefore the sum of the dry masses of each waste type. The calculated dry masses are shown in Table B1.

The as-placed dry density of waste in each field cell, in terms of [kg dry mass] m^{-3}, was calculated as the total dry mass of waste in a cell divided by the total cell volume taken up by waste. The results are shown in Table B1.

The composition of waste in each field cell was estimated by first calculating the proportion of the total wet mass of waste in a cell that comprised rich or poor waste as shown in Table B3 of Appendix B. Using data from the waste compositional analysis carried out on the two types of waste used in the filling of these field cells, the composition of waste in each cell could be determined. The results are shown in Table B3. A summary of all the above parameters is given in Table 3.2.

3.3.3 Determination of cover soil depth and permeability

The depth of cover soil to each cell was determined as described in the previous sub-section on cell depths, areas and volumes. Cover soils depths are given in Table 3.2.

Cell	Mass of waste in cell (kg)		As-placed density of waste in cells (kg m^{-3})	
	Wet	Dry	Wet (bulk)	Dry
1	88,390	54,900	679	422
2	74,500	50,270	697	470
3	59,640	42,025	762	537
4	123,580	95,060	1197	921

Table 3.2 Mass & density of waste in the field cells

The permeability of the cover soil at the field cells was measured in July 1998 by means of a Soil Moisture Corp. Model 2800K1 Guelph Permeameter (SoilMoisture Corp., 1987). This is a constant-head device which provides a quick and relatively simple method for determining field saturated hydraulic conductivity (k_{fs}). The measured permeability of the cover at Cells 1 – 4 was (Fourie, 1998):

1. Cell 1. 7×10^{-7} m s^{-1}
2. Cell 2. 8×10^{-8} m s^{-1}
3. Cell 3. 8×10^{-8} m s^{-1}
4. Cell 4. 5×10^{-8} m s^{-1}

3.3.4 Determination of cover soil composition

Collection of cover soil samples from the field cells for classification under the USCS system (Bowles, 1986) was done as part of the gas emission measurement study at the cells. The results of the classification study are given in Figure A5 of Appendix A.

The pH and conductivity of soil samples taken from various locations at the Weltevreden Landfill Site, where the field cells are situated, was measured by Shamrock (1998) as part of the feasibility study carried out before establishing the lower field cells at the site in 1995. The pH and conductivity of stockpiled soil at the site was found to be 3.8 – 4.0 and 1.30 – 1.40 mS cm^{-1} respectively. Samples from a test pit at an area soon to be excavated at that time had pH and conductivity values of 4.0 – 5.0 and 1.10 – 2.30 mS cm^{-1} respectively. Soil from both these sources was used as cover for the field cells.

4 MONITORING OF FIELD CELLS

A number of external weather conditions at the field cells were monitored. These are listed below along with the method of obtaining the data and its source.

4.1 Precipitation.

This was measured daily by means of a conventional raingauge installed at the landfill weighbridge. Measurements were taken by the site operating staff and transmitted on a monthly basis. The weighbridge is a distance of approximately 200 m from the field cells.

4.2 Ambient temperature.

Maximum and minimum daily temperatures were recorded daily at the landfill weighbridge by site operating staff. Ambient temperatures were also recorded at the site during gas emissions measurements.

4.3 Atmospheric pressure.

This was measured at the field cells during occasions of gas emission measurement. Both these temperature and pressure measurements were used for generation of gas emission fluxes at the field cells as described by Morris (2001).

4.4 Leachate

The leachate collection systems at the field cells were fitted with stoppers. The volume of leachate produced by each field cell was measured discretely at approximately bi-monthly intervals by collecting the total quantity present in the leachate collection system of the cell. A long flexible hose was fitted to each nozzle during leachate collection so that air would not be sucked up into the cells when the flow of leachate ceased. At the field cells, this flow rarely ceased completely except in the middle of winter (dry season). It was feared that keeping a pipe open with very low flows of leachate running through it could lead to ingress of air into the cell. As a result, the pipe was resealed once the flow rate from it was sufficiently low (typically less than one litre per minute). Calibrated 25 or 4 litre buckets, accurate to the nearest 200 ml or 100 ml respectively, were used in combination to collect the leachate flow from the pipes.

4.5 Collection, handling & storage of leachate samples

Leachate was collected in 25 or 4 litre buckets according to the total volume of leachate produced. The leachate in the bucket was stirred to ensure a sample taken from it was representative of mean leachate quality and then a portion transferred to a one litre glass Schott bottle. Where more than one litre of leachate was available, the bottle was filled up as much as possible to minimise the reactive headspace in it. Where the total volume of leachate produced exceeded 25 litres, an equal portion of each 25 litre bucket of leachate was transferred to a holding bucket and the resulting mixture stirred before a sample was transferred to a bottle.

During visits to the field cells, collection of leachate samples was always the last activity to be undertaken and the samples were kept in shady conditions during transportation back to Wits. There, the bottles were stored in cool, dark conditions until analysis.

Within 24 hours of sample collection the parameters analysed at Wits had been measured and the samples were then immediately delivered to Cydna Laboratory, operated by the Health and Scientific Services division of the Greater Johannesburg Metropolitan Council (GJMC), where the remaining analyses were carried out. Once at Cydna, samples were stored in a dark fridge at 4 °C until analysis 1 – 2 weeks later. In all cases, the sample bottles were well shaken before any analysis was performed.

4.6 Leachate quality.

Chemical analysis of a number of leachate parameters was carried out by either University of the Witwatersrand personnel or the GJMC Cydna Laboratory. Results are given in Tables C2 – C5 of Appendix C.

4.7 Gas

Gas emissions through the cover soil to the field cells were measured at approximately monthly intervals. The static accumulation chamber technique was used throughout. Measurements were taken at three positions on the surface of each cell. Position I is the location of the internal monitoring instruments at the geometric centre of a cell in plan view. Gas measurements were taken here since soil cover to the buried bucket containing the instrument reading connections was disturbed repeatedly whenever instrument readings were taken, resulting in a possible preferential path for gas emissions at this position and hence higher gas emission fluxes than at undisturbed areas of cover. Two other positions were also selected for measurement: Position A situated on the cover surface of the cell half not including the leachate drain and Position B on the cover surface of the cell half including the leachate drain (with the cell areas bisected perpendicularly to the orientation of the leachate drain). These two positions were selected randomly by drawing a rough outline of the cell, dividing a cell half into approximate 2 m × 2m squares, numbering each square and cutting it out before finally placing all the squares in a box and drawing one at random. This procedure was repeated for both halves of all four cells.

Results of all the parameters measured as part of the gas measurement programme for all cells are given in Tables C6 – C9 of Appendix C.

4.8 Cover soil temperature & moisture content

During the latter stages of gas emission measurement at the field cells, cover soil temperatures were also measured by means of a temperature probe and/or installed thermocouples. The probe measured temperature at a depth of 5 cm. The thermocouple wires were copper-constantan insulated along their length so that only their bottom 2 cm were exposed. These exposed portions of wire were twisted firmly together to form the couple and then coated in epoxy resin to prevent corrosion. Two thermocouples were installed in the cover adjacent to the instrument cluster at the plan geometric centre of each cell. The ends were buried at a depth of 15 cm (upper cover readings) and 50 – 70 cm (lower cover readings) depending on overall cover depth. The exposed upper wire connections to the bridge were labelled and covered with an old can to disguise their presence and so prevent tampering or theft. The thermocouple bridge, which was made up at University of the Witwatersrand many decades ago, was calibrated periodically using a water bath, the temperature of which had been established with a glass mercury thermometer. Results of these measurements are given in Tables C10 – C13 of Appendix C.

Cover soil moisture content was determined on occasions of gas emission measurement by collecting a sample for laboratory analysis. Results are given in Tables C10 – C13.

4.9 Internal monitoring

As described in Section 3.2.8, a number of instruments were installed in the centre of each field cell for monitoring of internal conditions. The parameters measured and the methods used are detailed below. The instrument connections and outlets were housed in a plastic bucket which was buried 20 – 30 cm below the surface of the cover soil. This was to prevent theft or vandalism. The soil above the bucket had to be removed with a shovel each time readings were taken at approximately monthly intervals. All instrument readings were taken by University of the Witwatersrand personnel.

4.10 Waste temperature.

The temperature of the waste in each cell was measured at the base only. Initially, this temperature was measured using resistance cells (ELE International Inc. MC-310A Soil Moisture Temperature Cells) with an ELE International Inc. MC-302 Soil Moisture Temperature Meter. It became clear after a few months that this system was producing erroneous results, probably due to failure of the MC-310A cells in the aggressive environment of the field cells. After that, temperatures were measured by means of copper-constantan thermocouples with a corresponding thermocouple bridge used as described previously except that the thermocouple wires were pushed down the piezometer tube to the base of the cells on each occasion rather than installed in place to prevent corrosion problems. Readings were taken after a few minutes had elapsed. Results are shown in Tables C10 – C13.

4.11 Waste moisture content.

In-situ waste moisture content was measured at the top and middle of each cell by means of gypsum blocks (SoilMoisture Equipment Corp. 5201 Soil Moisture Blocks) and at the base of each cell by means of a gypsum block and resistance cell (ELE International Inc. MC-310A Soil Moisture Temperature Cell).

Electrical conduit cut to an appropriate length was used to carry the wire connections from the blocks and cells up to the bucket where readings were taken using the appropriate instrument. Results of the measurements are given in Tables C10 – C13.

4.12 In-situ gas composition.

The composition of gas in the pore spaces in the waste was measured using a Geotechnical Instruments Inc. GA-94A portable infrared gas analyser. The intake hose was pushed down the electrical conduit to the bottom, middle and top of the waste (except where piezometric levels indicated that standing leachate was occurring at that level) and the instrument pump operated for 30 seconds. Maximum concentrations of methane and CO_2, and minimum concentrations of oxygen, were measured to the nearest percentage point. The top of the conduit was thumb-sealed during measurements to minimise potential draw-down of atmospheric air during pumping. Results are given in Table C10 – C13.

4.13 Neutron probe

A 50 mm diameter aluminium tube with sealed bottom end was inserted into each cell as part of the instrument cluster. It was intended that this would be used for neutron probe (CPN International Inc. Neutron Probe CPN-501DR) measurement of in-situ waste density and moisture content. However, a site and material specific calibration of the probe had to be carried out before it could be used for data generation (Dickey, 1998). The difficulties of and long timeframe needed for carrying out this calibration, the fact that the instrument became available quite late in this study, the very stringent operating standards with regard to health and safety (IAEA, 1996) and the availability of other methods for determining in-situ moisture content and as-placed density meant that it was not considered worthwhile to use the probe. A longer term study at a later stage may find it beneficial to embark on calibration of the probe such as was carried out by Yuen (1999) for use in much larger field cells. Legal requirements regarding the use of such a probe in South Africa can be found in the Hazardous Substances Act, 1973 (Act 15 of 1973) (Cit. in Wiechers, 1999) and the relevant code of practice issued by the South African Department of Health (DoH, 1997).

5 RESULTS

5.1 In-situ monitoring of waste in the cells

Details of the instrumentation installed in each cell are given in Section 3.2.8.

5.1.1 Waste & cover soil temperature.

The temperature cells stopped performing after only a few months. The internal conditions in the cells were probably too aggressive. The thermocouples in the cover soil also ceased functioning after a short time, probably for the same reasons as the temperature cells.

5.1.2 Moisture content.

The calibrations carried out with the gypsum blocks (GBs) and resistance cells (RCs) in rich and poor waste were of some value. The GBs and RCs responded well to use in poor waste, although their most accurate

range was at gravimetric moisture content values below 20 %. The RCs were only of use in rich waste at gravimetric moisture content values below 50 %. The GBs did not respond to use in rich waste at all, probably due to the absence of pore suction pressures in the large void spaces typical of rich waste. The above moisture content values are lower than the initial moisture contents of the respective waste types placed in the cells and, since leachate was produced, it must be assumed that in-situ moisture content values ranged above these values. This, coupled with the fact that calibrations were carried out in rich and poor waste types only and not on waste mixtures, meant that precise determination of in-situ waste moisture content was not possible. The results are of use for indicative (qualitative) purposes only. However, although not of much use for MSW, it should be noted that the GBs seem to provide a reliable and inexpensive way of measuring moisture contents in ash-rich wastes at lower moisture contents.

5.1.3 Settlement of waste

Actual settlement was not quantitatively measured as no benchmarks were established to allow this. However, observations of the cover to all cells over time indicated that subsidence was taking place at the plan centre of each cell, with associated cracking at the edges of the cover. It seems more likely that this was primarily due to settlement of the waste rather than cover soil, and it was thus concluded that waste settlement was occurring in all cells, although it was most extensive in Cell 1. This observed settlement was considered a welcome sign that waste material was being consumed, i.e. that active anaerobic biodegradation had commenced.

5.2 Cover soil properties

A number of properties of the cover soil to the field cells could have impacted on the quantity and quality of gas and leachate production.

5.2.1 Physical properties.

Cover soil depth was different at each cell. Cover depth was highest at Cells 1 and 3 and lowest at Cell 4. The greater depth of soil at Cell 3 than at the other cells in relation to total cell volume may be a contributing factor to the low levels of gas and leachate emission from the cell. The composition and USCS classification of the cover soil at the cells is given in Figure A5 of Appendix A. Cover soil permeability values are given in Section 3.3.

5.2.2 Chemical properties.

The pH of cover to the field cells was very low due to contamination of the land in the vicinity of the cells by run off from gold mine tailings. This may have affected leachate quality.

5.2.3 Vegetative growth.

Vegetation has a marked effect on evapotranspiration from a soil surface. No vegetation was present on the cover soil of any cells after the first summer season. Although it was initially slow to take, vegetative growth on the cover soils of all the cells was well established by the end of the third summer season.

All of the items discussed in the above sub-sections could have impacted on the quantity and quality of leachate collected from the cells. Any points raised need to be kept in mind during the following discussion on leachate production.

5.3 Emissions

As described earlier, four field cells containing 80 – 130 m^3, or 60 – 125 tonnes, of waste were set up as described in Section 3.2. Cell 1 contained only rich waste, Cells 2 and 3 contained mixtures of rich to poor waste in ratios of 64:36 and 44:56 respectively and Cell 4 contained only poor waste. All masses and proportions were in terms of wet mass of waste. Raw data from the field cells are given in Tables C2 – C13 of Appendix C.

5.3.1 Gas measurement

Measurement of LFG emissions through the cover of each field cell was carried out at three different cover locations on 11 occasions between Days 264 and 721. Negligible methane emissions were measured on any occasion, although small methane fluxes were detected at Position I (over the soil disturbed to reach instrument housings) at Cells 1, 2 and 4 during the second summer (rainy) season. Larger fluxes of CO_2 were detected on most occasions. Emission measurements were discontinued after Day 721 as fluxes were too low for the results to be of any real benefit to this study. Results are not presented in this section, but are given in Tables C6 – C9 of Appendix C.

The presence of, albeit small, methane fluxes at Position I on the cover of Cells 1, 2 and 4 during the second rainy season suggested that methanogenic conditions were developing in these cells to some extent. Cell 3 may not have been methanogenic by this stage. The depth of cover soil to the cells may have affected LFG emission measurements and no sensible conclusions can be drawn from the magnitude of emissions at this stage.

The gaseous environment in the pore spaces of waste in each cell was sampled as part of the in-situ monitoring programme at the field cells. This was done by sticking the intake hose of an infrared gas analyser down the conduit paths to the top, middle and bottom of the waste in each cell (given that piezometric readings indicated that no standing leachate was present). Measurements were carried out for one season only (first winter to second summer). The quantitative accuracy of the data is suspect, but it did reveal that methane was present in every cell and that methane concentrations were higher in summer than in winter. Methane concentrations were highest in Cell 4 (comprising a maximum of 44 % of total gas volume), followed by 1 and 2 (maximum 30 % of total gas volume), and again lowest in 3 (maximum 15 % of total gas volume). The ratio of methane to CO_2 concentrations within the cells ranged from 0 – 85 % in Cell 1, 0 – 100 % in Cell 2, 0 – 50 % in Cell 3 and 0 – 131 % in Cell 4.

These patterns of gas production are in agreement with the limited results of the LFG emission flux measurements. Cell 4 was producing most biogas with the highest proportion of methane, Cells 1 and 2 were behaving in a similar fashion with less gas production than Cell 4 and Cell 3 was producing low levels of gas.

5.3.2 Leachate production

The total volume of leachate produced in each field cell was collected at discrete intervals and a sample analysed for a number of quality parameters. No clogging of the leachate collection system was ever encountered in any cell, although a metalic 'sheet' was washed through with leachate flow at Cell 4 on a couple of occasions early in the measurement programme. From reports in the literature (Rowe, 1998) this appeared to be typical clog material which means it would have consisted mainly of calcium, carbonate, silica, magnesium and iron. The 'sheet' was not analysed for composition as this seemed an unwarranted expense. Since leachate flow at Cell 4 never dried completely, even during dry winter months, it was assumed that clogging of the leachate delivery system had not occurred.

In addition to plotting leachate quantity and quality over the time period of this study, the results are also presented in terms of the numbers of pore volumes any precipitation or collected leachate volumes represent. The properties of waste (specific gravity, gravimetric moisture content, voids ratio, porosity and volume of voids) necessary to calculate the pore volumes in the waste in each field cell were determined and are given in Table B4 of Appendix B. Presenting results in terms of pore volumes leached allows them to be viewed in a more meaningful light and enables direct comparisons between the results obtained from experiments at different scales to be drawn. It is important to note that quoted pore volumes are initial values in all cases and do not take into account any settlement of waste during decomposition.

The variation of rainfall and leachate production with time is shown in Figure C1. The monitoring period was close to 3½ years. The leachate quantity is expressed in millimetres (volume of leachate divided by cell surface area) and the scale is shown on the right of the figure. There are four wet seasons evident, with 3 periods of little or no rain.

Cells 2,3 and 4 shown a very consistent rate of leachate production with the poor refuse having the highest rate of these three. Of interest here is the time taken for a cell (e.g. Cell 4) to begin producing leachate again after a quiescent period of no rain, as shown by the small increase shortly after Day 900, which is some time after the start of that particular rainy season. These 3 cells show similar behaviour to the mini-landfill containing only poor refuse that was operated on the Wits campus for a period of 5 years. This latter work clearly showed the ability of this particular type of refuse to store moisture during wet periods and then evaporate it during subsequent dry periods, thus creating additional storage capacity.

Cell 1, which contained only rich waste, shows completely different behaviour to the other three cells. For a period of almost 2½ years it produced virtually no leachate at all and certainly much less than the other 3 cells. If the study had been terminated at the end of 1998 (Day 426), which would have occurred had the follow-up WRC contract not been granted, the conclusion could have been drawn that the 'rich' refuse had better moisture retention capacity and the lowest likelihood of generating leachate. Figure C1 clearly shows that this would have been grossly incorrect. On Day 931, near the end of the 3rd wet season, there was a sharp increase in the volume of leachate collected from Cell 1. A volume of 1555 litres was collected and

the leachate was very dark in colour and extremely foul smelling: clearly not merely stormwater that had somehow entered the leachate collection system. On subsequent collection days, this cell always produced by far the most leachate, with the other 3 cells always producing relatively small quantities.

There was no obvious reason for the sudden increase in leachate production in Cell 1. Inspection of the top surface showed no indication of cracking, although the existence of micro-cracking due to desiccation during the dry winter months cannot be ruled out. The most likely explanation is that during the first two wet seasons, rainfall that did penetrate through the soil cover, filled up storage capacity within the refuse which had probably been placed at moisture contents below the field capacity. Unlike Cells 2-4, which were able to evaporate much of this moisture during dry periods, the moisture content within Cell 1 continued to increase until the field capacity was reached, after which time any moisture penetrating the cover resulted in leachate generation.

Despite the apparently large volume generated from Cell 1 during the last year or so of the study, it is in fact only about 2½% of the total rainfall. Since Day 931, the volume is about 4% of the rainfall volume since Day 931. The production of leachate in terms of the number of pore volumes leached is shown in Figures C2 a-d. The right hand axis of each of these figures shows the pore volumes of leachate produced. Obviously Cell 1 is the highest, with about 0.05 pore volumes of leachate having been generated. The values for the other 3 cells are less than 0.02 pore volumes. When considered in terms of pore volumes, the difference between Cell 1 and Cells 2-4 is not so pronounced as was apparent from Figure C1. This is because the pore volume of Cells 2-4 is lower that Cell 1, an outcome of the lower density (higher air volume) of Cell 1, (see Table B4).

5.3.3 Leachate Quality

When considering leachate quality in the following section, the results have been expressed in terms of pore volumes of leachate. This has the advantage of bringing all 4 cells to a similar basis of comparison (which is useful when considering time to stabilisation – see Section 6.4 later) and also removes the time factor. This is useful because periods during which there is no rainfall (winter) do not distort the results in any way. For purposes of illustration the temporal data has also been included.

Figure C3 shows the variation of pH with time for the 4 cells. Cell 1 initially had low values, reaching a value of just over 5 on the 2nd sampling occasion. Thereafter it increased steadily, reaching a neutral pH after about 400 days. The other 3 cells had higher pH values right from the start of the study, although Cell 2 showed a dip at Day 382. After Day 400 the pH for all 4 cells remained relatively stable, at values that are consistent with methanogenic conditions having been established. These comparisons are however, a little misleading and a different picture emerges if we consider pore volumes of leachate, as shown in Figure C4a-

d. Note that the horizontal axis for Cell 1 is different to that for Cells 2-4. It can now be seen that in Cell 1, the initially low pH values are associated with extremely small volumes of leachate, indeed it may more correctly be considered 'squeezate' (i.e. liquid squeezed out of the waste by the weight of overlying material). By the time the leachate pH rises to values in excess of 7.5 the cumulative volume produced is minimal. Once appreciable volumes are produced, the Cell 1 leachate remains stable. The sharp dip in the pH of the Cell 2 leachate can now be seen to have occurred at a small pore volume fraction and the pH is near neutral for most of the study. Cells 3 and 4 also have pH values that are neutral or near-neutral for the most part, although the Cell 4 pH does appear to be decreasing from the initially high values.

The primary significance of the pH data is that all cells appear to have reached methanogenic conditions despite the lack of measurable gas fluxes through the cell covers. These data are consistent with other parameters measured, eg. the distinct decrease in the COD value for leachate from Cell 1 with time (see Table C2).

Figure C5 gives the variation of cumulative COD (expressed in terms of the initial dry weight of solids in each cell) with time. The results are similar to Figure C3 in the sense that Cell 1 has very low values until the first major leachate flush occurred on Day 931. After this time there is a sharp rise in cumulative COD, with Cell 1 reaching 200mg for every kg of original dry refuse. As before, the values from Cells 2-4 show a gradual increase.

Rather than plot the data from each cell separately as was done for pH, Figure C6 draws all 4 cells together, in terms of cumulative COD leachate versus number of pore volumes leached. There is very little difference between Cells 2-4, although Cell 4, which has experienced the largest proportion of pore volumes flushed (after Cell 1) seems to be stabilising, with only a gradual increase in cumulative COD evident. Cell 1 seems to have achieved a steady state condition with a consistently high production rate. In terms of pollution potential, this plot of cumulative COD against pore volumes shows Cell 1 refuse to be particularly problematic. Even at equivalent pore volumes leached, the Cell 1 data is about 3 times higher than the next highest value and, unlike Cell 4, shows no sign of tapering off.

Figures C7 and 8 show the temporal variation of cumulative chloride leached and the value in terms of pore volume leached respectively. Figure C7 is essentially the same as Figure C5 and does not warrant further comment at this stage. Figure C8 shows Cell 1 to have already produced about 6 to 10 times as much chloride per kg of original dry mass than any of the other cells. It is also continuing to produce chloride, albeit at what appears to be a decreasing rate. It appears that Cell 1 is some way from reaching a stable condition (where the waste is fully flushed) whereas Cell 4 does show a tendency towards such a condition. The implications of these substantial differences between Cell 1 and Cells 2-4 are discussed in Section 6.4, together with some possible explanations. The temporal and pore volume variation of cumulative ammonia leachate are, as shown in Figures C9 and C10 respectively, similar to the previous comparisons. A slight

difference is the discernible increase in rate of ammonia production in Cells 2-4 from about Day 1100. The cumulative values are still a lot less than in Cell 1, which furthermore shows no sign of a drop in ammonia production. If anything, a slight increase seems evident. Interestingly, Cells 2 and 3 appear to be tracking Cell 1 in terms of cumulative ammonia leached per pore volume. This could mean that a great deal of ammonia is still to be leached and that in terms of this parameter, Cells 2-3 are a long way from becoming stable. On the other hand, it is too early to say whether or not the ammonia trend in Cells 2 and 3 will rather follow that of Cell 4, which is showing a much smaller rate of cumulative ammonia leached. Clearly it is desirable that monitoring should continue for a number of years yet.

The only metal that was regularly monitored was nickel and this is summarised in Figures C11 and C12 in the same form as before. Figure C11 shows a very sharp rise in cumulative nickel leached for Cell 1 at a very early stage. After that it remains very static until the major leachate flush occurred on Day 931. Since that time it has climbed steadily, at a constant rate. In terms of pore volumes leached, Cell 1 is about a factor of 10 higher than any of the other cells and even at comparable values of pore volumes leached, the difference is approximately 5. Once again Cell 1 appears to have a far greater potential impact on the subsurface. The fact that the differences between Cell 1 and Cell 2 to 4 are most pronounced for nickel is probably a function of the waste composition.

Alkalinity removal was essentially the same as for the previous contaminants. Cumulative totals of alkalinity removal were higher than for all the other parameters. This buffering capacity may have been a contributing factor to the surprisingly neutral pH values found. The clog 'sheet' washed through in leachate from Cell 4 on two occasions almost certainly contained calcium carbonate and this may have lowered potential concentrations of leachate alkalinity on these occasions.

Analysis of leachate samples for copper and cadmium content was discontinued after Day 103 as concentrations of these parameters were found to be negligible. Analysis of cobalt and zinc content in leachate samples continued until the end of the measurement programme, but concentrations of these two parameters were found to be very low and erratic. Since all these four metals were only included as back-up data to nickel monitoring, results of which proved to be very promising, they are not included or discussed in this section, but are given in Tables C2 – C5 of Appendix C.

5.3.4 Water balance of cells.

The specific gravity, voids ratio and initial gravimetric moisture content of the waste in each cell were known. Using these values, the degree of saturation of the waste at placement could be calculated for each waste type as shown at the top of Table C1. Run-off from the cells was prevented by construction of berms around the perimeter of the cell block. Assuming for the time being that the cover soils had no moisture storage capacity, any precipitation landing on the surface of the cell cover (P) must infiltrate (I) the waste and be stored (S), appear as leachate (L), or be evaporated (E). Using A pan evaporation data (E_A) for Johannesburg, the difference between P and E_A immediately prior to the first appearance of leachate can be

determined and the degree of saturation at field moisture capacity, and hence the gravimetric field moisture capacity, calculated. This is shown in Table C1. Results are only shown up to day 1055, which is the end of the 3rd dry season. Although some data are available after this date, it does not represent a complete year and is thus incomplete for the purpose required in this part of the discussion.

Referring to the water balance equation ($W + I = S + E + L$), W (the moisture entering with the waste) doesn't change and so if S is constant, any increase in I will be matched by an equal increase in (E + L) and so $\Delta P - \Delta L = \Delta E$. Figure C1 shows the seasonal nature of precipitation at the field cells. As was done with calculation of water balances at the test cells on the Wits campus, ΔE was evaluated at the end of each dry season when leachate flow had ceased or was extremely limited. The results of these calculations are shown in Table C1. The table also shows values of $\Delta E / E_A$ and $\Delta E / \Delta P$, representing the proportion that evapotranspiration from the cells comprises each of these two denominators. Note that in the table and discussion, use of the 'Δ' symbol has been dropped, so ΔP has become P, ΔE has become E and so on.

From the data at the top of Table C1, it is interesting to see that the bulk density of waste in Cells 1, 2 and 3 was reasonably similar but the bulk density of Cell 4 waste was much higher. This was also the case with the degree of saturation, both as-placed and at field capacity. Field moisture capacities in the cells were very different, ranging from 65 % in 1 to 32 % in 4, reflecting the differences in as-placed gravimetric moisture capacity. The degree of saturation and moisture capacity values in these cells are much higher and lower, respectively, than those encountered in the lysimeters or test cells, reflecting the much higher bulk density and lower voids ratio values of the waste in the field cells.

Leachate from waste can appear ahead of complete pore saturation as a consequence of moisture following preferential flow paths through, rather than percolating fully, the waste. This, in addition to any waste settlement after placement that may have occurred in the field cells due to biodegradation and surcharge loading from the cover soil, may mean that the initial appearance of leachate in the collection system did not represent 'true' leachate. The above values for the degree of saturation and moisture content at field capacity were calculated assuming that the appearance of leachate did represent pore saturation, and they should therefore perhaps be considered speculative.

The water balance calculation comprising the remainder of Table C1 assumed that no run off is possible and that no moisture was stored in cover soil. The values of E / P in Table C1, that is the proportion that losses by evapotranspiration comprise of total incident precipitation, show that almost all incident rainfall (P) up to Day 1055 had not appeared as leachate but was lost to evaportranspirative processes. There are three main alternative fates for rainwater landing on the cell cover (other than appearing as leachate). These are that it:

1. Appears as run off from the cover.

2. Is intercepted and stored in the cover soil before being evaporated.

3. Infiltrates the waste where it is stored before being evaporated (as assumed in the water balance calculation).

The berm built to control run off from the cover was breached on a few occasions during heavy rainfall in the early stages of the monitoring programme at the cells. The berm was successfully improved after the first summer season, however, and so the high losses from the cells in the second and third summer seasons cannot reasonably be attributed to this. The most likely scenario is therefore a combination of (2) and (3). The moisture storage capacity of the cover soil is unknown, although it is likely to be relatively small. At present, this means that the storage (S) term in the water balance calculation applies to a field cell as a whole (waste plus cover) rather than just to the waste in a cell.

The results from these field cells again show that evaporative losses from semi-arid landfills are large and can be an enormously significant control on the production of leachate, even where vegetative growth is slow to take root as was the case with these cells. Scale seems to have an important effect on the level of evapotranspirative losses, with higher seasonal E / P values found in the field cell water balance calculations than were found in the test cells on the Wits campus. This has important implications for full scale semi-arid landfills.

The values of E / E_A (the proportion that calculated evapotranspirative losses comprise potential losses estimated from A pan data) in Table C1 increased steadily each year from about 32 % in the first year to just under 100 % in the final period. This is probably due to the fact that each period was successively wetter. The values indicate that an average of a little more than 4 mm per day was being evapotranspired from the cells. No significant differences in the behaviour of the different waste types and mixtures in the four cells were evident by the end of the 3rd dry season.

6 IMPLICATIONS OF FINDINGS

The field cells at Weltevreden landfill are still at a fairly early stage of degradation, with a maximum of about 0.05 pore volumes having passed through the stored waste. On-going monitoring is clearly necessary in order to gain maximum benefit from the investment already made. The University of the Witwatersrand Research Committee has allocated funding for a period of 2 years (2001/2) to continue monitoring and hopefully will provide support beyond this time. In spite of the waste in the field cells being relatively poorly degraded, a number of useful results can be extracted from the gathered data, an achievement that would not have been possible if monitoring was terminated at the end of 1998 as would have occurred had WRC not provided the funding for this phase of the study (ie January 1999 to April 2001).

The discussion of the results focuses on two prime issues, ie the water balance of the field cells and the time required to reach final stabilisation of the stored waste.

6.1 Water balance of the Weltevreden field cells and the validity of the climatic water balance approach to landfill permitting

Permitting of new landfill sites and the closure of existing sites takes place in accordance with the document, 'Minimum Requirements for the Disposal of Waste by Landfilling', (DWAF, 1998). The objective of the Minimum Requirements is to ensure that the most cost-effective means are used to protect the environment and public health from the adverse impacts of municipal solid waste disposal. In this document the requirements for providing an underliner for a municipal solid waste landfill are based primarily on the size and location (defined in terms of climatic variables) of the landfill. Since the present study focussed on the second of these criteria, ie the climatic water balance, or climatic index, discussion will be limited to this factor.

6.1.1 Climatic index

The climatic index uses published, easily available figures for the weather station closest to the landfill site in question and is defined in terms of a simple atmospheric water balance, with the leachate generating potential being evaluated by the difference between precipitation and evaporation (based on pan evaporation).The climatic index, which is referred to as the Climatic Water Balance, B, is defined (Blight, 1996) as:

$B = R - E$

where

B is the climatic water balance, in mm of water

R is the rainfall in mm

E is the evaporation from the landfill cover surface (usually taken as 0.7xA-pan or 0.88xS-pan evaporation).

Using available rainfall and evaporation records, a value for B is calculated for the wettest year on record. A value for B is then re-calculated for successively drier years to establish whether:

(a) B is positive in less than one year in five for which data are available, or

(b) B is positive in more than one year in five for which data are available

If the first of these conditions applies, no leachate management is deemed necessary, whereas if the second condition applies a leachate management system is required. The reason for carrying out a recalculation is that the wettest year on record may only be because of unseasonal rainfall, and it would be a distortion to base the climatic classification on a single abnormal result. The above, highly simplified calculation is likely to be conservative as it ignores both run-off from the landfill surface and the moisture storage capacity of the waste. Whilst it would be ideal to simulate actual daily (or even hourly) precipitation and evaporation rates,

these are of course not known in advance. Furthermore, high intensity and short duration events will usually result in a greater percentage of runoff than is accounted for by using average values. The approach outlined above will thus likely overestimate leachate generation. It nevertheless forms the basis for a rational evaluation of the need for installing expensive underliner systems.

Using the above procedure, together with available climatic records, the Weltevreden site clearly falls into the designation, 'B", ie a site where a leachate management system is not required and the landfill is considered likely to generate leachate only sporadically, if at all. In view of this, do the results of the field cells monitoring support this designation? An evaluation of this question is provided below.

6.1.2 Leachate volumes at field cells and the relationship to precipitation

During the first two years of monitoring at the field cells, extremely small quantities of leachate were generated, despite the total rainfall being about 1300 mm. Cell 1, which contained only 'rich' waste had produced the lowest volume of leachate by this time. Well into the third wet season, however, the response of Cell 1 in particular changed quite dramatically. Relatively large volumes of leachate were collected on every site visit made thereafter and by the end of March 2001, (the 4th wet season) the total leachate collected from Cell 1 was 5590 litres. This still represents only about 2½% of the total rainfall during the period of the study, although the leachate produced during the last 12 months of the study is equivalent to 4% of the rainfall during this period. The remaining three cells did not exhibit similar behaviour to Cell 1 and continued to produce leachate at a fairly constant rate, with Cell 4 producing the most leachate after Cell 1, but still only a total of 1 070 litres.

An obvious question is why did Cell 1 change its response to precipitation and what does this mean in terms of the Climatic Water Balance approach to landfill designation? As discussed in Section 5.3.2, there was no visible deterioration of the cover at Cell 1 and the change in behaviour is likely a result of the storage capacity of the refuse becoming fully utilised and infiltration through the cover thus easily manifesting as leachate. It appears that the nature of the waste, being highly non-homogeneous and having many, large voids, meant that it was unable to efficiently evaporate moisture during dry periods. The waste in Cells 2 to 4, having at least some proportion of ash and dust, had an improved ability to generate capillary forces that aided the evaporation of stored moisture during periods of no precipitation. Two other factors probably contributed to the generation of leachate:

i) runoff from the surface of the cells was prevented by the construction of retaining berms around the perimeter of the cells. This meant that even during high-intensity rainfall events, water was stored on top of the cells and was thus able to infiltrate the cover.

ii) The initial height of the waste in Cell 1 was only about 1.15m. This meant that the storage capacity was limited and water that penetrated beyond this depth could not be re-evaporated as it was stored within the tyre and stone drainage layer.

Despite these factors, the volume of leachate generated thus far is still relatively small. If we consider that the Minimum Requirements allows up to 200mm of leachate per annum, the volumes being generated by the waste in Cell 1 are insignificant. The rainfall during the period of the study has on 2 occasions exceeded the annual average and thus some generation of leachate was not unexpected.

The extremely small volumes of leachate generated by Cells 2 to 4 point to a somewhat unexpected outcome. Simply by blending waste from 'rich' and 'poor' communities (or ash-poor and ash-rich waste), the hydraulic characteristics of the waste can be vastly improved. The permeability decreases because there are fewer very large voids and the water retention capacity is similarly improved, thus enabling evaporation of stored moisture to occur, providing additional storage capacity for future rainy periods. Although it was not an intended outcome of this study, this result may provide a useful operational guideline to landfill operators in South Africa: blend waste from a range of sources rather than landfilling in isolated, separate cells or sections of landfill space.

6.2 Degree of flushing and time to reach stable conditions

If the Minimum Requirements are adhered to, the ingress of moisture into stored waste is limited and the proportion that might infiltrate through the cover and into the waste, is retarded from emerging from the base as leachate. In our semi-arid climate, where evaporation exceeds rainfall significantly, this often results in the development of a so-called, 'dry-tomb', wherein the lack of adequate moisture ensures that decomposition of the waste is extremely slow. The use of a daily cover of soil further inhibits moisture movement within the landfill.

Whilst it may seem that the 'dry tomb' approach, if properly implemented, provides an inherently environment-friendly solution to waste disposal, the exact opposite may in fact be true. Minimising the current costs of waste disposal may be at the expense of future generations. The waste may retain its pollution potential until sufficient moisture enters the landfill to trigger microbiological degradation processes and thus the formation of leachate and biogas. It is unlikely that cover systems and underliners can be expected to function perfectly in perpetuity. Eventually the potential pollutants inherent in the waste must be returned to the environment in some form or another.

A phrase that is frequently used when describing the 'dry-tomb' approach to landfilling is that of 'isolating the landfill from the environment'. The thinking appears to be that underliners, such as geomembranes, are

now available that can be expected to last for hundreds of years, without deteriorating to the degree that they will become permeable to leachate. Furthermore, cover systems can be designed, constructed and maintained adequately to minimise infiltration into the waste and thus prevent leachate generation. Whilst it is true that the quality and durability of geomembranes are constantly improving, as is the design and construction of cover systems, a crucial aspect that often appears to be overlooked is that of the 'contaminating lifespan' of a landfill. In the USA, federal and state regulations require that waste disposal facilities be designed to function for an active life, plus a post-closure period of typically 30 years, during which time active monitoring of the landfill and its environs is required. A similar requirement is made in the Minimum Requirements document. By implication it therefore seems as if the expectation is that if the landfill satisfies the prescribed performance criteria during this post-closure period, it no longer poses a risk to the environment thereafter.

The question that thus needs to be asked is whose responsibility the landfill becomes after the post-closure monitoring period. The owner of a landfill is likely to be more interested in maintaining the integrity of the cover system during operation and immediate post closure than the period thereafter. If the waste has been effectively isolated from the environment, then at the end of the 'period of care' the landfill may have retained its full potential to contaminate the environment.

6.3 The contaminating lifetime of a landfill

The contaminating lifetime of a landfill may be thought of as the time after which the concentration of certain, specified contaminants in the leachate emanating from a landfill will always be below certain, specified limits. The contaminating lifetime of a landfill may thus be defined differently by different authorities, depending on the perceived 'priority pollutants'. It is also important to note that it is insufficient to merely satisfy these requirements at the end of the post-closure care period; the concentrations of the specified contaminants should never rise above the specified limits at any time in the future either. This once again highlights the problem of the 'dry-tomb' approach in which the pollution potential remains virtually unaltered until some time after the end of the care period.

There are many opinions on the time that a landfill could be perceived to be in its 'polluting phase'. Long term data to substantiate these opinions are less forthcoming. Belevi and Baccini (1989) for example suggest that lead could continue to be leached in dangerous quantities from municipal waste for at least two thousand years. Obviously the data to back up this theory are not available. Rowe (1995) describes a more pragmatic attempt to define the contaminating lifetime of a landfill by looking at the change in chloride concentration in the leachate over a period of ten years and then fitting numerical models to the data to facilitate extrapolation to longer time periods. Chloride was chosen because it is a conservative indicator and

is not attenuated by adsorption or other chemical processes. At the Keele Valley landfill in Ontario, Canada, he found that ten years after the start of placement of waste, the chloride concentration was still increasing. The peak concentration had yet to be reached and results will have to be monitored for many years to facilitate numerical modelling. During the same period there was a decrease in the concentration of the volatile organic compound dichloromethane (DCM). This seems to indicate a degradation of DCM in the waste in-situ, thus making a case for long-term storage of waste having some benefits.

Another example where monitoring of chloride has been used to good effect is the Vejen landfill in Denmark, (Christensen et al, 1993). At this site the upper aquifer is a 10 to 20 m deep sandy deposit, with the water table only 3-5 m below the ground surface. Groundwater flow velocities are of the order of 150 to 200 m per year. Landfilling occurred from 1962 to 1981 and there was no engineered leachate collection system. Annual precipitation at the site is between 700 and 900 mm and the landfill is covered with only a soil cover. Infiltration into the waste is thus likely to be high. Measurements made in 1992 showed chloride concentrations were of the order of 1000 mg/l close to the landfill, decreasing to less than 35 mg/l (which is close to background values) within 250 to 300 m from the landfill. At the same time, a range of Specific Organic Compounds had disappeared within 100 m of the landfill. Once again it seems as if a significant amount of degradation of certain organic compounds can be achieved in-situ, or at least before the organic contaminant travels too far in an underlying aquifer. The rate of degradation, usually measured by the parameter half-life, is a function of the degradation environment. Best estimates (using field measurements at actual landfills) for the half-life of DCM, benzene and toluene was given as 2, 1,8-4,9 and 1,8-5,7 years respectively, (Rowe, 1995). Even though fermentable products may be effectively leached out of stored waste, there remains the problem of inorganics and heavy metals . Lu et al (1981) monitored the change in concentration of a number of parameters with time in actual landfill leachate and derived equivalent 'half-lives'. The values for cadmium, copper and chromium were 11,6 years, 5,1 years and 0,8 years respectively.

The discussion above illustrates that it is extremely difficult to predict the contaminating lifetime of a landfill. The one thing that can be said with some certainty is that biological degradation delayed is not biological degradation avoided. Whilst some compounds will indeed degrade in-situ in the landfill (such as volatile organics), this is not the case for all compounds. The 'dry tomb' approach currently used in South Africa is thus likely to delay the time at which unacceptable contaminants begin entering the environment. If we accept that it is extremely difficult to predict when a landfill has reached the end of its contaminating lifetime and become 'benign', it follows that the question of who takes responsibility for unacceptable releases to the environment once the post-closure period of care is over must be asked.

It is in the interests of the owners and operators of a landfill to minimise emissions of leachate to the environment during the operational and post-closure care period. After this time it becomes someone else's

liability. It may be argued that the prescriptive requirements of some authorities (eg the requirement of 30 years of post-closure monitoring by the USEPA and the Minimum Requirements) implicitly take care of the problem and, if rigorously adhered to, will ensure that a benign state will have been achieved by the time the statutory post-closure period is over. However, there is no guarantee that a benign state will be achieved within this period, particularly if moisture ingress to the waste is actively prevented. The dilemma then facing the designer of a landfill is: 'If I adhere to the prescriptive requirements governing the design of landfills (such as the maximum allowable outflow rates specified in Section 8.4.3 of the Minimum Requirements), am I absolved of environmental pollution that might occur post-closure care?' In essence, does a designer only have to satisfy the Minimum Requirements or does provision need to be made to ensure that the system has a finite contaminating lifetime that is less than the care period?

6.4 Indication of time to reach stability based on field cell data

The vexing question of how long we need for landfills in semi-arid climates to reach a benign state is one that has not been addressed at all. In South Africa it appears (understandably) that our first priority was to ensure that municipal solid waste is collected, transported and deposited in a secure and well-managed facility. This is now being done country wide, at least in the larger urban metropoles, and we now need to consider the possible consequences of our approach to storing waste in a way that renders it a long-term liability. Results from the field cells are used to discuss the time that it may require for large landfills in semi-arid parts of the country to reach a stable, low-risk condition.

For a landfill to pose no further environmental risk, complete stabilisation of organic material and flushing of pollutants is required. This flushing depends on the rate of decay of the waste. Only once compounds have been broken down to soluble components or particles small enough to be transported in suspension can they be removed in leachate. COD and certain metal concentrations decline rapidly when methanogenesis begins. Chloride on the other hand is found in leachate at high concentrations and is not a function of leachate pH. It is thus a useful indicator of how much flushing has occurred. The data from the field cells have been replotted in terms of incremental chloride in mg, per kg of initial dry mass, in Figure C13. For Cell 1 there is an increase in concentration, which peaks at about 16mg/kg, after which time it begins decreasing at a fairly consistent rate. What is of most importance in this plot is the final figure for Cell 1. After about 0.05 pore volumes of flushing, a value slightly in excess of 4mg/kg had been achieved. This still corresponds to a concentration of over 200mg/l. In the Minimum Requirements document, no final compliance limit is set for chloride concentration. Taking the Swiss regulation of 100mg/l, Röhrs et al (2001) have shown that it will take between 0.35 and 0.7 pore volumes of flushing to achieve this limit. Considering that in Cell 1 at Weltevreden it has taken almost four years to achieve 0.05 pore volumes of flushing, it will take at least 28 years to flush the waste in Cell 1 to a condition such that the leachate concentration achieves this limit. This despite the fact that the waste depth in Cell 1 is little more than 1m. In

a full-scale landfill there will be a much greater thickness of waste and it will take a considerably longer time to flush it to the required level of chloride concentration. Indeed, as a starting point it could be argued that for each one metre of waste in a landfill, 28 years of flushing are required to reduce chloride concentrations to acceptable levels.

The picture is even worse if we consider ammonia concentrations, as shown in Figure C14. After 0.05 pore volumes of flushing in Cell 1, the ammonia concentration was still 600mg/l and expressed in terms of mg/kg it was still rising. Kylefors and Lagerkvist (1997) have predicted that it would take 800 years to reach ammonia concentrations of 10mg/l, which might be considered to be an acceptable value for the landfill to be designated as stable or 'fully flushed'. Clearly it is impossible to verify time periods of this magnitude at full scale and we have to rely on smaller scale experiments such as those conducted in this project.

Whatever the time scale needed to achieve full flushing, it is becoming increasingly clear that it is of the order of decades or even centuries. In our semi-arid climate it is likely to be even greater. Work done at the old Waterval landfill that was closed in 1978 has shown that there is no evidence of seasonal leachate migration through the waste body and it appears that all the moisture entering the waste body is retained and re-evaporated before penetrating to the base of the landfill (Blight, 1995). Under this scenario, it may well be impossible to even achieve a moderate degree of flushing (less than 0.05 pore volumes) during the operational life and after care period of a landfill in such a climatic zone. As shown above, at 0.05 pore volumes, the amount of ammonia released can still be rising and certainly nowhere near reaching an acceptably low concentration.

6.5 Implications for design and operation of landfills in South Africa

The conclusions summarised below apply particularly to landfills located in the semi-arid and arid parts of the country. The arguments could quite reasonably be extrapolated to the more humid and sub-tropical parts of the country but, everything else being equal, landfills in these areas produce more leachate (which requires management) and thus achieve a higher rate of flushing.

It is an inescapable conclusion that many landfills in South Africa have undergone a relatively low degree of flushing and thus retain a significant amount of their pollution potential. This 'residual' pollution potential will only be removed by either flushing with moisture, or by generation and emission of biogas. This process is also moisture limited. We must thus recognise that we are storing a large quantity of potentially contaminating material for future generations to deal with. Whilst it may be correctly argued that current levels of sanitary landfilling are a quantum level above what they were only two decades ago, we need to recognise the implications of our current approach to landfilling. Having recognised this, we can decide to

adopt measures to address the problem, eg finding ways to accelerate decomposition without imposing an additional risk to human health or the environment.

It is also clear that we need to recognise the inadequacy of current after-care periods. It is highly unlikely that any landfill in the drier parts of the country will have reached an acceptable state of flushing at the end of the 30 year post-closure period. These 'semi-stabilised' landfills will thus become the custodian of the State, potentially imposing sizeable remediation and rehabilitation costs on future generations.

7 CONCLUSIONS AND RECOMMENDATIONS

The support of the Water Research Commission enabling us to continue monitoring the field cells at the Weltevreden landfill has provided some invaluable information that has implications for the way landfills are designed and operated in South Africa. Before addressing the specific aims of this project, it is worth briefly re-visiting the objectives and context of the original phase of the work (funded under contract # K5/670). At the time the original proposal was submitted, many local authorities in South Africa were still sending refuse from 'white' and 'black' suburbs to separate landfills. The rationale of the proposal submitted to the WRC was that the waste from 'black' suburbs could have a significantly lower pollution potential than that from 'white' suburbs and less stringent (and less expensive) requirements could be appropriate for landfills accepting this type of waste. The reasons for this hypothesis were the expected superior hydraulic characteristics of the waste and the waste composition (much less putrescible matter).

Needless to say, after 1994 the absurdity of the apartheid landfill disappeared and waste going to a particular landfill was drawn from all socio-economic groupings. To some extent, the original justification of the work also thus fell away. Preliminary findings from the Weltevreden field cells, together with results from the Wits 'mini-landfills', indicated that there may well be some synergistic benefits of disposing of the two refuse types together (as was indeed happening at operational landfills by 1995) and the field cells could thus be expected to continue to provide useful information. This has proved to be correct, as discussed below in terms of the original objectives of the second phase of work. Before discussing the results in these terms, the original objectives are restated below:

As described in the project proposal, the objectives of this project were to:

i) Continue to monitor the emissions from the field test cells (at Weltevreden municipal landfill) in order to obtain full advantage of the money already spent on construction of the cells.

ii) Monitor changes in the moisture content of the waste with time and relate this to ambient climatic conditions

iii) To use these data, together with those already obtained, to refine and improve current landfilling standards to increase affordability for disadvantaged communities

Discussing these objectives separately:

7.1 Emission monitoring

The results of the biogas monitoring were disappointing, in the sense that very small fluxes through the soil cover was detected at any of the cells. This is not to say that methane and carbon dioxide were not being generated. As shown by the discrete measurements made from within a vertical tube inserted into the waste, there was indeed gas being generated within the refuse, an observation that is confirmed by the near-neutral pH of leachate from all cells. The relatively thick, well-compacted soil cover probably restricted gas fluxes to small quantities and it is possible that gas may have been emerging on the less well compacted side slopes of the landfill. The apparatus developed by Morris (2001) is unable to measure fluxes on steep slopes and it was thus not possible to test this hypothesis (on a full scale landfill this restriction is less of a problem because the slopes form a relatively small percentage of the surface area and a higher degree of compaction is achievable than on our small test cells). Morris (2001) reported similar finding at the large urban Bisasar Road landfill in Kwa-Zulu Natal. Despite this landfill being in a high rainfall region and being a B^+ classification landfill, he measured negligible biogas emissions at all but a small number of locations. Thus while it was likely that biogas was being generated to some extent, its measurement proved unsuccessful and indicated that the quantities were probably minimal. The most valuable data obtained was undoubtedly the leachate data.

As described in the report, for the first 2½ years of operation, the field cells produced negligible quantities of leachate. It was only after Day 931 that Cell 1 began to produce significant quantities of leachate and this trend continued to the end of the study. The remaining three cells, however, continued to produce leachate at very low rates and by the end of the study had been subjected to a mere 0.01 to 0.015 pore volumes of flushing. Cell 1, which by this stage had reached about 0.05 pore volumes flushed, was still producing unacceptably high strength leachate and clearly nowhere near reaching a stable condition, despite containing little more than a metre thickness of waste.

The first objective was thus only partially met in terms of biogas emissions, a factor that is principally due to what appeared to be very low biogas generation rates. It was certainly met in terms of leachate emissions measurements. The leachate drainage and collection system continued to function extremely well and the data has proved invaluable. Evaluation of the data gathered so far goes a long way to providing an indication of the limitations of current provisions for landfill after-care, as discussed further in Section 7.3.

7.2 Monitor changes in the moisture content of the waste and relate this to climatic conditions

The original intention was to use measurements of moisture content throughout the waste profiles in each cell to determine whether leachate could be expected to be generated at some time in the future. This proved to be somewhat unnecessary because all four cells produced enough leachate during the course of the study to make meaningful comparisons with rainfall and evaporation by performing cell-specific water balances. It was just as well this occurred as the moisture monitoring within the waste body was largely unsuccessful. The moisture meters (and the thermocouples for measuring temperature changes within the waste) both

corroded extremely quickly within the aggressive environment of the waste body. The gypsum blocks did not suffer from corrosion but at the relatively high water contents within the waste the resolution of the blocks was such that the readings were of little use. In addition, the large pore spaces, particularly in Cell 1, meant that the blocks were not necessarily in intimate contact with the waste and could thus not measure suction accurately.

7.3 Suggested refinements to current landfilling standards

The suggestions made in this section do not discuss possible changes to landfilling standards to make waste disposal more affordable for disadvantaged communities, as was the intention of the original proposal. This is because the waste is no longer segregated and any particular landfill now receives waste from a variety of sources, thus making differentiated standards irrelevant. The possible refinements to current landfilling standards that are discussed focus on the likely long-term polluting potential of landfills, which is a subject relevant to all communities.

In keeping with many parts of the world, the South African Minimum Requirements specify a post-closure aftercare period of 30 years for municipal solid waste landfills. Implicit in this specification is the assumption that after this relatively long time, the landfill will have become fully flushed (by one or both of leachate and biogas emissions) and be in a state such that it poses no risk to the surrounding environment or adjacent communities. It is increasingly becoming a concern in many countries abroad that this is an inadequate aftercare period. Many of these countries have a temperate climate at best and in South Africa, where much of the country is arid or semi-arid, the problem is exacerbated by the lack of moisture ingress to the waste body.

The results of the Weltevreden test cells illustrate this point clearly. Even though the waste thickness was of the order of only one metre in all cells, a maximum of 0.05 pore volumes of flushing occurred, with 3 of the 4 cells having less than 0.015 pore volumes of flushing. In the case of Cell 1, which had the highest degree of flushing, the concentration of contaminants such as ammonia were still rising and the waste was clearly nowhere near having stabilized. As argued in this report and substantiated by many recent and current international studies, the time taken to reach a benign state could be of the order of decades or even centuries for landfills in semi-arid climates operated according to the 'dry-tomb' philosophy (which is the status quo).

The recommendation to draw from this study is that the validity of the current aftercare period be re-evaluated, particularly in the context of South Africa's stated commitment to the concept of sustainable development. If found to be inadequate (as this report argues to be the case) recommendations need to be made as to how the degradation rates within problematic landfills can be accelerated without causing an increased risk of unacceptable leachate or biogas emissions.

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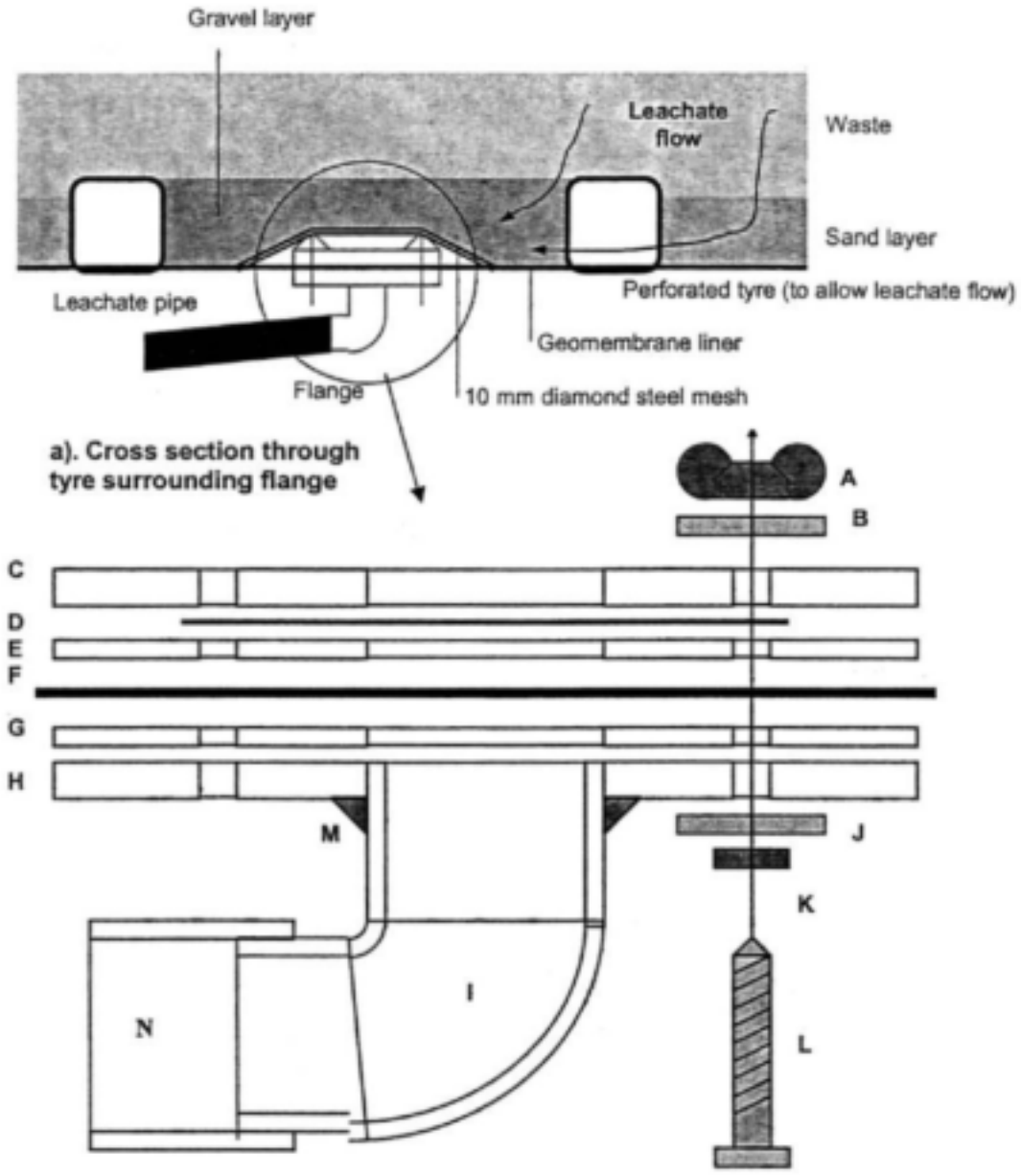
APPENDIX A: FIELD CELLS CONSTRUCTION DETAILS: FIGURES



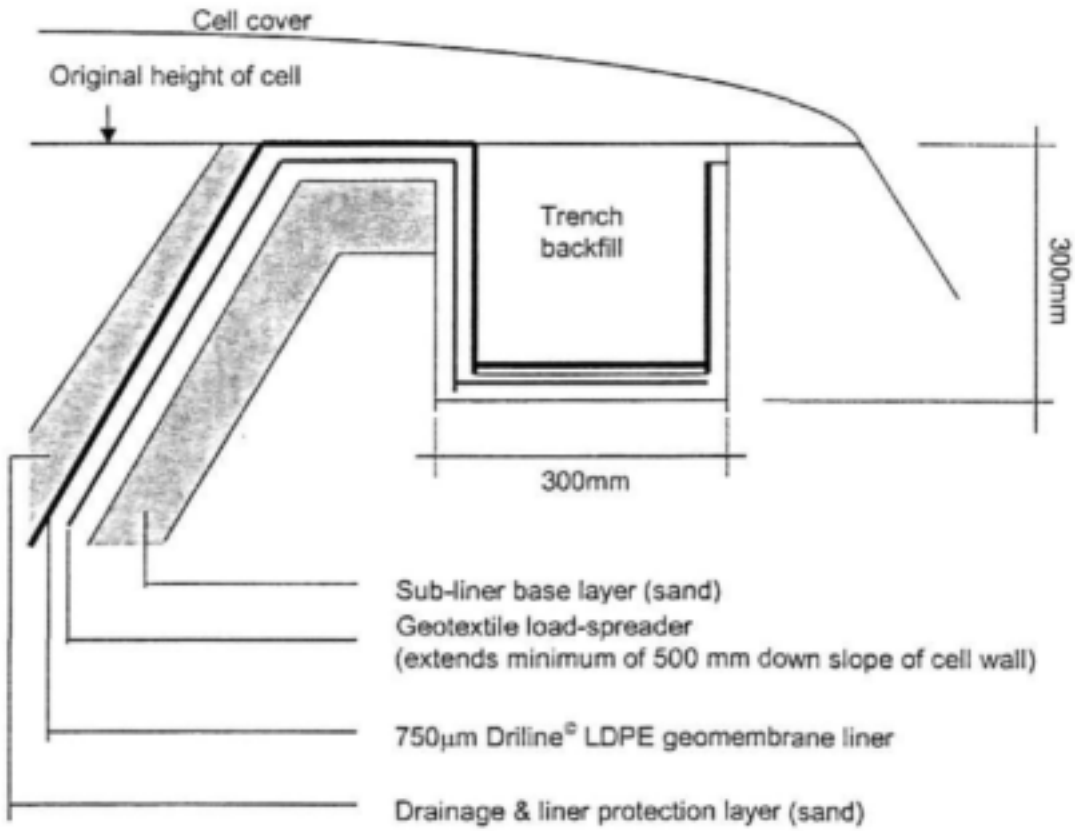
Notes: 1. A. Wing nut*. B. Steel washer*. C. 6 mm perspex top flange plate. D. Rubber sealant strip. E. 3 mm rubber gasket. F. 750 μm Driline© LDPE geomembrane. G. 3 mm rubber gasket. H. 6 mm perspex bottom flange plate. I. Plastic 90° angle. J. Steel washer*. K. Steel spring-washer*. L. Steel 6 mm diameter bolt*. M. Epoxy resin cemented join. N. HDPE leachate drainage pipe.

*Total of eight per flange (holes at 45° spacings in plan view).

2. Figure not to scale.

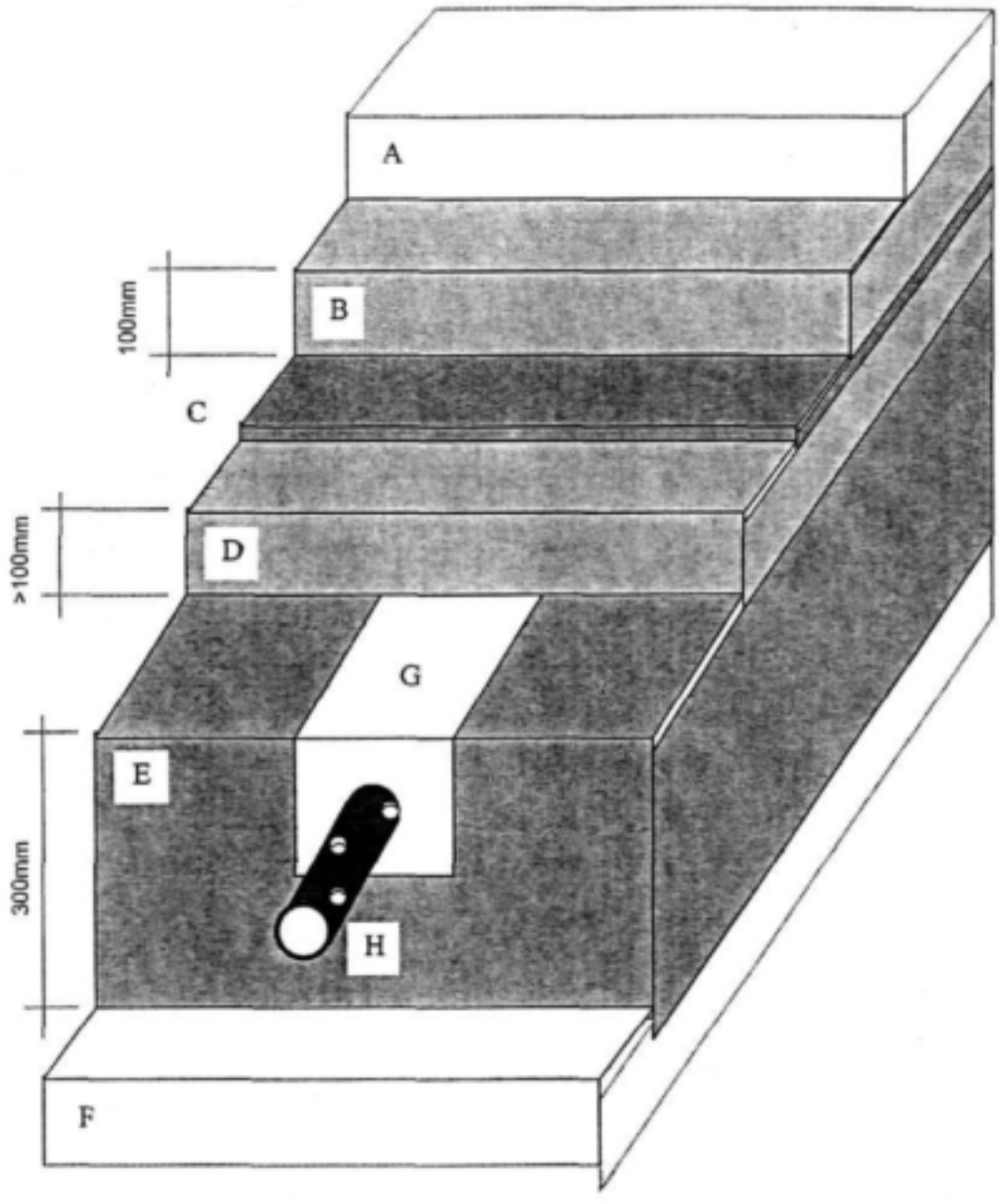
b). Cross section through flange showing construction components

Figure A1 Leachate pipe to geomembrane connection flange detail



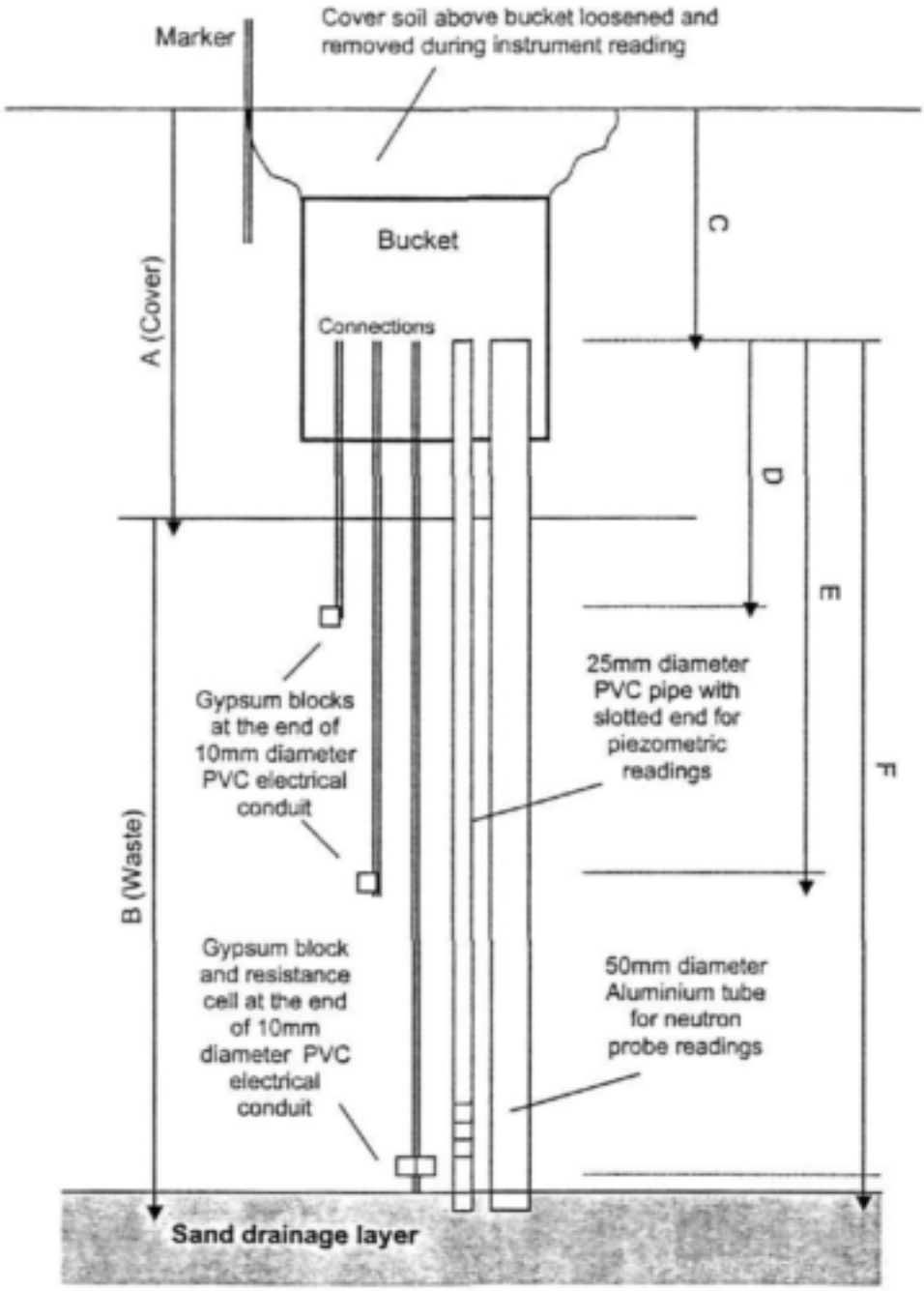
Note: 1. Figure not to scale.

Figure A2 Field cell liner anchor trench detail



Notes: 1. A. MSW in upper field cell. B. Sand layer for leachate drainage & liner protection.
C. 750 μm Driline© LDPE geomembrane sheet. D. Sand sub-liner base layer.
E. MSW in lower field cell. F. Clayey sand cover layer for lower field cells.
G. 100 mm by 100 mm trench, backfilled with 13 mm gravel, containing gas vent pipe for lower cells. H. 50 mm diameter LDPE pipe, perforated with four 10 mm holes at 90° spacings at 250 mm centres.
2. Figure not to scale.

Figure A3 Detail of lower cell gas vent system & upper-lower cell interface



Notes: 1. Not to scale.

2. Dimensions A – F are given in Table B5 of Appendix B1.

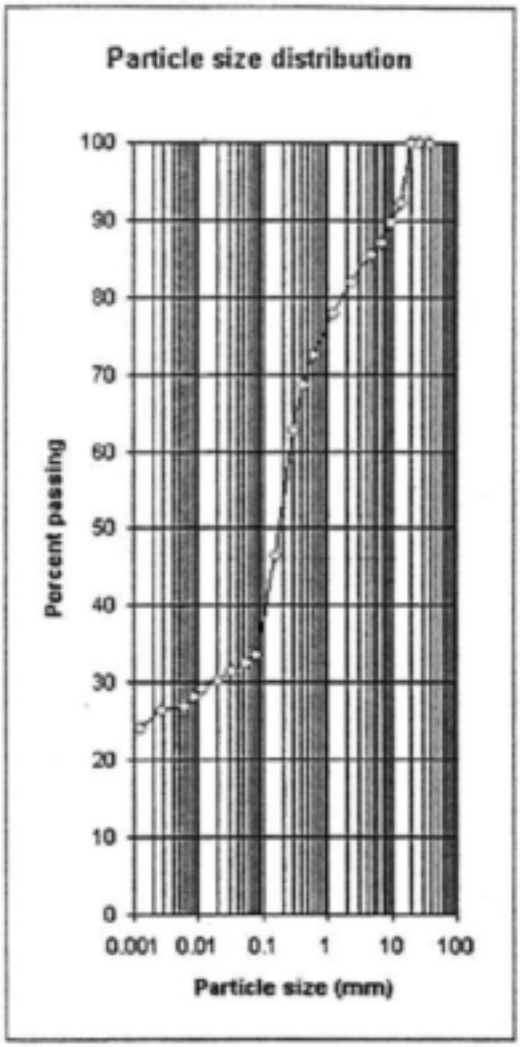
Figure A4 Detail of monitoring instruments installed in field cells

Liquid Limit (%)	30
Plastic Limit (%)	13
Plasticity Index	17

Linear Shrinkage (%)	5
Specific Gravity	2.71
USCS Classification	**SC**

Laboratory sample description: Slightly greeny/grey yellow/brown gravelly clayey sand

Particle size	Percent passing	Description	
mm	by mass	type	%
37.50	100.0	Gravel	20
26.50	100.0		
19.00	100.0		
13.20	92.2		
9.50	89.6		
6.70	87.2		
4.75	85.7		
2.36	82.0		
1.180	78.0	Sand	47
0.600	72.5		
0.425	68.6		
0.300	62.6		
0.150	46.6		
0.075	33.6		
0.0540	32.6	Silt	8
0.0316	31.5		
0.0201	30.4		
0.0116	29.3		
0.0083	28.2		
0.0059	27.1		
0.0028	26.6		
0.0012	24.2	Clay	25
Total percent passing:			100



Note:

1. Standard analyses applied throughout as per the Unified Soils Classification System (USCS) methodology as detailed in Bowles (1986).

Figure A5 Analysis of cover soil at the field cells

APPENDIX B: FIELD CELLS CONSTRUCTION DETAILS: TABLES

Field Cells						
Wet mass of waste: daily input (kg)						
Cell 1	Cell 2		Cell 3		Cell 4[1]	Day of filling
Rich	Rich	Poor	Rich	Poor	Poor	
12600	12420	0	0	0	8400	1
47050	5520	2500	8100	2500	2040	2
28740	9380	5500	12080	9760	31380	3
0	0	2080	0	0	0	4
0	20200	16900	0	3380	6620	5
0	0	0	5820	3200	27180	8
0	0	0	0	14800	-2500	9
0	0	0	0	0	15700	10
0	0	0	0	0	20460	11
0	0	0	0	0	14300	12
Total wet mass of waste (kg)						
88390	47520	26980	26000	33640	123580	
	74500		59640			
Volume of waste in cell (m^3)						
130.11	106.95		78.26		103.27	
As-placed wet (bulk) density of waste (kg m^{-3})						
679	697		762		1197	
Total dry mass of waste[2] (kg)						
54901	29516	20754	16149	25877	95062	
	50269		42026			
As-placed dry density of waste (kg m^{-3})						
422	470		537		921	

Notes:

1. 2500kg transferred from Cell 4 to Cell 3 on Day 9 to enable Cell 3 to be completed.
2. Initial gravimetric moisture content of waste was 61% for rich waste and 30% for poor waste in the field cells and 67% for rich waste and 38% for poor waste in the test cells.

Table B1 Mass & density of waste in field cells & test cells

Cell	Surface[1]	Section[2]	Dimensions[3] (m)								Areas (m^2)	
			d	a	b	x	t	j	k	y	$A_{section}$	$A_{surface}$
1	B	L	10.7	5.2	5.6	5.0	5.6	1.3	0.6	8.8	51.57	96.05
		N	10.7	4.6	5.2	4.5	5.0	1.1	1.6	8.0	44.48	
	T	L	16.5	7.2	7.9	7.0	7.9	1.7	0.8	14.0	113.41	220.83
		N	16.5	7.2	8.0	7.0	7.7	1.6	2.2	12.7	107.42	
2	B	L	10.2	4.2	4.9	4.1	4.9	1.0	0.3	8.9	42.84	85.95
		N	10.2	4.2	4.9	4.2	4.8	0.2	1.1	8.9	43.11	
	T	L	15.8	6.2	7.3	6.0	7.3	1.4	0.5	13.9	98.46	196.28
		N	15.8	6.1	7.1	6.1	7.0	0.4	1.4	14.0	97.82	
3	B	L	9.3	3.4	3.6	3.4	3.6	0.5	0.5	8.3	30.80	66.29
		N	9.3	3.8	4.0	3.8	4.0	0.2	0.2	8.9	35.49	
	T	L	14.5	5.7	6.0	5.6	6.0	0.8	0.7	13.0	79.74	162.40
		N	14.5	5.6	6.0	5.6	6.0	0.2	0.3	14.0	82.66	
4	B	L	10.0	4.9	5.4	4.8	5.3	1.2	0.8	8.0	45.40	96.35
		N	10.0	5.2	5.9	5.2	5.8	0.5	1.0	8.5	50.95	
	T	L	15.2	7.5	8.1	7.3	8.0	1.8	1.0	12.4	105.43	214.49
		N	15.2	7.4	8.1	7.4	8.0	0.7	1.4	13.1	109.06	

Notes:

1. T = Top, B = Bottom
2. L = Section including leachate drain, N = Section not including leachate drain
3. These cell dimensions are defined in Figure 3.11 of Section 3.5.2.

Table B2 Dimensions & areas of the field cells

	Cell 1	Cell 2	Cell 3	Cell 4
Wet mass of rich waste (kg)	88390	47520	26000	0
Wet mass of poor waste (kg)	0	26980	33640	123580
Total wet mass of waste (kg)	88390	74500	59640	123580
Proportion of rich waste (%)	100	63.8	43.6	0
Proportion of poor waste (%)	0	36.2	56.4	100
Waste composition (% by wet mass)				
Putricible (garden & food waste)	47.0	36.5	30.6	18.0
Ash & inert material	0.0	20.6	32.2	57.0
Paper & card	24.0	16.8	12.7	4.0
Metals	8.5	6.7	5.7	3.5
Glass	12.0	8.4	6.4	2.0
Textiles	0.5	1.0	1.3	2.0
Plastics	7.0	6.6	6.4	6.0
Miscellaneous	1.0	3.4	4.7	7.5
Total	100.0	100.0	100.0	100.0

Table B3 Composition of waste in the field cells & test cells (waste composition data from Shamrock, 1998)

Cell[1]	Total volume of waste	Wet mass of waste	Bulk density of waste	Gravimetric moisture content[2]	Proportion of waste type contained		Specific gravity	Initial conditions2		
					Poor waste	Rich waste		Voids ratio	Porosity	Volume of voids
	m^3	kg	$kg\ m^{-3}$	%	% dry mass		G_s	e	n	m^3
1	130.11	88390	679.3	61	0	100	2.55	5.04	0.835	108.58
2	106.95	74500	696.6	0	41.1	58.9	2.52	4.36	0.813	86.99
3	78.26	59640	762.1	0	61.2	38.8	2.50	3.66	0.785	61.47
4	103.27	123580	1196.7	30	100	0	2.47	1.68	0.627	64.78

Notes:

1. Lysimeters (L), Test Cells (H), Field Cells (no suffix).
proportion of each waste type (rich or poor) contained in terms of dry mass.
2. Calculation of voids ratio, porosity and volume of voids does not take into account any waste settlement during decomposition.

Table B4: Properties of the waste

APPENDIX C: MONITORING RESULTS

Description (*time period*)	Cell 1	Cell 2	Cell 3	Cell 4	Units
Initial					
Bulk density at placement	679.3	696.6	762.1	1196.7	kg m^{-3}
Gravimetric moisture content at placement	61	48	42	30	%
Degree of saturation, Sr, at placement	30.9	27.7	28.7	44.1	%
Day 0 - Day 34 (first appearance of leachate)					
Precipitation when leachate produced	160	160	160	160	mm
A pan evaporation in same period (E_A)[1]	150	150	150	150	mm
Degree of saturation, Sr, at field moisture capacity	32.9	30.0	31.3	47.4	%
Gravimetric field moisture capacity	65.0	51.9	45.9	32.3	%
Day 34 - Day 315 (end of first dry season)					
Cummulative precipitation in that period (P)	310	310	310	310	mm
Cummulative leachate removed (L)	0.03	0.16	0.51	0.67	mm
Net precipitation added to waste (P - L = E)	309.47	309.34	308.99	308.83	mm
A pan evaporation in same period (E_A)[1]	940	940	940	940	mm
E / E_A	32.9	32.9	32.9	32.9	%
E / P	99.99	99.95	99.83	99.78	%
Day 315 - Day 690 (end of second dry season)					
Cummulative precipitation in that period (P)	750	750	750	750	mm
Cummulative leachate removed (L)	-0.03	-0.16	-0.51	-0.67	mm
Net precipitation added to waste (P - L = E)	750.43	750.56	750.91	751.07	mm
A pan evaporation in same period (E_A)[1]	1310	1310	1310	1310	mm
E / E_A	57.3	57.3	57.3	57.3	%
E / P	100.00	100.02	100.07	100.09	%
Day 690 - Day 931 (end of observations)					
Precipitation to restart leachate flow (P)	482	482	482	482	mm
Leachate removed at that time (L)	7.04	0.62	0.41	0.36	mm
Net precipitation added to waste (P - L = E)	474.96	481.38	481.59	481.64	mm
A pan evaporation in same period (E_A)[1]	1000	1000	1000	1000	mm
E / E_A	47.5	48.1	48.2	48.2	%

Notes:

1. Data from Blight (2000).

Table C1 Waste & water balance data for the field cells

Day[1]	Leachate Volume	pH	Conductivity	Alkalinity as $CaCO_3$	Ammonia as N	Nitrate as N	Chloride as Cl	COD as O	Metals					
									Ni	K	Cd	Cu	Zn	Co
	litres		mS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
0	0													
34	0.5	5.8	5.2	1200	78	0	240	7820	0.72	180	0	0	22	0.7
69	4	5.1	10.67	1600	200	5.6	320[2]	8325	14	200	0	0.6	180	6
103	2.5	5.5	9.73	1350	180	0	400	6600	8.3	270	0	0	52	4.9
382	8.5	6.5	6.93	2300	100		530	3000	0	280			1	0.12
406	13.6	6.5	10.55	4000	350		800	7530	0	950			0.19	0.15
445	19	7.3	9.5	3400	360		640	7190	0.04	660			0.47	0.13
480	19	7.2	11.5	5500	850		940	2985	0.07	400			0.48	0.11
503	16.5	7.4	11	5000	850		930	2290	0.08	850			0.35	0.08
556	13	7.5	10.6	4400	70		980	1500	0	180			0.48	0
622	13.5	7.25	6.85	3600	50		940	3725	0.06	1580			0.08	0.06
649	10	7.6	5.43	2500	74		1150	4580	0.08	610			0.1	0.06
721	7	7.5	5.3	5000	50		1140	1490	0.14	820			0.12	0.1
931	1555.5	7.35	8.76	5500	240		530	2956	0.1	670			0.23	0.15
997	632	7.1	10.74		500		650	1900	0.1				0.09	0.2
1119	1340	7.3		2500	250		410	910	0.06				0.06	0.25
1182	840	7			250			770	0.03				0.06	0.34
1257	1100	7.3			600		220	790	0.11				0.06	0.16

Notes:

1. Day 0 is 31 October 1997

2. Inferred value. Original sample lost before parameter measured.

Table C2 Cell 1 leachate analysis data

Day[1]	Leachate Volume	pH	Conductivity	Alkalinity as $CaCO_3$	Ammonia as N	Nitrate as N	Chloride as Cl	COD as O	Metals					
									Ni	K	Cd	Cu	Zn	Co
	litres		mS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
0	0													
34	8.5	6	3.8	450	28	0	140	1490	0,34	36	0	0	3.4	0.46
69	14.5	5.8	6.94	1500	63	15	305[2]	5450	1	120	0	0	2	1
103	1	6.2	5.9	1500	100	0	470	5400	0.77	190	0	0	8	1.3
137	7.5	6.6	1.92	750	41		180	1535	0.07	170			0.09	0.2
350	22.5	5.73	4.51	650	65		220	2650	0,24	150			2.2	0.3
382	35	6.2	5.93	2200	150		260	5000	0,07	140			0.55	0.12
406	58.8	6.9	5.9	2500	200		300	2940	0,04	240			0.79	0.12
445	54.5	7.3	7.15	3000	280		360	880	0,04	330			0.17	0.12
480	46	6.9	6	3500	100		320	785	0	340			0.18	0.11
503	36.5	7.05	5.9	2800	310		320	780	0	330			0.12	0.09
556	41.5	7.3	6.5	2850	620		340	1300	0	420			0	0.1
622	39	7.5	9.9	1950	930		420	880	0,04	570			0.03	0.07
649	33	7.38	3.62	4000	200		550	1045	0,07	300			0.18	0.08
721	24	7.4	4.88	4500	60		860	890	0.1	510			0.09	0.11
931	122	7.23	8.38	4350	390		480	1232	0.1	740			0.05	0.1
997	47	7.2	10.39		750		700	1120	0,11				0.02	0.1
1119	57	7.1		1500	190		200	190	0,03				0.02	0.06
1182	117	7.1			400		210	450	0.03				0.01	0.04
1257	86	7.5			550			490	0.13				0.02	0.03

Notes:

1. Day 0 is 31 October 1997

2. Inferred value. Original sample lost before parameter measured.

Table C3 Cell 2 leachate analysis data

Day[1]	Leachate Volume	pH	Conductivity	Alkalinity as $CaCO_3$	Ammonia as N	Nitrate as N	Chloride as Cl	COD as O	Metals					
									Ni	K	Cd	Cu	Zn	Co
	litres		mS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
34	17	6	2.7	800	33	0	140	2280	0.08	80	0	0	2.9	0.11
69	16	6.6	4.67	2450	26	0	230[2]	3380	0	79	0	0	1	0
103	17.5	7.1	5.45	2200	200	0	320	3600	0	190	0	0	0	0.14
137	17.5	7.1	4.36	1500	135		470	855	0.06	260			0	0.17
185	15	7.5	4.76	2328[2]	191[2]		330[2]	870	0.071[2]	153[2]			0.039[2]	0.159[2]
224	13.5	7.3	5.8	3000	350		600	870	0.08	280		0	0.07	0.15
264	0.2	7.74	7.07	1000	190		640	1160	0.84	220			0.56	0.39
291	Trace													
350	15	6.34	4.64	800	120		220	2420	0.27	180			0.49	0.21
382	18	6.6	2.81	1200	80		120	860	0.04	86			0.21	0.05
406	23	7	3.44	2000	100		200	470	0.05	140			1	0.07
445	17	6.9	3	1000	60		110	2280	0	84			0.15	0.08
480	15.5	6.5	2.95	1100	28		130	690	0	100			0.2	0.08
503	19.5	6.65	3.7	1400	110		220	500	0	110			0.12	0.07
556	16	7.1	4.6	1900	270		300	520	0.04	270			0	0.12
622	16	7.2	5.35	500	150		390	655	0.05	310			0.07	0.08
649	14.5	7.26	2.54	500	92		430	640	0.06	190			0.08	0.08
721	13.5	7.2	2.77	2600	20		470	360	0.06	210			0.09	0.1
931	67	7.6	10.01	4800	290		780	1133	0.09	570			0.04	0.12
1119	25	7.5		7000	500		880	850	0.1				0.04	0.05
1182	77	7.3			930			1200	0.04				0.02	0.03
1257	79	7.6			1000		370	990	0.18				0.02	0.05

Notes:

1. Day 0 is 31 October 1997
2. Inferred value. Original sample lost before parameter measured.

Table C4 Cell 3 leachate analysis data

Day[1]	Leachate Volume	pH	Conductivity	Alkalinity as $CaCO_3$	Ammonia as N	Chloride as Cl	COD as O	Metals			
								Ni	K	Zn	Co
	litres		mS/cm	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
34	20[3]	6.8	7.7	2600	91	530	8720	0	180	0.12	0.11
69	20[3]	6.7	9.9	3350	220	920[2]	12375	1	260	1	1
103	17.5	7.8	15.03	6500	520	1300	9700	0.23	760	0	0.19
137	44	7.5	12.77	4800	525	1680	4140	0.18	1040	0	0.18
138	20.1	7.5	9.39	3900	400	1370	2800	0.09	580	0	0.18
185	21.5	7.9	11.37	5500	630	1400	1620	0.3	1240	0.58	0.18[2]
224	22.4	7.4	14.65	7500	650	1700	1685	0.3	870	0.53	0.18
264	21.5	7.75	15.03	7000	850	1800	1825	0.21	540	0.28	0.14
291	21	7.77	15.08	14500	700	2300	2300	0.21	1900	1.6	0.15
350	43	7.38	15.94	7500	750	1400	1820	0.12	1250	0.18	0.11
382	27	7	10.9	4000	350	900	6000	0.03	310	3.3	0.18
406	95.5	7	7.71	4000	200	350	3840	0	200	1	0.23
413	62	6.8	5.32	2300	95	220	8070	0	220	2.9	0.18
445	58	7.3	6.15	2700	170	260	915	0.06	160	1.6	0.142[2]
480	47.5	6.9	5.4	2900	140	220	680	0	170	0.77	0.15
503	40.5	6.9	4.7	2300	190	160	535	0	130	0.59	0.07
556	40	7.2	5.5	2200	90	320	320	0	130	0	0.1
622	22	7.35	6.55	1600	50	480	620	0.04	330	0.19	0.07
649	21	7.44	3.62	900	48	730	650	0.1	420	0.3	0.11
721	14	7.4	4.5	4000	75	1050	400	0.08	370	0.03	0.1
931	78	7.1	2.03	1050	63	67	99	0.07	9.9	0.08	0.09
997	24	6.85	4.9		250	400	200	0.06		0.01	0.05
1119	102	6.77		360	70	39	100	0.03		0.01	0.04
1182	113	6.9			150	40	69	0.03		0.01	0.05
1257	75	7.1			200	53	74	0.03		0.01	0.03

Notes:

1. Day 0 is 31 October 1997 2. Inferred value. Original sample lost before parameter measured. 3. Inferred value due to leachate pipe leak.

Table C5 Cell 4 leachate analysis data

Day	Gas Emission Flux (g m^{-2} day^{-1})						Soil Moisture Content (%)	Runs failing R^2>0.5 criterion
	Position A		Position B		Position I			
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2		
264	0	11			0	2	5.5	1/6
	0	-						
291	0	3			0	0	3.6	0
312	0	-			0	-	3	2/4
349	-11	-255			0	-	8.2	1/12
	0	19			0	2		
	0	4			0	92		
377	0	10			0	-104	13.9	0
	0	-34			0	0		
	0	114			0	-108		
391	0	117			-	-	18.5	2/12
	0	-7			0	0		
	0	-22			0	38		
482	6	35	0	5	290	520	12.4	0
503	0	0	0	0	15	57	15.6	0
556	0	0	0	0	49	57	12.1	0
649			0	0	0	0	3.4	0
721	0	0	0	0	0	0	5.9	0

Notes:

1. An empty box indicates no measurement taken. 2. A symbol '-' indicates that gas was detected but that the R^2>0.5 criterion for dC/dt was not satisfied.

Table C6 Gas emission measurements at Cell 1

Day	Gas Emission Flux (g m^{-2} day^{-1})						Soil Moisture Content (%)	Runs failing R^2>0.5 criterion
	Position A		Position B		Position I			
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2		
264	0	3			9	22	5.5	0
291	0	0			0	11	3.6	0
312	0	-			0	7	3	1/4
349	0	5			0	64	8.2	0
	0	114			0	50		
	0	11			0	20		
377	0	110			132	123	13.9	0
	0	0			0	15		
	0	98			128	56		
391	0	-114			64	44	18.5	2/12
	-	-			0	51		
	0	0			0	45		
482	-	8	0	10	250	394	12.4	1/6
503	0	0	0	0	122	119	15.6	0
556	0	0	0	0	76	108	12.1	0
649			0	0	0	30	3.4	0
721	0	0	0	0	0	24	5.9	0

Notes:

1. An empty box indicates no measurement taken. 2. A symbol '-' indicates that gas was detected but that the R^2>0.5 criterion for dC/dt was not satisfied.

Table C7 Gas emission measurements at Cell 2

Day	Gas Emission Flux (g m^{-2} day^{-1})						Soil Moisture Content (%)	Runs failing R^2>0.5 criterion
	Position A		Position B		Position I			
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2		
264	0	3			0	10	5.5	1/6
	0	-						
291	0	13			0	17	3.6	0
312	0	5			0	-	3	1/4
349	0	-8			0	0	8.2	0
	0	15			0	98		
					0	39		
377	0	0			0	22	13.9	0
	0	0			0	25		
	0	-75			0	-43		
391	0	0					18.5	1/4
	0	-						
482	0	8	0	6			12.4	1/6
	0	-						
503	0	0	0	0	0	0	15.6	0
556	0	0	0	0	7	56	12.1	0
649			0	0	0	0	3.4	0
721	0	0	0	0	0	63	5.9	0

Notes:

1. An empty box indicates no measurement taken. 2. A symbol '-' indicates that gas was detected but that the R^2>0.5 criterion for dC/dt was not satisfied.

Table C8 Gas emission measurements at Cell 3

Day	Gas Emission Flux (g m^{-2} day^{-1})						Soil Moisture Content (%)	Runs failing R^2>0.5 criterion
	Position A		Position B		Position I			
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2		
264	0	15			0	17	5.5	0
291	0	11			0	-	3.6	1/4
312	0	14			0	10	3	1/4
349	0	15			0	61	8.2	0
					0	68		
					0	85		
377	0	0			48	69	13.9	0
	0	-96			0	69		
	0	0			0	60		
391							18.5	
482	-	-	9	7	162	208	12.4	2/6
503	0	0	0	0	242	83	15.6	0
556	0	0	0	0	58	76	12.1	0
649			0	0	0	26	3.4	0
721	0	0	0	0	0	0	5.9	0

Notes:

1. An empty box indicates no measurement taken. 2. A symbol '-' indicates that gas was detected but that the R^2>0.5 criterion for dC/dt was not satisfied.

Table C9 Gas emission measurements at Cell 4

Day	Temperature			Piezo-metric level	Cover soil grav. moisture content	Gravimetric moisture content of waste			Gas composition in waste pore spaces					
	Waste	Cover Soil							Top of cell		Middle of cell		Bottom of cell	
	at base	15cm depth	70cm depth			Top of cell	Middle of cell	Bottom of cell	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
	°C	°C	°C	cm	%	%	%	%	%	%	%	%	%	%
103													0	15
186	22					>25	>25	>25					0	9
244	18			0		<25	<25	<25						
264	17.5			0	5.5	<25	>25	<25					0	6
291	17.5			0	3.6	<25	>25	<25					0	15
312					3									
349					8.2									
350	19.5			0		>25	>25	25					0	2
377					13.9									
382	17			0		>25	>25	102	0	1	7	26	0	0
391					18.5									
405	20			0		>25	>25	108	5	14	20	31		
445	20			0		>25	>25	108	26	38	30	38	27	37
480	20			0		>25	>25	108	26	36	30	36	17	20
482					12.4									
503	20	23.5		0	15.6	>25	>25	115	17	32	28	35	0	2
556	20	16.5		3	12.1	>25	>25	120	11	26	24	31		
622	20			0		>25	>25	120	1	15	8	22	6	20
649		22			3.4									
721	22	15	17	0	5.9			120	1	17	8	21	0	10

Notes: 1. Piezometric level is measured up from base of cell.

2. The 'top' and 'middle' waste moisture values are from gypsum block data only. The 'bottom' value is from gypsum blocks & resistance cell.

Table C10 Parameters monitored at Cell 1

Day	Temperature			Piezo-metric level	Cover soil grav. moisture content	Gravimetric moisture content of waste			Gas composition in waste pore spaces					
	Waste	Cover Soil							Top of cell		Middle of cell		Bottom of cell	
	at base	15cm depth	60cm depth			Top of cell	Middle of cell	Bottom of cell	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
	°C	°C	°C	cm	%	%	%	%	%	%	%	%	%	%
103													9	23
186													2	11
224													2	9
244	18			0		<20	<20	65						
264	17.5			0	5.5	<20	>25	65					5	18
291	17			0	3.6	<20	>25	70					1	9
312					3									
349					8.2									
350	18			0		>25	>25	65					0	3
377					13.9									
382	17.5			1		<20	>25	75	5	15	14	20	15	29
391					18.5									
405	18			20		>25	>25	70	7	16	22	30		
445	19			21		>25	>25	>75	29	35	25	30		
480	19.5			20		>25	>25	>75	26	32	22	30		
482					12.4									
503	20	22.5		21	15.6	>25	>25	>75	29	32	30	33		
556	18.5	18		13	12.1	>25	>25	>75	25	30	20	20		
622	21			0		>25	>25	>75	11	19	16	25	16	26
649		25.5			3.4									
721	21	13	16	0	5.9			>75	14	28	8	21	8	21

Notes:

1. Piezometric level is measured up from base of cell.
2. The 'top' & 'middle' waste moisture values are from gypsum block data only. The 'bottom' value is from gypsum blocks & resistance cell.
3. Waste moisture values are inferred from gypsum block and resistance cell calibrations carried out in rich and poor wastes only.

Table C11 Parameters monitored at Cell 2

Day	Temperature			Piezo-metric level	Cover soil grav.moisture content	Gravimetric moisture content of waste			Gas composition in waste pore spaces					
	Waste	Cover Soil				Top of cell	Middle of cell	Bottom of cell	Top of cell		Middle of cell		Bottom of cell	
	at base	15cm depth	70cm depth						CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
	°C	°C	°C	cm	%	%	%	%	%	%	%	%	%	%
103													2	7
186													0	0
224													0	0
244	18			0		<20	<20	90						
264	17			0	5.5	>25	>25	85					1	5
291	17			0	3.6	>25	>25	90					2	8
312					3									
349					8.2									
350	16.5			0		>25	>25	>90					0	5
377					13.9									
382	16.5			0		>25	>25	>90	2	7	7	25	0	1
391					18.5									
405	16			5		>25	>25	>90	5	25	10	27		
445	15			3		>25	>25	>90	10	30	12	32		
480	13			0		>25	>25	>90	8	27	13	31	9	27
482					12.4									
503	13	24		0	15.6	<20	<20	>90	10	27	15	30	15	31
556	15	23		1	12.1	>25	>25	>90	12	27	7	23		
622	22			0		>25	>25	>90	1	18	4	21		
649		26			3.4									
721	19	21	23	0	5.9			>90	0	14	1	12	3	20

Notes:

1. Piezometric level is measured up from base of cell.
2. The 'top' & 'middle' waste moisture values are from gypsum block data only. The 'bottom' value is from gypsum blocks & resistance cell.
3. Waste moisture values are inferred from gypsum block and resistance cell calibrations carried out in rich and poor wastes only.

Table C12 Parameters monitored at Cell 3

Day	Temperature			Piezo-metric level	Cover soil grav. moisture content	Gravimetric moisture content of waste			Gas composition in waste pore spaces					
	Waste	Cover Soil				Top of cell	Middle of cell	Bottom of cell	Top of cell		Middle of cell		Bottom of cell	
	at base	15cm depth	50cm depth						CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
	°C	°C	°C	cm	%	%	%	%	%	%	%	%	%	%
103													2	6
186													0	0
224													0	0
244	10			0		20	20	50						
264	10.5			0	5.5	>30	>30	50					4	8
291	10			0	3.6	30	30	50					4	9
312					3									
349					8.2									
350	11			0		>30	>30	>50					1	4
377					13.9									
382	10			13		>30	>30	>50	8	20				
391					18.5									
405	10			46		>30	>30	>50	44	33				
445	10			34		>30	>30	>50	42	33				
480	10			30		>30	>30	50	42	33	43	33		
482					12.4									
503	10	29		26	15.6	30	>30	>50	42	32	44	34		
556	15	23.5		20	12.1	30	>30	>50	27	24	35	29		
622	20			6		30	>30	>50	10	16	9	15		
649		25			3.4									
721	21	22	23	0	5.9			>50	2	14	1	9	0	10

Notes:

1. Piezometric level is measured up from base of cell.
2. The 'top' and 'middle' waste moisture values are from gypsum block data only. The 'bottom' value is from gypsum blocks & resistance cell.

Table C13 Parameters monitored at Cell 4

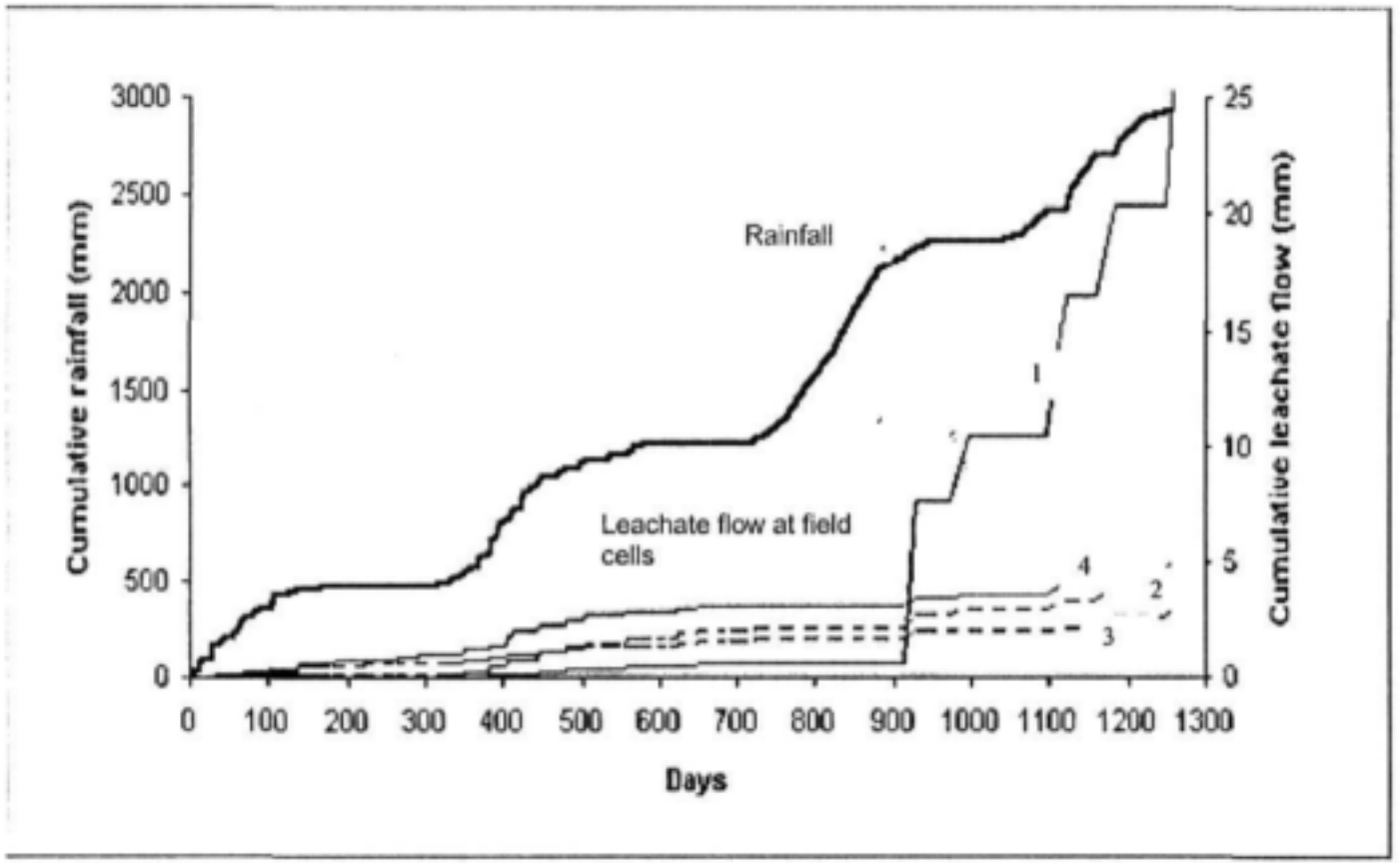
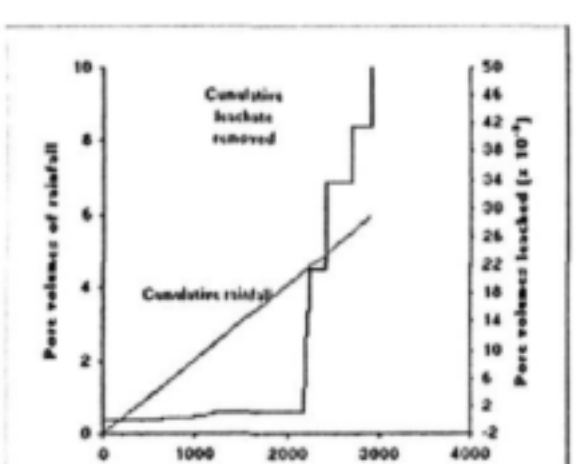
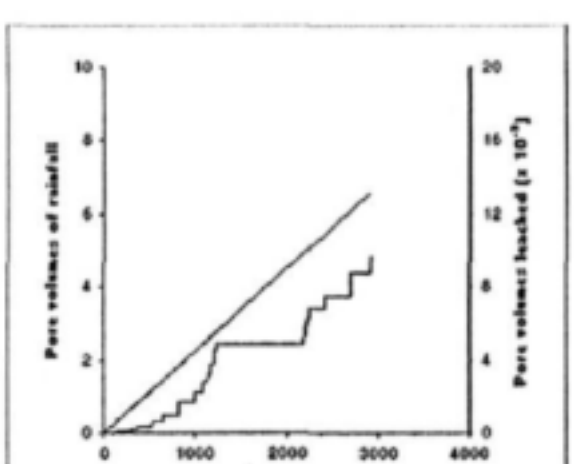


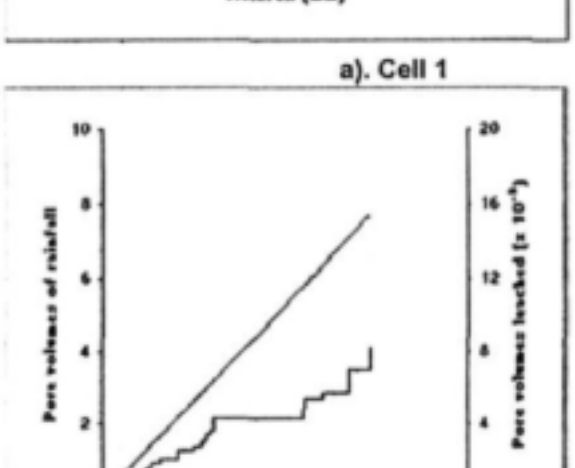
Figure C1 Rainfall & leachate flow at the field cells



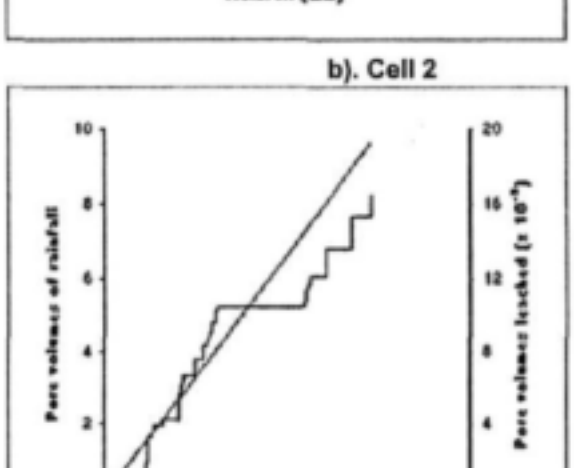
a). Cell 1



b). Cell 2



c). Cell 3



d). Cell 4

Figure C2 Rainfall & leachate flow at the field cells in terms of waste pore volumes

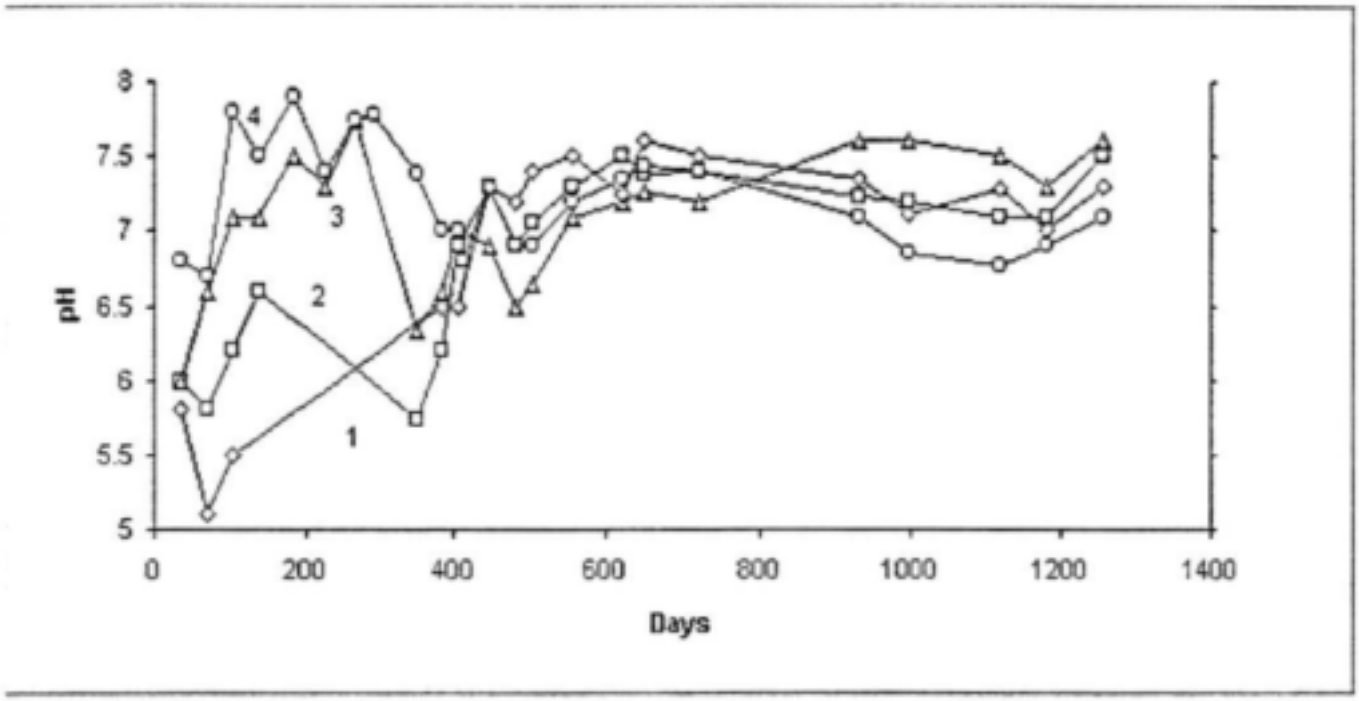
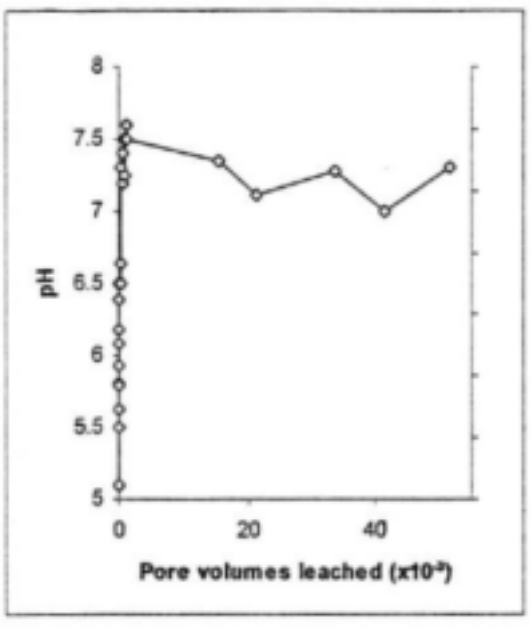
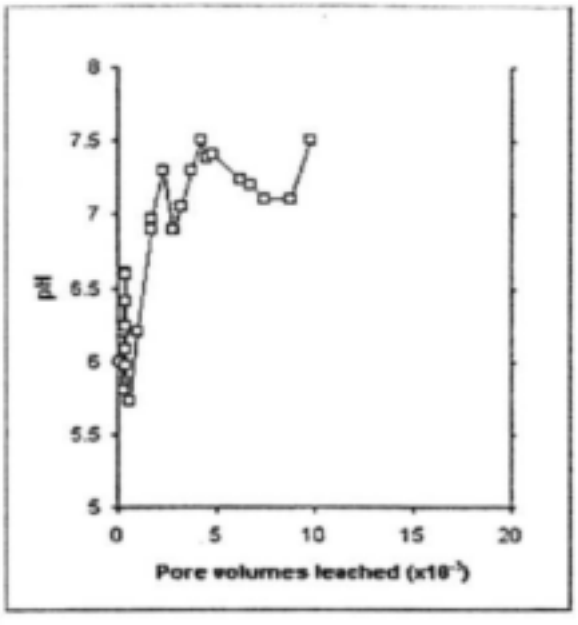


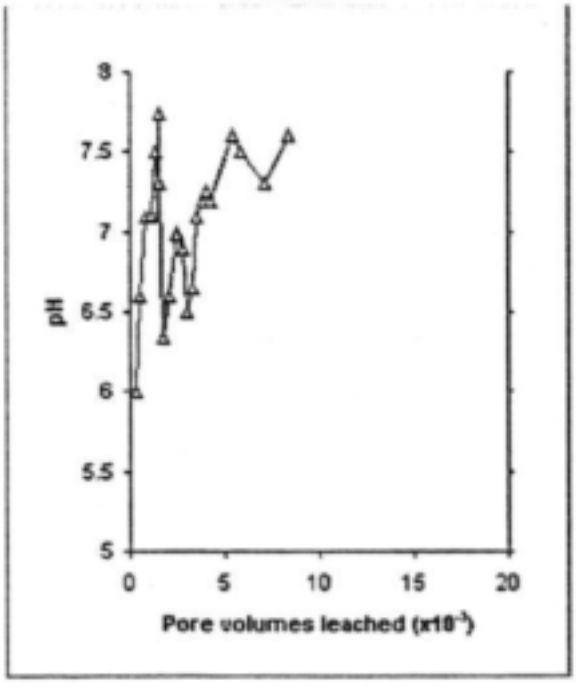
Figure C3: Temporal pH data



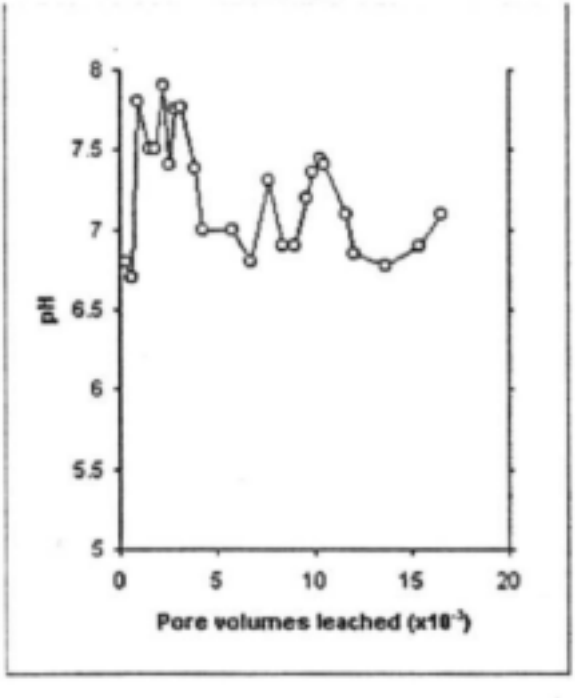
a). pH at Cell 1 in terms of pore volumes leached



b). pH at Cell 2 in terms of pore volumes leached



c). pH at Cell 3 in terms of pore volumes leached



d). pH at Cell 4 in terms of pore volumes leached

Figure C4:Variation of pH with pore volume

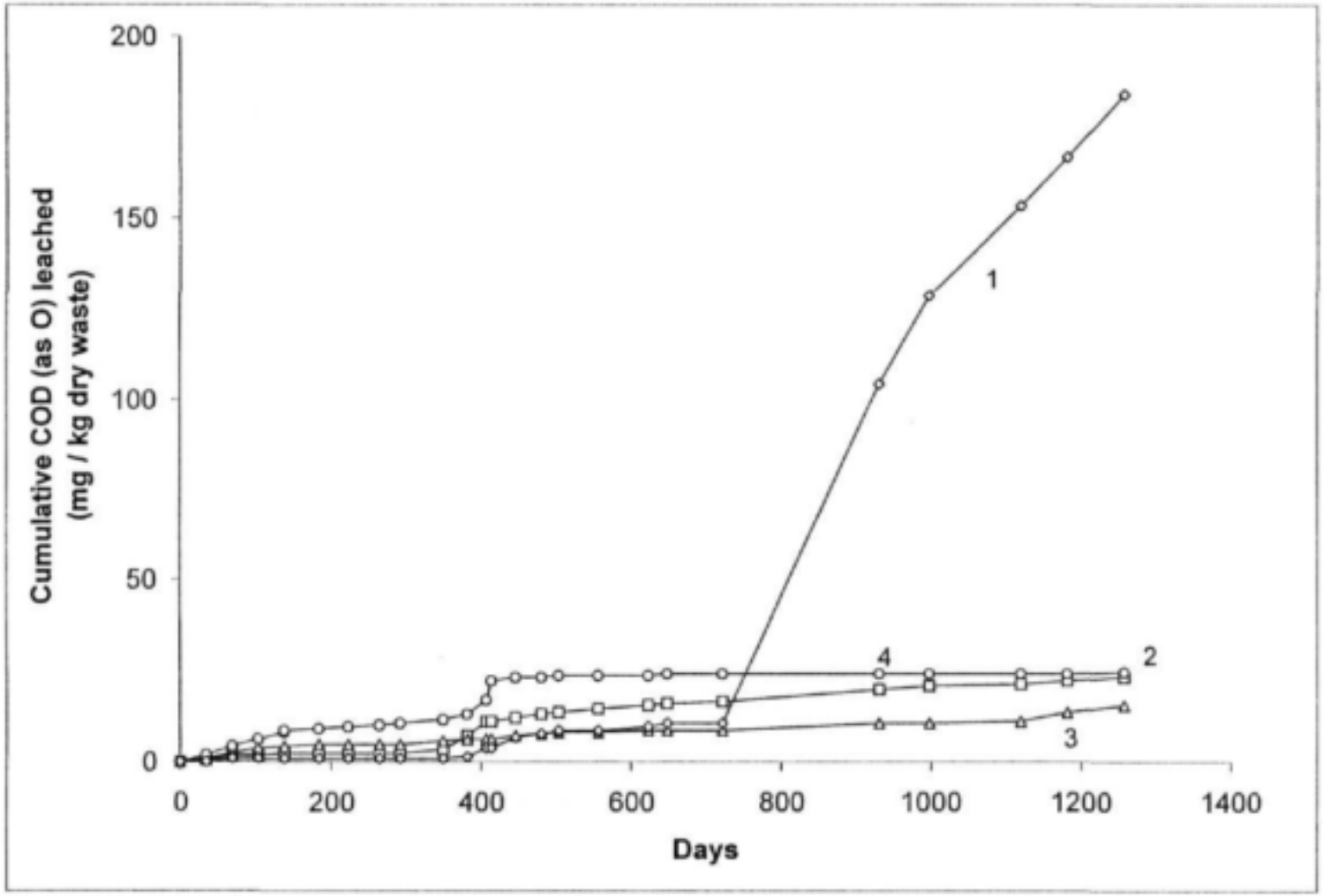


Figure C5: Temporal COD removal data

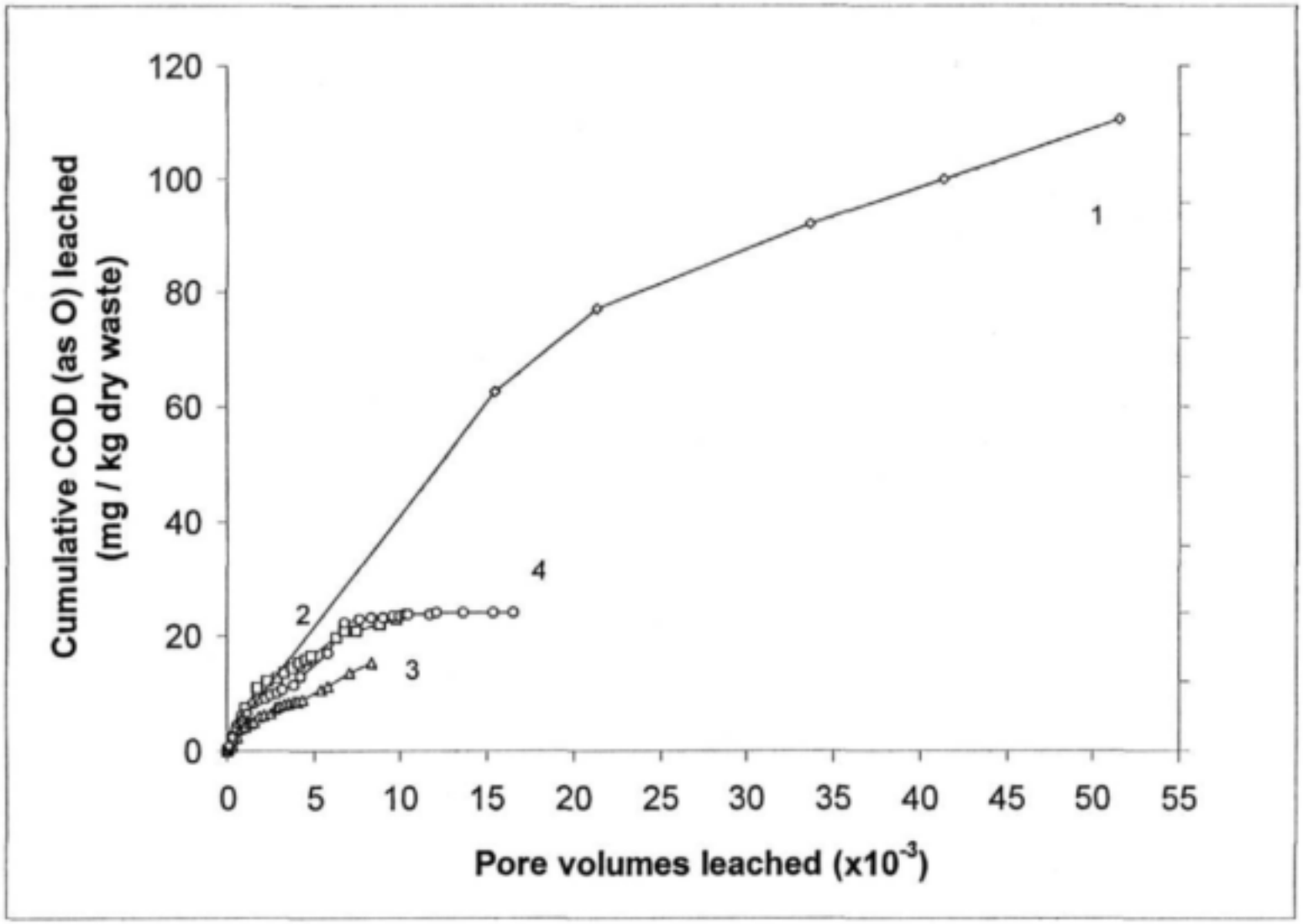


Figure C6: COD removal at field cells in terms of pore volumes leached

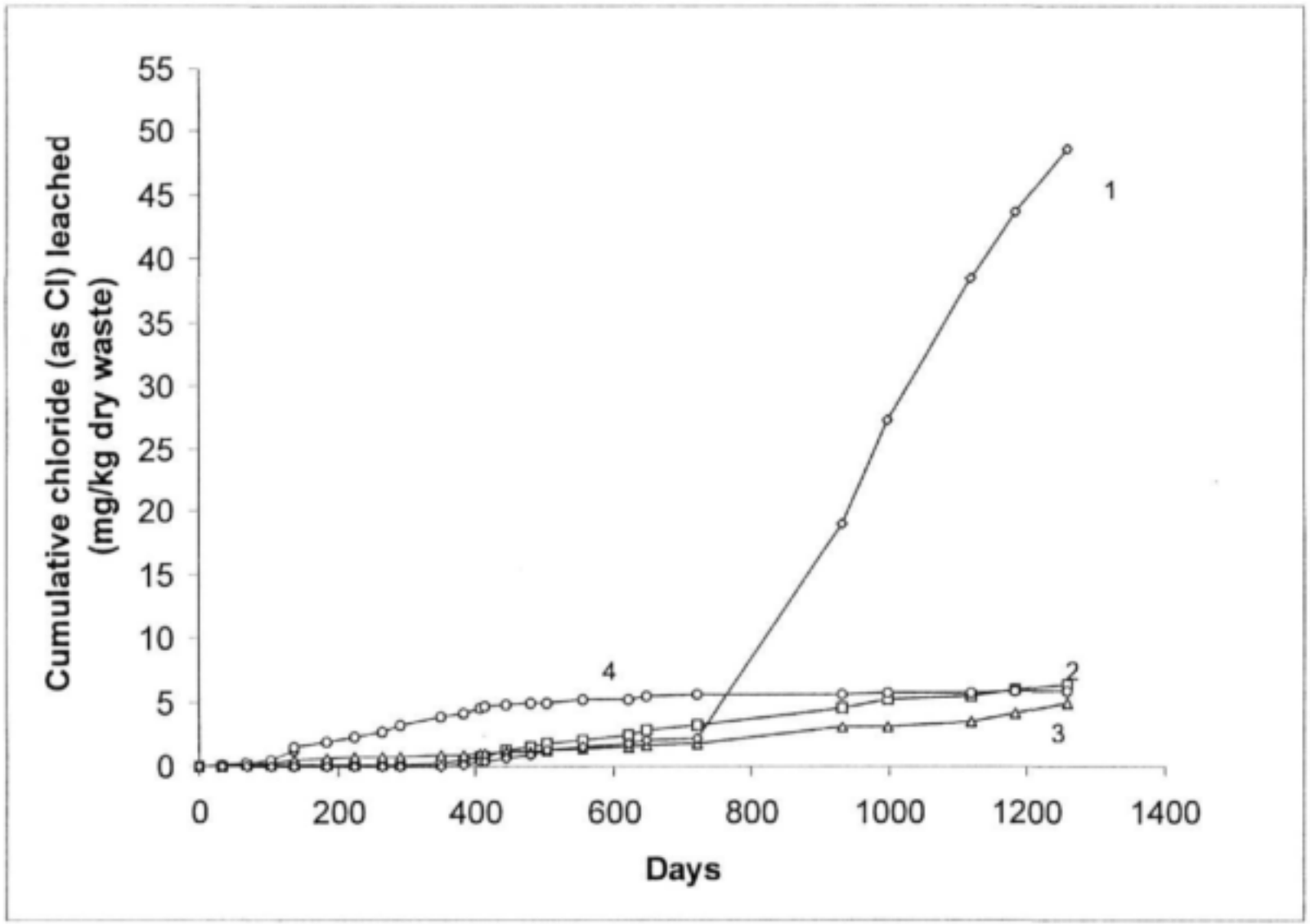


Figure C7: Temporal chloride removal data

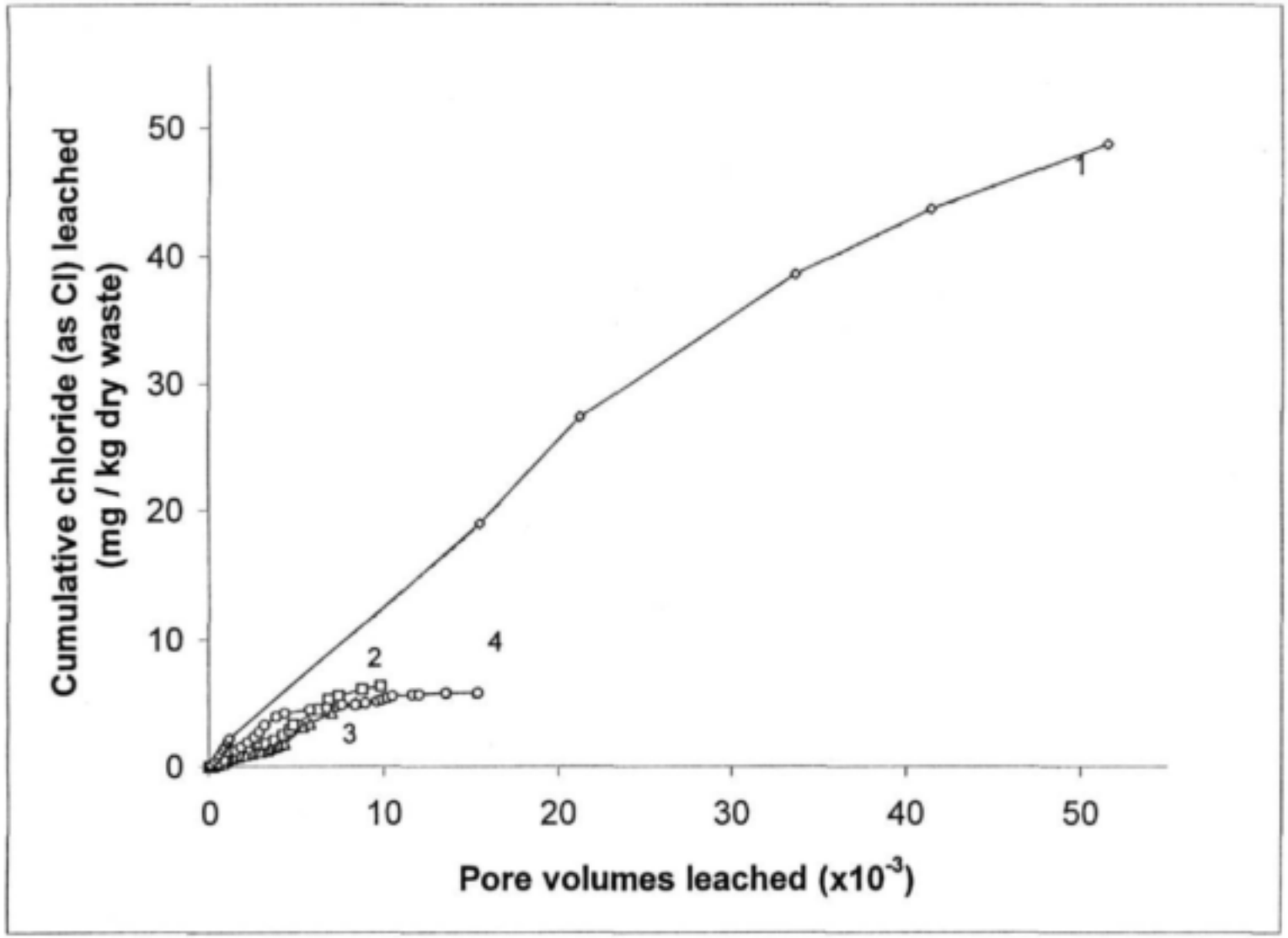


Figure C8: Chloride removal in terms of pore volumes leached

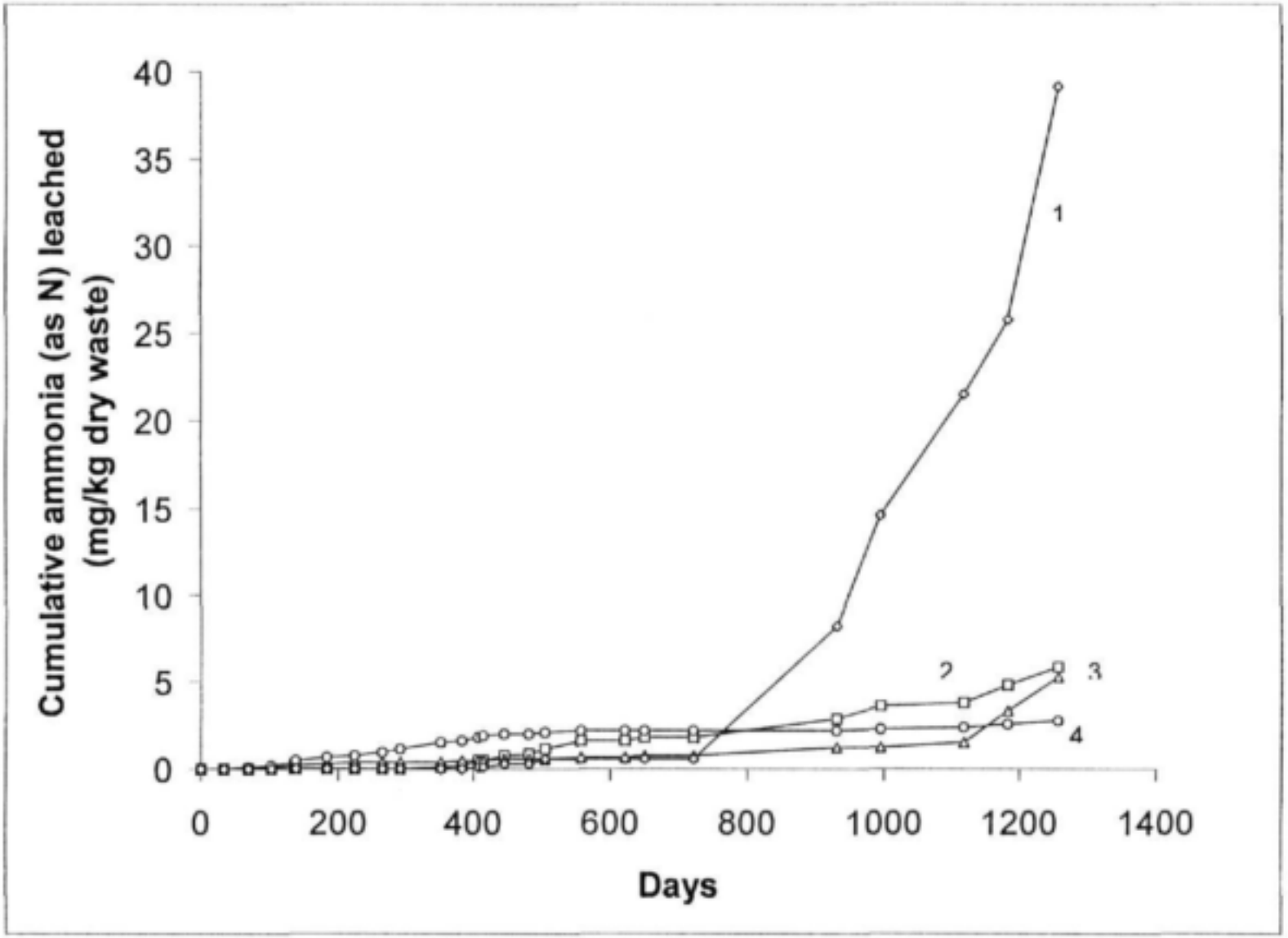


Figure C9: Temporal ammonia removal data

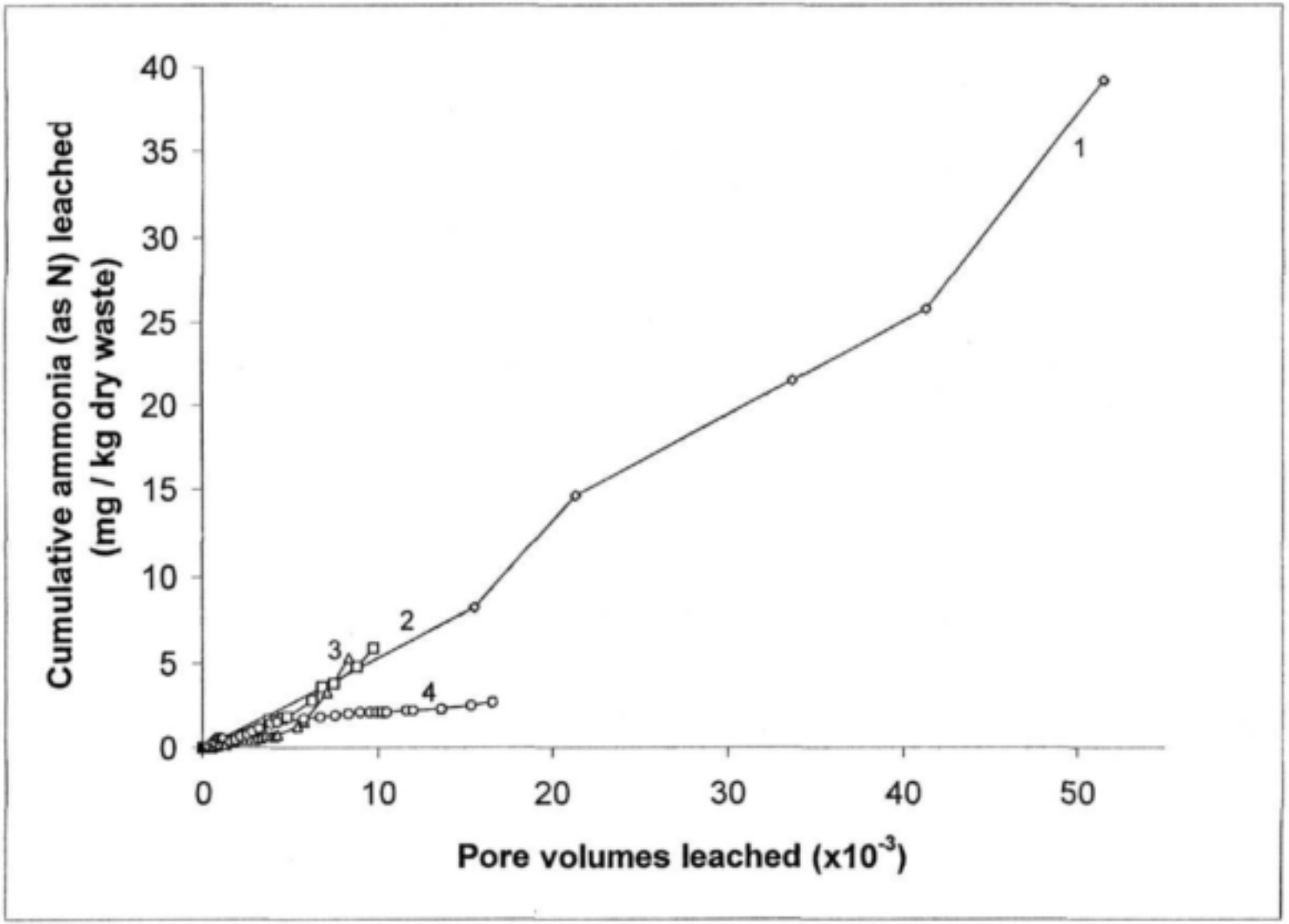


Figure C10: Ammonia removal in terms of pore volumes leached

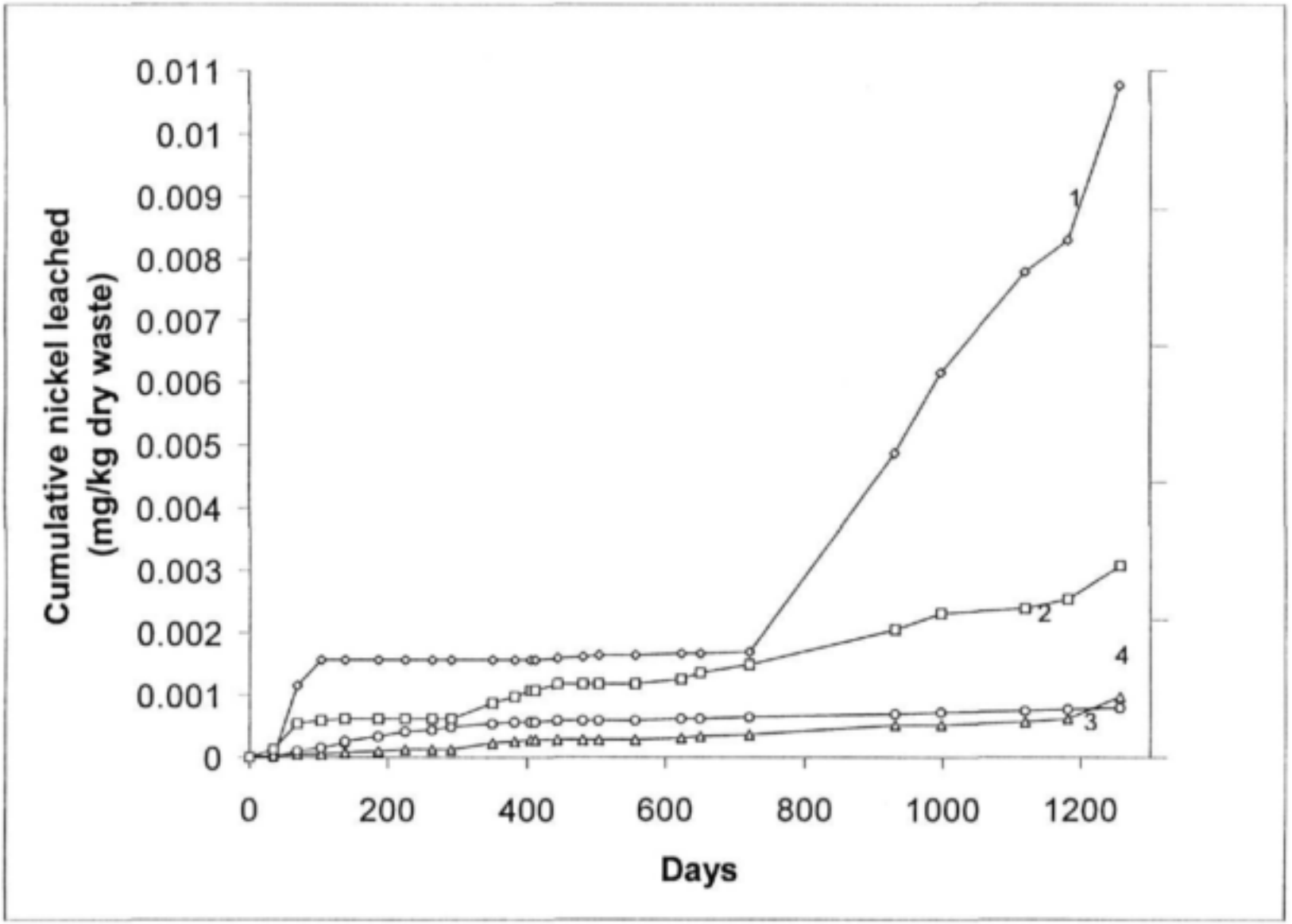


Figure C11: Temporal nickel removal data

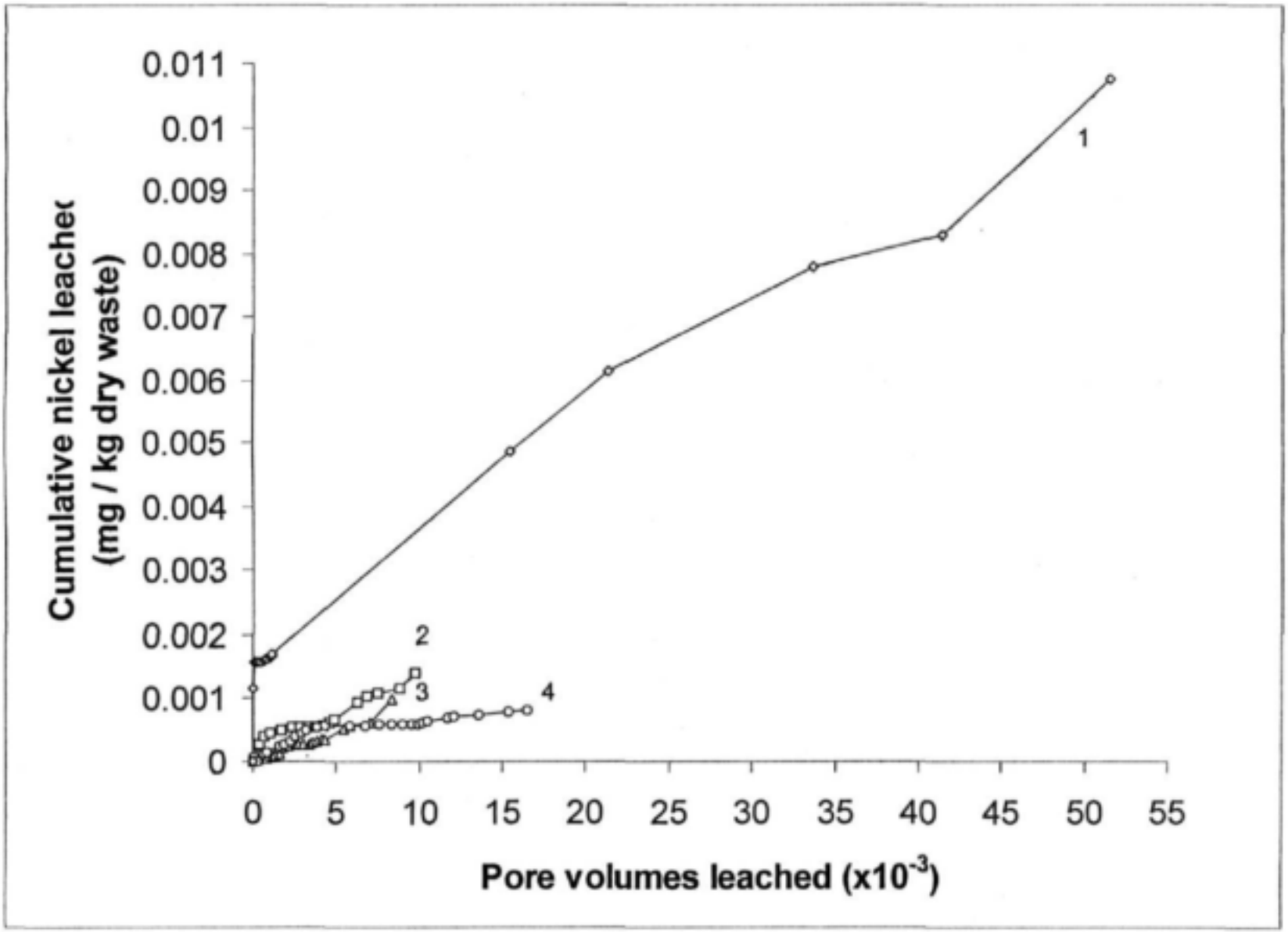


Figure C12: Nickel removal in terms of pore volumes leached

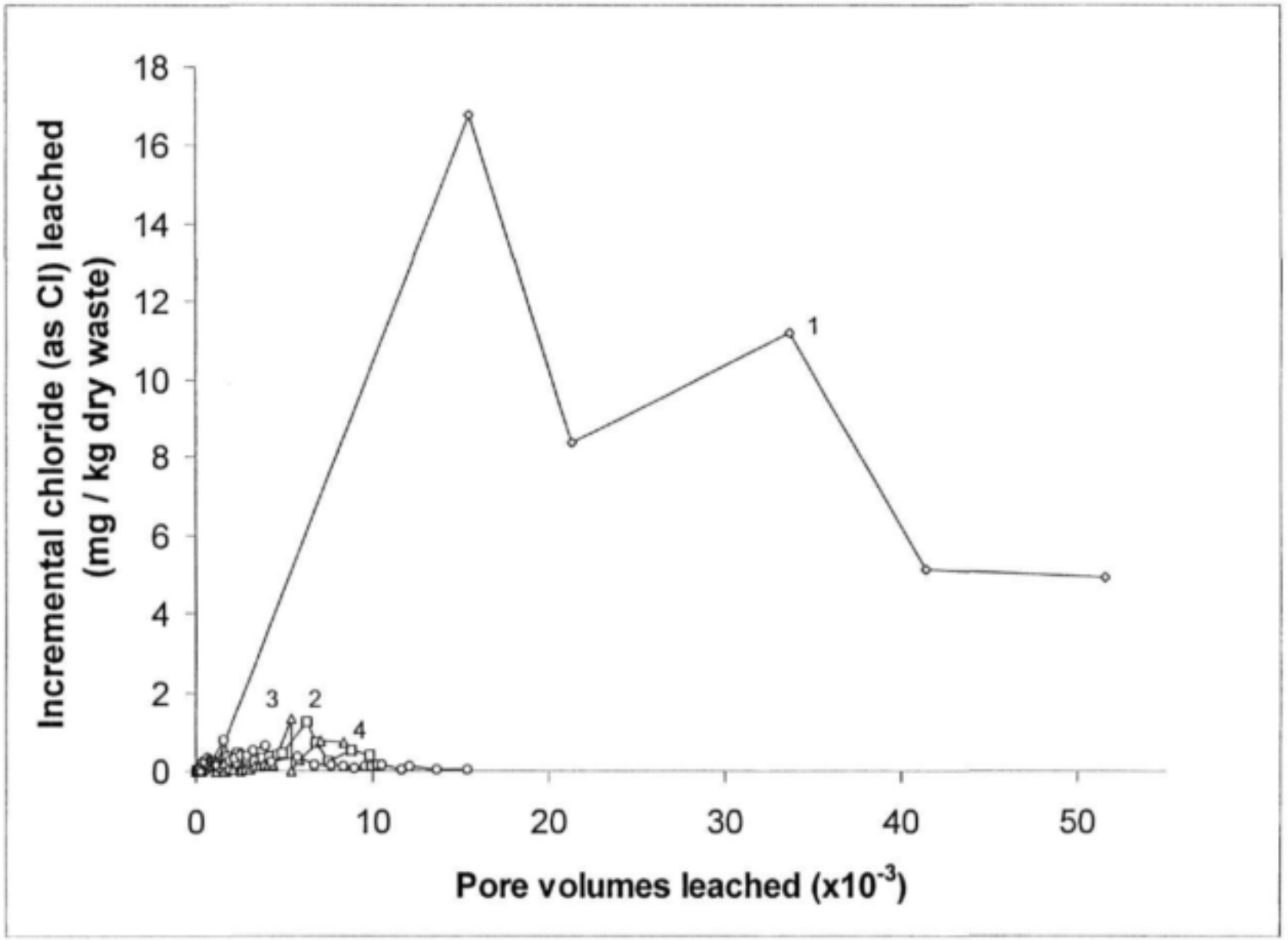


Figure C13: Incremental chloride concentrations as a function of pore volumes

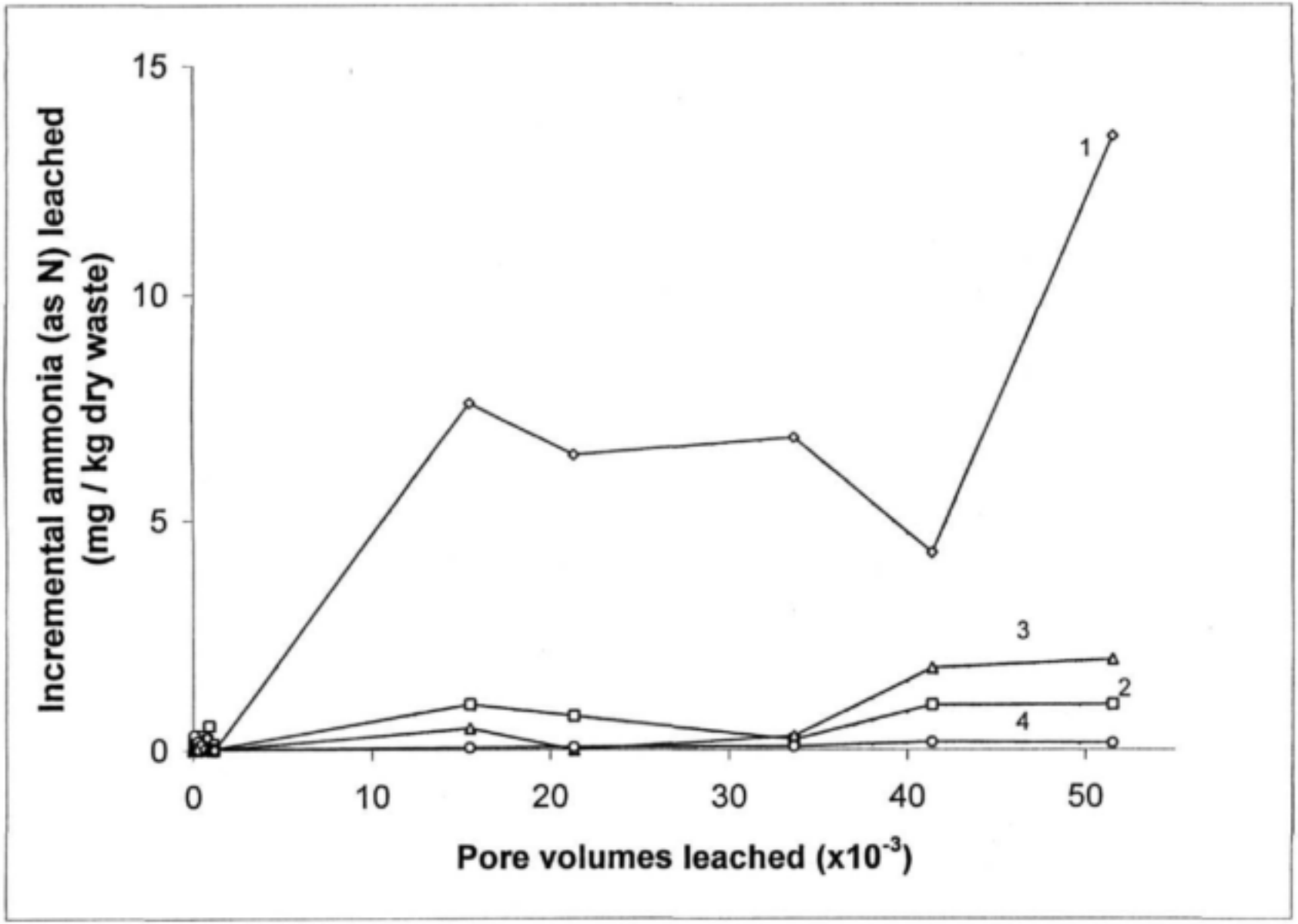


Figure C14: Incremental ammonia concentrations as a function of pore volumes

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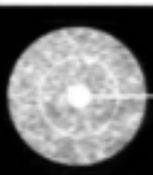

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