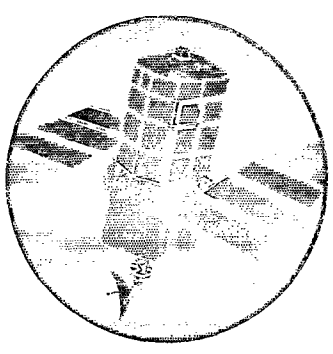
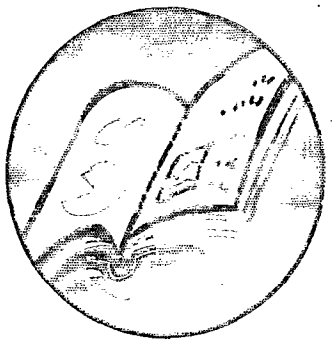
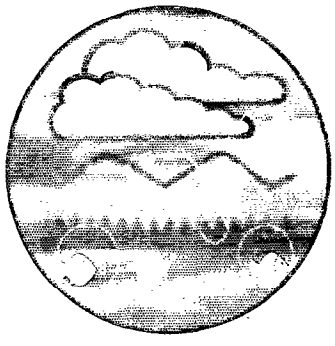
A Review of the Brogborough and Landfill 2000 Test Cells Monitoring Data

Research and Development
Technical Report
P231

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Keith Knox

Research Contractor:

Knox Associates

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Statement of use
This R&D report reviews data from two field-scale landfill test cell projects which were developed to accelerate waste stabilisation. Brogborough was developed to maximise energy recovery and Landfill 2000 to develop a bioreactor cell rotation approach to landfill. This report demonstrates the degree of enhancement that can be achieved and provides valuable information on landfill degradation processes and gas generation patterns.

Research contractor
This document was produced under R&D Project CLO316 by:

Knox Associates
Barnston Lodge
50 Lucknow Avenue
Mapperley Park
Nottingham NG3 5BB Tel: 0115 962 0866 Fax: 0115 962 0844

Environment Agency's Project Manager
The Environment Agency's Project Manager for R&D Project CLO316 was:
Dr Louise de Rome - ETSU, B156 Harwell, Didcot, Oxon., OX11 0RA

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DISCLAIMER

KEYWORDS

Test cells; landfill gas; accelerated stabilization; leachate quality; waste hydraulics; gas quality; microbiology; gas modelling; landfill processes; leachate recirculation.

FOOTNOTE

Since the report was first prepared it has been determined that work will not continue at the Brogborough test cells beyond 1998. A final phase of work will be undertaken to complete the collation of all data from the cells but some of the suggested uses of the cells given in this report would not be possible within the time now available.

EXECUTIVE SUMMARY

1. This report reviews data from two field-scale landfill test-cell projects, namely Brogborough and Landfill 2000.

2. These two projects were begun in 1986 and 1991 respectively. The Brogborough project was still continuing in 1997, while the Landfill 2000 project was terminated in Spring 1995.

3. Both projects were set up to accelerate waste stabilization, Brogborough with the intention of maximising energy recovery and Landfill 2000 to develop a bioreactor cell rotation approach to landfill, in which stabilized solid residues could be recovered and the engineered cell re-used after 3 years.

4. At Brogborough, six 15,000t cells were constructed, each measuring 40m x 25m x 20m deep. The enhancement techniques investigated were:

   - low density tipping;
   - mixing with 50% industrial/commercial waste;
   - addition of sewage sludge during infilling;
   - retrospective water addition;
   - retrospective air injection.

5. At Landfill 2000, two 1,000 tonne cells were constructed, each measuring 36m x 23m x 5m maximum depth. The enhancement techniques used were:

   - addition of sewage sludge during filling (both cells);
   - addition of sewage effluent after filling;
   - recirculation of leachate (one cell only).

6. Both sets of cells were designed for containment of leachate and the collection and measurement of landfill gas. Both sets were completed with low permeability top caps and in both cases some leakage of water occurred into the cells.

7. At Brogborough, active gas extraction was used while at Landfill 2000 only passive venting was used.

8. At Brogborough a variety of gas flow measurement techniques was used and eventually venturi meters were adopted, linked to data loggers for continuous monitoring. For this evaluation, weekly hot wire anemometer data have been used for the period before the venturis were installed, and venturi data subsequently. During the period when both methods were in use, their results were found to compare very well.

9. At Landfill 2000, only occasional gas flow measurement was undertaken until late 1993, when continuous monitoring was installed in the non-recirculation cell. A novel time-of-travel flow meter using a thermal tracer was used. A similar flow meter was installed in the recirculation cell only in December 1994, three months before the end of the study.

10. Both projects featured a variety of strengths and weaknesses in their design, construction, management and monitoring. However, both have produced extremely valuable data showing the degree of enhancement that can be achieved at large scale using the techniques investigated. Both have also generated valuable information on landfill degradation processes and on gas generation patterns.

11. At **Brogborough**:

- methanogenesis and gas generation began earlier and at a faster rate in cells to which sewage sludge or (to a lesser extent) non-hazardous industrial waste had been added;

- gas generation rates increased steadily in all cells over a 6-7 year period and were still increasing in some cells after 8-9 years. This is contrary to the expectations from gas models, which predict maximum rates much earlier, followed by exponentially declining rates;

- enhanced rates as high as $22m^3$ LFG/t.a were reached in a cell which had air injected into it. This may have been partly due to improved distribution of moisture into dry wastes;

- similarly high rates developed in a cell to which large volumes of water were added retrospectively. Although the enhancement took longer to develop than in the air injection cell, the high rates have been sustained for longer;

- rates in the control cell have reached $13m^3$LFG/t.a which is above the upper end of the typical observed range for conventional landfills.

12. At **Landfill 2000**:

- methanogenesis became established within one year in both cells;

- enhanced rates up to $17m^3$ LFG/t.a developed in the cell in which leachate was recirculated at a rate equivalent to a hydraulic retention time of $\sim$1 year in the waste mass;

- even in the non-recirculation cell a gas generation rate of $\sim 8m^3$LFG/t.a developed;

- the high gas generation rates were achieved in spite of unusually low temperatures (range 7-17°C, mean ~12°C) in both cells, caused by their shallow depths;

- stabilization of waste was not achieved in three years. Solid samples in early 1995 still had biochemical methane potentials of 76 (recirculation cell) and 161 (non-recirculation cell) m^3 LFG/dry tonne;

- a significant proportion of gas generation was due to H_2/CO_2 utilization;

- a significant proportion of gas generation occurred in the gravel leachate drainage layers;

- high rates of methane generation were also able to occur within the waste mass even though the *in situ* moisture remained strongly acetogenic. This is contrary to conventional expectations but is supported by similar results from test cells in Sweden.

13. The results from both sets of text cells show that acceleration of degradation rates by a factor of ~2 should be achievable at full-scale landfills using relatively simple techniques.

14. In neither study were all factors optimised, and a greater degree of enhancement may be achievable.

15. The results from both sets of cells have shown that neither temperature nor bulk leachate composition are necessarily a good guide to the level of methanogenic activity.

16. No large-scale test cells have been used to investigate accelerated contaminant flushing, either in the UK or abroad.

17. It is recommended that the Brogborough test cells be continued as long as possible, to:

- confirm the shape and duration of the gas generation profiles;

- confirm gas yields;

- demonstrate the accelerated flushing bioreactor concept.

1. INTRODUCTION

Two field-scale landfill management projects, Brogborough and Landfill 2000 were begun in 1986 and 1991 respectively. The projects differed greatly in scale and range of variables, but had similar objectives. The Brogborough test cells were intended to determine how landfill gas (LFG) production could be influenced by waste composition and by landfill practices. Landfill 2000 was intended to investigate the practicality of accelerating waste stabilization. Both studies have therefore involved the monitoring of leachate and gas production and quality, and of conditions inside the cells, and both have incorporated manipulation of management practices or waste composition in ways thought likely to influence the rate of waste decomposition.

Both projects have received support either from DTI and/or DoE (subsequently the EA). DoE commissioned Knox Associates to carry out an independent assessment of the knowledge gained up to mid 1994 and of what further useful information could be obtained. Subsequently the Environment Agency (EA) commissioned Knox Associates to up-date the review to include data up to early 1997.

The principle aims of the review were:

- To assess the contribution made by the two projects towards increased understanding of landfill processes and landfill management strategies.

- To make specific recommendations for the work programmes of both projects.

Within these two main aims, the following specific objectives were identified:

(i) Analyse and interpret all available gas, leachate and other relevant project details from both sets of test cells, with respect to their:

strengths and weaknesses;
contribution to our knowledge;
potential to generate further useful information.

(ii) Prepare and present an interim report on Brogborough, with recommendations for continued short-term work.

(iii) Prepare an interim report on Landfill 2000, with recommendations for continued short-term work.

(iv) Compare the results from both projects with available data from other large-scale landfill test cell projects worldwide.

(v) Assess how data from the two projects may be used to validate models of landfill processes, particularly landfill gas production and emission models.

(vi) Advise on possibly redefining objectives of either project to ensure they are used to maximum benefit.

(vii) Produce a comprehensive final report.

2. BROGBOROUGH TEST CELLS

2.1 Introduction

Six large-scale (15,000t) test cells were constructed at Brogborough landfill in 1986. Their long term purpose was to allow gas production from landfills to be maximised and this objective was to be met by studying, in individual cells, factors thought to be likely to enhance gas production. The construction and operation of the cells was funded by the DTI, through ETSU, and they have continued to fund the operation and control of gas extraction, gas monitoring and settlement monitoring up to August 1996, all carried out by AEA Technology. Additional monitoring work on leachate, since 1992 has been funded by the Department of the Environment and the EA and carried out by WRc. Operation of the cells since August 1996 has been funded by the EA.

The assessment of the Brogborough cells for this review consisted of four aspects:

- the strengths and weaknesses of the study;
- knowledge gained from the results available up to early 1997;
- the potential to generate further useful information;
- recommendations for continued work in the next two years and beyond.

These aspects are described below, following a brief description of the construction and operation of the cells.

2.2 Description of the Brogborough Test Cells

The design and construction of the cells has been described in detail previously (Campbell and Croft, 1990). A schematic layout of the cells and cross-section details are shown in Figure 1. Each cell measures 25m x 40m and the depth, when infilling was completed, was approximately 20m. Figure 2 shows the key dates in the construction, operation and monitoring of the cells, together with brief details of the waste inputs and the factors being studied. Chronological highlights in the management and monitoring of the cells are shown in Tables 1 and 2.

Construction and filling of the cells took place in two phases. The initial intention was to fill to a depth of 10m and this was completed by the end of 1987. However, it was then found necessary to add a further 10m, to keep pace with infilling operations in the main Brogborough landfill, which completely surrounds the test cells. This second phase of infilling was completed by late 1988 and clay capping was applied in the Spring of 1989. Most of the monitoring data on which the review is based are from after this point. Initially, gas was allowed to flow passively from the cells, and herringbone systems of slotted pipe in brick-filled trenches were incorporated at three depths, during infilling, for this purpose.

These are indicated in the cross-section in Figure 1. Active gas extraction from vertical wells was initiated in mid 1990. Connections to the two lower 'herringbones' were lost during the Phase 2 infilling, but the uppermost herringbone remains accessible and was used in Cell 3 for the additions of water and leachate.

Each cell is penetrated by three vertical wells, labelled A, B and C. The A and B wells were first installed in November-December 1988 before capping materials were placed. They were drilled to the base of the cells at 250mm diameter and completed with 125mm casing, slotted to ~2m below ground level. Following capping, they soon became unserviceable and were re-drilled in August-September 1989 at 300mm, and again completed with 125mm casing. In Cell 5 only, they were subsequently redrilled a second time, in January 1991, and completed with 210mm diameter casing.

The A and B wells in each cell are both used for gas extraction, and have at times been used for monitoring of leachate level and quality. However, most of the leachate monitoring has been done via the 'C' wells. These boreholes were drilled at 400mm diameter in August 1991, for the primary purpose of recovering solid samples for microbiological work and chemical analysis. The boreholes were drilled to the base of each cell, just into the underlying clay base and were completed with slotted 300mm diameter casing and a gravel pack, up to ~ 0.5m below the cap materials.

In addition to the boreholes, each cell contains three probes for temperature and gas quality monitoring within the wastes, installed to depths of ~7m, ~12m and ~17m below the top of the cap.

The layout of the upper herringbone, wells and gas/temperature probes is shown in plan for a typical cell in Figure 3.

2.3 Assessment of the Strengths and Weaknesses of the Brogborough Test Cell Project

In assessing the strengths and weaknesses of the project, and the results obtained, reference has mainly been made to two objectives:

(i) to accelerate the **initiation** of methanogenesis;
(ii) to accelerate the **rate** of methane generation.

Although increasing methane **yield** was one of the original aims of the test cells this can not be achieved until the degradation of the wastes is close to completion. In the event, none of the test cells had reached even 50% of the expected yield by the time of this review and none is likely to approach completion within the next two years. Only brief reference is therefore made to this third objective.

Choice of variables

Constraints on the number of variables which could be tested were inevitable because of budget limitations and the need to ensure that the cells were large enough to simulate full-scale landfills. The chosen size of 40m x 25m per cell was larger than any previous UK test cells. This size has been justified by the results obtained, but meant that only six cells could be constructed within the available budget. At least one had to be retained as a control, so the number of variables which could be examined was restricted to five.

Experiments conducted in the UK and overseas prior to the start of the project in 1986, mostly at laboratory or pilot scale, had studied many different variables. Eleven of those which had appeared to be most effective in accelerating decomposition are listed in Table 3, which identifies those that have been examined so far in the Brogborough study. In two cells (Nos. 5 and 6) the waste composition was varied, in one cell (No. 2) the waste emplacement technique was varied, and two cells (Nos. 3 and 4) were subjected to post-infilling perturbation.

The Table 3 variables not yet examined are considered below. Most have been shown to be very effective, at least in small-scale trials. For three of them, the opportunity to include them was lost once the cells had been filled, but the other three are post-infilling techniques, which could be included in future work.

- The use of a **pre-composting basal refuse layer** has become relatively common practice at MSW landfills in Germany and Denmark. It has been found to be universally effective in initiating methanogenesis and ensuring that only methanogenic leachate is produced. It is not known whether the presence of a methanogenic basal layer has any effect on conditions in higher lifts or on decomposition rates in the landfill as a whole.

- The use of **shredded waste** has been shown to lead to enhanced degradation rates, in experiments dating back to the early 1970s. It is one of the measures most commonly proposed in the current debate on techniques for sustainable landfilling, and is invariably used as a pre-treatment before anaerobic refuse digestion processes. Its inclusion in one of the original test cells might have been of greater value than, for example, the low density cell. Its omission from the study is regarded as a weakness.

- **Seeding with methanogens** was probably not a feature of Cell 5 because the sludge used was dewatered primary sludge, rather than anaerobically digested sludge. Its main effect was probably therefore to add extra moisture and some readily degradable organic matter.

- **Control of pH** during leachate recirculation or by inclusion of alkaline materials within the wastes has been found to assist the early establishment of methanogenesis. It is possible that this may have been one of the mechanisms at work in Cell 6 but in an uncontrolled, unquantified way. pH control during leachate recycle could be incorporated in future work at the cells.

- **Temperature** has been shown in many studies to have a direct effect on gas production rates, within the range 10-50°C. The air injection in Cell 4 was intended to produce higher temperatures by stimulating a brief period of aerobic composting activity. In practice the three air injection exercises appear to have had little effect on temperature in Cell 4. The absence to date of temperatures above 40°C from any of the cells is a significant omission in a study whose objective is to increase gas production rates. This variable could be studied in future work using either recirculated leachate or gas flare exhaust as a vehicle for introducing heat into the cells.

- **Leachate recirculation** has been effective in many studies in promoting more rapid stabilization. This is thought to be due to the wetting of a higher proportion of the wastes and possibly to more efficient distribution of nutrients and bacteria. The moisture addition to Cell 3 so far has largely comprised external water, added in large, short-lived episodes and it thus differs significantly from recirculation as usually envisaged. It would still be possible to incorporate leachate recirculation in one or more of the cells, and this would add greatly to the value of the study.

Each cell has so far incorporated only one variable thought likely to enhance decomposition processes. In one respect this is an experimental advantage, because it avoids confusing the effects of two or more variables and allows individual variables to be assessed independently. In practice, achievement of the highest possible rates of degradation may require a combination of several treatments, such as shredding, pre-composting layer, leachate recirculation and heating. It would be possible to adapt one or more cells to examine combined variables in future work.

Construction and management of the cells

Strengths and weaknesses of the construction and management of the cells are summarized in Table 4 and discussed below.

The phase 2 infilling from 10m to 20m depth is regarded as a strength, even though it took extra time and resources. This greater depth and the associated compaction and settlement of the wastes, are much more typical of modern landfills and provided greater confidence that effects observed in the cells could be reproduced in real landfills.

The three-year delay between the completion of infilling and the start of air and water additions is a strength. The delay provided the opportunity to compare the behaviour of replicate cells (Nos. 1, 3 and 4). Similarly the behaviour of Cell 2 in settling to a similar density to other cells during Phase 2 infilling, provided an effective fourth control cell. The spread of behaviour observed among Cells 1, 2, 3 and 4 up to mid-1992 provides a useful basis on which to assess the results of Cells 5 and 6, and effects of subsequent perturbations to cells 3 and 4.

There appears to be reasonable hydraulic continuity within the individual cells. This is apparent from the results of water injection into Cell 3 in February 1994 shown in Figure 4. During the injection, over a 5-day period, some short-circuiting to the C and B wells occurred but over the following 2-3 months, equilibration of levels occurred. From the injection of 231m^3 of water (equivalent to 231mm over the 1000m^2 cell) a net rise of ~2-2.5m in leachate level occurred in the A, B and C wells. This indicates a fairly even rise over the whole of the cell and an effective porosity of ~10% v/v. The sub-cap herringbone drain/gas vent was thus able to re-introduce liquid at a very high rate of ~45mm/d evenly into the wastes, and could form an effective component of a leachate recirculation scheme. The similarity of leachate levels in the A, B and C wells, and the equilibration between them also means that the leachate level data from the C wells are probably fairly representative of the cell as a whole and that they indicate a zone of continuous leachate saturation. This in turn means that pumped leachate samples from the C wells are more likely to represent the whole saturated zone rather than isolated perched leachate zones.

Good hydraulic continuity in the cells may be partly due to the low proportion of daily cover used. This was quoted as being ~5% by volume, of a coarse, sandy soil. At many full-scale landfills daily cover is closer to 20% by volume and is often very clay rich.

There appears to be good hydraulic isolation between the individual cells, and between the cells and the surrounding landfill. This is apparent from the behaviour of leachate depths since 1989, shown in Figure 5. Head differences of several metres have been maintained between the cells, with a consistent ~6m difference between adjacent cells 5 and 6. In spite of the higher initial leachate level, the rate of rise in Cell 5 has been similar, since 1989, to that in other cells. These rises have varied by a factor of ~2 from ~1m/a in Cell 6 to ~2m/a in Cell 4. At an effective porosity of 10% this corresponds to 100-200mm/a of infiltration. Such infiltration rates are consistent with expectations for the clay cap, which is extensively cracked, and settlement will also have contributed to leachate level rises. The variations between cells may simply reflect the variations in the capping materials and in the impact of cracks upon percolation. There is no evidence of any contribution from inflow of leachate from the landfill via the cell walls. However, levels in Cell 4 have risen sharply since mid 1995 and it is possible that some connection with Cells 3 or 5 may exist at these levels.

Following the addition of 231mm of liquid to Cell 3 in February 1994, there was no evidence of any effect on leachate levels in the C wells of the adjacent Cells 2 and 4, shown in Figure 4.

The surface of the clay cap is extensively cracked, with the widest and deepest cracks extending down the line of the boundaries between the cells, where the cell walls have settled less than the wastes. Inspection of these cracks on 28.9.94 revealed no visual evidence of anoxic conditions and no odour of landfill gas. While this is simply based on observation, it is consistent with the cells being largely contained and hydraulically isolated.

The cells were not constructed with a leachate collection layer or abstraction facilities. This may limit the achievable rates of abstraction, if a decision is made to examine recirculation as a variable. It would certainly affect leachate flow patterns. There would be an element of lateral flow through the wastes towards a vertical abstraction well, rather than uniform vertical flow into a drainage blanket and thence to an abstraction sump. Leachate pumping for sampling purposes from the C wells has indicated potential problems with leachate abstraction. Typically, volumes of 0.5-2m^3 ($\equiv$ 0.5-2mm over the cell area) have been abstracted in approximately 20 minutes. In many cases this has been enough to dry out the well at the time of pumping, and recovery has usually been incomplete by the following day when sampled. A practical abstraction scheme for recirculation would be more likely to be based on low-rate submersible pumps, controlled by level switches and operating intermittently.

Collection and measurement of all gas produced in the cells is important for the success of the project, but both may be subject to inefficiency. Well-head gas settings were adjusted weekly during the greater part of the study, up to August 1996, and even at this frequency some difficulty was experienced in optimising the settings. Applied suction may be too great at some times and too little at others, allowing gas to escape via other routes or drawing air into the cells. Subsequently, the frequency of site visits fell to 4-6 weekly and large variations in gas flow rates occurred. For example, unusually high flows in Cells 2 and 6 in 1996/7 (see Figure 36) were associated with a high proportion of air ingress, up to 50% of the gas flow. Many of the vertical extraction wells have experienced distortion and blockage and they are likely to vary in their characteristics, and this could affect apparent gas recoveries. The effects of differential settlement and distortion of pipelines may occasionally affect flows, due to blockages by condensate. Cracks in the clay cap and weakness around well-heads may allow gas to escape to atmosphere, or may allow ingress of air. There are thus numerous factors which may be causing inefficient collection of gas. They have been considered in more detail in other projects funded by ETSU.

The clay cap is cracked in many places and differential settlement has occurred. These could lead to ponding and increased percolation of rainwater into the cells. If large rises in leachate level were to occur, the depth of unsaturated waste could fall to the point where the efficiency of gas collection was significantly impaired. This is of greatest concern in Cells 3, 4 and 5, where the depths of unsaturated waste beneath the cap are only ~5m, ~4m and ~4m respectively. In other cells the unsaturated waste depth is greater and a continuing rise of 1-1.5m/a in leachate level may have little effect on gas extraction during the next two years. However, Cell 4 has exhibited very high rates of rise in the last two years, which could adversely affect gas collection if they continue.

Monitoring

Comments on the monitoring are summarized in Table 5 and discussed below.

Many different techniques for measuring gas flows have been used during the course of the

project and until mid-1995 none was regarded as entirely satisfactory. Weekly hot-wire anemometer (HWA) measurements have been taken throughout the study during routine maintenance visits. Venturi meters were installed in all cells during 1993 between January and October. Hourly recording of gas flow data from the venturi meters began in November 1993. Some uncertainty subsequently arose concerning the accuracy of the venturi meter data. A thorough assessment by AEA Technology during 1995 demonstrated that the venturi data are accurate to within $\pm 15\%$ and probably better than this. Comparison with hot-wire anemometer data during the period when both methods were in use indicated that the HWA data are also broadly correct. The review has been based on venturi meter data from November 1993 onwards and HWA data prior to that. While individual HWA readings may be subject to uncertainty (e.g. from short-term fluctuations in gas flow rate) it is likely that these uncertainties will be mainly random and that long-term cumulative data will be representative. Gas flow measurement and collection results have been, in fact, internally consistent within cells. Graphs of cumulative gas flow, presented in Figure 6, show that the behaviour of each cell is distinct, and that the data are probably usable as a means of comparing the effectiveness of different treatments.

Temperature has been measured primarily in the static gas probes for most of the study. However, since January 1994, the temperature of the pumped leachate has also been recorded. These results are included in Table 6 and shown graphically in Figure 7. There is a gap from 2.4.92 to 3.2.93 in the gas probe temperature data for all cells, and slightly longer for cells 4-6. The static gas probe data are useful for assessment of the general order of temperatures in the cells and provide some information on changes over time. However, there is uncertainty over the accuracy of some of the readings: data from probes at three depths are shown in Figures 8-10, with mean values in Figure 11 for all cells, from 1989 to 1994. In late 1989 it can be seen that the temperature in all cells appeared to rise very sharply and then to fall again equally sharply. It is very unlikely that the cells will have actually behaved in this way. Similarly, in mid-late 1993, the mean recorded temperature in several cells rose sharply and then fell back in early 1994. These results must also be regarded as questionable. The uncertainties in the gas probe data, the gap in the data record during 1992/93, and the very short period of overlap between gas and leachate data, are significant weaknesses in the monitoring of the project.

Leachate levels have been dipped very frequently during the study but the results are less informative than they could have been. The data obtained by AEA Technology have been recorded only as depth below the top of the clay cap and by WRc as depth below the top of the well casing. None of the wells has ever been surveyed and the leachate levels cannot reliably be related to ordnance datum. An attempt has been made to do so for this review, using cap survey data, in order to interpret changes following the addition of water to Cell 3. The results of this computation are shown in Figure 4, but are subject to considerable uncertainty.

Estimation of leachate depth depends upon accurate knowledge of either the cell base levels or the cell depths. The latter were not included in reports available at the time of the main review but have subsequently been estimated by AEA Technology, using estimates of the original cell depths, adjusted for subsequent settlement. The resulting calculated values of leachate depth are shown graphically in Figure 5. Attempts to estimate cell base levels from borehole logs on the C wells or from occasional report references to leachate depths have proved very inconsistent, leading to ~2m uncertainty in cell base level.

Pumped leachate samples, following evacuation of one or more bore volumes, have only been obtained since January 1994, which was more than six years after the initial placement of refuse. Up to 1992 only bailed samples were taken. From May 1992-December 1992 samples were taken with a Waterra, after pumping out some leachate, but the volumes pumped amounted typically to less than one tenth of a bore volume. During 1993 no leachate analysis at all was undertaken due to a gap in the funding. The data prior to 1994 are of very limited usefulness because they are likely to have been subject to changes while standing in the boreholes. This will particularly have affected components such as pH, NH_3-N, BOD and COD, making it virtually impossible to use them to assess whether conditions were acetogenic or methanogenic in the wastes. Results for major parameters in pumped leachate samples from January 1994 to February 1996 are given in Table 6.

There remains uncertainty regarding how representative the current pumped samples from 'C' wells in 1994 may be of the wastes as a whole. Logs of the 'C' wells, drilled in July/August 1991, show that they penetrated the full depth of the wastes and were completed with slotted well-screen and a gravel pack up to just below the clay cap, in each cell. The wells therefore intercept the whole of the saturated and unsaturated zones and would intercept any perched leachate horizons that may have been present. The consistency of the results, following repeated pumping does not suggest that perched leachate is a significant factor in any cell. However, pumped samples will be dominated by leachate from horizons with the highest transmissivity and these are likely to be near the top of the saturated zone. There could be quality stratification within the saturated zone that would not be revealed by the current monitoring facilities. Some supporting evidence for this comes from the quality in Cell 3 following massive addition of water in February 1994. Concentrations of inorganic ions in the pumped samples immediately following the addition of 231 m^3 of water were at ~50-60% of their previous level (see Table 6). No comparable dilution occurred in any other cell at this time, so that rainwater percolating through the cap can probably be ruled out as the cause. The extent of dilution was much larger than would have occurred if the added water had mixed rapidly with the whole cell. Calculations suggest that only ~385m^3 of leachate need have mixed with the added water to bring about the observed dilution. At a typical value of 50% v/v for the total moisture content in the saturated zone this would equate to a pre-addition saturated waste depth of only ~800mm in the cell. Concentrations subsequently returned to their earlier values, suggesting that equilibration of the added moisture may have occurred over a longer period. Again in March 1995, all six cells exhibited a significant dilution and subsequent recovery. This dilution may be attributable to rainwater percolation during an unusually wet and prolonged winter. Based on this

evidence it is possible to conclude that the pumped samples are derived from only a shallow thickness of waste at the top of the saturated zone, and that they provide no confirmation of leachate quality in the lower parts of the cells. Piezometers installed to specific depths would be needed to assess the degree of possible stratification.

Excellent settlement data have been obtained throughout the project. Detailed surveys have been undertaken approximately every quarter since the completion of capping.

No analysis of the waste was carried out prior to deposit. Samples were taken for analysis in November/December 1988 during the installation of the first set of A and B wells, following completion of the Phase 2 infilling. Two samples were taken from each cell, at depths of 6m and 18m. They were submitted to Reading University for analysis of cellulose and lignin. No information on the methods used, or supporting data such as moisture content or loss on ignition, have been discovered. Nevertheless, the results may be useful as baseline data that could be compared with samples excavated at the end of the study to assess loss of degradable organic matter.

2.4 Knowledge Gained from Results to Date

The most important findings from the results reported up to early 1997 are summarized in Table 7. They are discussed below.

Each cell appears to behave in an individual, characteristic way and the behaviour, 8-9 years after infilling, of cells which have not been perturbed since, appears to be still diverging in many important respects. This is apparent from leachate depths (Figure 5), cumulative gas flow (Figure 6), temperature (Figures 7 & 11) and settlement data (Figure 12). The spread of behaviour for Cells 1-4 up to mid-1992, and Cells 1 and 2 subsequently, provides an indication of the range exhibited by control cells, and thus a useful basis for assessing the effect of pre- and post-infilling variables such as waste composition, air injection and water addition.

Gas generation

None of the **initial** treatments (waste composition and waste density) led to unusually high rates of decomposition but two (5 and 6) led to higher rates than in the control cells and to earlier establishment of methanogenesis. The highest, initially, was Cell 5 (primary sewage sludge addition) whose cumulative gas flow has averaged $\sim 10 m^3/t.a$. This is towards the upper end of, but does not exceed, values experienced in gas extraction schemes at full-scale landfills. In both Cells 5 and 6, the modified waste composition led to higher initial gas production rates than from control cells. In Cell 5 it is likely that the addition of a significant amount of moisture at the time of infilling was the main cause. The presence of readily-degradable organic matter in the sewage sludge may also have contributed. In Cell 6,

the pH buffering effect of the industrial wastes may have helped to promote the early growth of methanogens. The low initial density in Cell 2 was not maintained once Phase 2 infilling was undertaken. No enhancement of gas production occurred in Cell 2, which has consistently had the lowest gas production rate of any cell.

Post-infilling additions of air (Cell 4) and water (Cell 3) have led to unusually high gas production rates, exceeding those in either the controls or in Cells 5 and 6.

The effects of air injection into Cell 4 can be seen in Figure 6. Up to mid-1992 cumulative gas production was within the range of the other control cells, and the behaviour of Cell 4 was very similar to that of Cell 1. Air injections were then made as follows:

27-28	April	1992	560m^3 added via well B
	Feb	1993	244m^3 added
2-6	June	1993	11,101m^3 added

Very soon after the first air injection, Cell 4 began to deviate from the established pattern of cell behaviour. Gas production rate increased and the cumulative gas production overtook Cell 1 by late summer 1992, Cell 6 by late summer 1993 and Cell 5 by mid-1994. The gas production rate in Cell 4 doubled in the two years following the first air injection, to ~22m^3/t.a. It became the fastest of all the cells by mid 1994. Its gas production rate has subsequently eased to ~18m^3/t.a but this still exceeds any reliable published figure for a UK landfill.

Water addition to Cell 3 has been as follows:

2	July	1992	98.5m^3 water added
20-23	April	1993	21m^3 leachate added
21-25	Feb	1994	231m^3 water added

The effects in Cell 3 have been similar to those for Cell 4 but occurred slightly later. Cumulative gas production began to deviate from its established trend in early 1993 (Figure 6). Gas production rate has increased faster than in any cell except Cell 4, and Cell 3 currently has the fastest rate of production, at ~21m^3/t.a.

These changes in Cells 4 and 3 occurred within a period of approximately two years. They suggest that gas production rates well above those previously demonstrated at full-scale can be achieved using relatively simple post-infilling perturbations. The fact that they have now been sustained for several years indicates them to be of real value to landfill operators.

The gas production curves in Figure 6 are of great value because there has previously been very little large-scale information about the pattern of gas production at UK landfills. In the two cells that have produced the least gas so far (Control cells 1 and 2) the rates are still increasing, 9 years after the last placement of waste. Rates in these two cells now exceed

$10m^3/t.a$, i.e. above the high end of typical UK landfills. In the two cells that have produced the most gas (Cells 3 and 4), rates remain steady, at ~21 and ~$18m^3/t.a$ respectively, even though both have now produced ~50% of their expected yield. They reached their maximum rates ~5 years (Cell 4) and ~6 years (Cell 3) after the last placement of wastes, and 2 and 3 years after the perturbations that preceded their improvement. Cell 5, which was the highest gas producer initially, is now declining, and appears to have reached its peak rates in ~1994, five years after the last placement of waste. It would be of great value to continue monitoring all the cells for as long as possible, to study the peaking and decline of gas flow rates, and eventually the ultimate yields.

A high proportion of the initial gas potential remains within all of the cells. The cumulative gas yield to date does not exceed $100m^3/t$ from any cell and in most cells it is considerably lower. The spread between the best and worst cells, nine years after waste placement, was from ~$65m^3/t$ (Cell 2) to ~$100m^3/t$ (Cell 4). Compared with conventional expectations (albeit unproven in practice) of ~$200m^3/t$ or more, it appears unlikely that more than 30-50% of the initial gas potential has yet been released.

The study will therefore not provide information about gas **yields** within the next 2 years. It is likely that on the order of 100-$140m^3/t$, or more, gas potential remains in the wastes in all cells, and current production rates are only ~$21m^3/t.a$ in the most productive of them. Although the rates are still increasing in some cells, it is inconceivable that any of the cells will have produced anywhere near its full potential in two years. It is most likely that as the degradable components become depleted, gas production rates will fall, regardless of how well optimised the environmental conditions and bacterial populations have become. This is already apparent in Cell 5, and rates in Cells 3, 4 and 6 appear to have levelled off.

Gas quality

Methane concentrations in the extracted gas are shown graphically in Figure 13.

In all six cells, the percentage of methane increased from ~20-40% initially, to values in the range 55-60% after six years. Latterly, there have been some very large fluctuations in methane content but these are thought to be artifacts and there is no clear evidence of any real change in the cells themselves. The fluctuations in quality in 1996 and 1997 are largely attributable to the extended intervals between site visits to adjust the gas extraction settings. Variations in extraction rate occurred following blockage and unblocking of the extraction lines. This resulted in the drawing in of large volumes of air. For example, in Cell 2, from July to October 1996, the oxygen concentration rose to 10%, while CH_4 plus CO_2 came to 50%. This indicates that the gas consisted of 50% air, and the flow rate (Figure 36) rose to double what it had been. Similar phenomena occurred in Cell 6 and to a lesser extent in the other cells.

In Cell 5, the percentage of methane was high from an earlier stage than in the other cells and was ~50% in 1989. In combination with its gas flow rates, this means that Cell 5 has

produced the highest energy yield for most of the study. It seems reasonably safe to conclude that the early attainment of high methane concentration is linked to the inclusion of sewage sludge in the cell.

In most cells, the increase in percentage CH_4 showed no obvious correlation with any specific events such as the perturbations to Cells 3 and 4. In fact, the graphs for Cells 1, 4 and 6, in Figure 13, are all very similar. The similarity of these graphs suggests that the long-term increase in methane concentration is not linked to any of the treatments used in the different cells but may be due to more fundamental factors such as the nature of the MSW substrate and the development of landfill microbiological populations. These possibilities are discussed in section 4 of this report.

Temperature

Temperature data from 1989 onwards for the top, middle and bottom gas probes are shown in Figures 8-10 and their mean values in Figure 11. Temperature data for the pumped leachate samples from 1994-1996 are shown in Figure 7.

In the first few years, the gas temperatures in the top and middle probes were a few degrees higher than in the bottom probes and spanned a narrower range. Subsequently, however, the temperatures in the top and middle probes in the different cells have diverged, and now span a wider range than those in the bottom probes, which have remained much more constant during the study. The differences between cells have become far greater than the variations within cells.

Gas temperature, as recorded in the probes at three depths, has not been a good indicator of biological activity. Cell 5 has had, and maintains, the highest temperatures overall, but Cells 4 and 3 now have the highest gas production rates and yet the mean gas temperature recorded in Cell 3 is more than 10°C colder than in Cell 5. The first perturbations to Cells 4 and 3 evidently caused the gas production rate to increase from April-July 1992 onwards, but produced no evidence of any sustained increase (or decrease) in temperatures. This comment must be qualified by the observation that no temperature data were reported for the period 4/92 to 2/93 (5/93 in the case of Cells 4-6). Nevertheless, temperature data were reported for periods when subsequent additions of air or water were made, and they showed no evidence of temperature changes attributable to the perturbations. Cell 2 has the lowest temperature and lowest gas production rate, but its mean temperature has been falling steadily throughout the study, while its gas production rate has been rising continuously.

Leachate temperatures (Figure 7) at the beginning of 1994 were several degrees cooler than gas probe temperatures. This may have been due to the moderating effect of the underlying ground. Subsequently, leachate temperatures have increased in all cells and by February 1996 were much closer to gas probe temperatures. This increase may reflect the continuing rise in leachate levels, taking the upper part of the saturated zone further away from the cooling effect of the underlying ground. As with the gas probes, the spread of leachate

temperatures between the cells varies from a range of ~5°C to a range of ~15°C and the relative ranking of cell leachate temperatures is similar to that of the gas, with Cell 5 clearly the warmest and Cell 2 the coolest. The large volume of water added to Cell 3 in late February 1994 had a dramatic cooling effect on leachate temperature in March 1994. By May 1994 the effect was greatly reduced and by mid-1995 the temperature in Cell 3 was towards the higher end of the range of all the cells. This cooling effect and subsequent recovery over a period of months is consistent with leachate quality data that suggest only limited mixing of added water initially, followed by more or less complete equilibration over the longer term. It is noteworthy that while the leachate was initially cooled by water additions, there was no corresponding effect on gas temperatures.

Previous research has suggested that temperature may be an important **determinant** of biological activity, but it is only one of several important factors, and the results from these test cells suggest that measurements in gas probes and pumped leachate samples may not necessarily be reliable **indicators** of activity in the cell as a whole, especially when there are differences in other important factors like waste composition, moisture content and perhaps microbial population.

Settlement

Data for cumulative settlement since July 1989 are shown in Figure 12. Settlement in the different cells in that period has varied by a factor of nearly two, ranging from ~1.2m to ~2.0m, or from ~6 to ~10% of the original depth of waste. The initial shape of the settlement curves in late 1989 (see Figure 12) suggests that higher rates of settlement may have occurred earlier, i.e. during surcharging while overtipping and capping. Since monitoring began, after capping, all cells have exhibited declining, or steady, rates of settlement, except for Cells 3 and 4, which have exhibited increasing rates from 1994 onwards.

Cells 5 and 6 have settled the most and have exhibited almost identical settlement at all times. This is in spite of their having different initial waste composition, a 6-7m difference in leachate saturation depth, and significant differences in gas production patterns. Cells 1 and 4 exhibited identical settlement until early 1994, since when Cell 4 has settled at an increasing rate. Cumulative settlement in Cell 4 is now approaching that in Cells 5 and 6 and its recent acceleration is likely to be attributable to the high rates of degradation. The acceleration in settlement in Cell 3 is also attributable to the high rate of degradation that has developed. Cell 2 has consistently settled the least, and continues at a very consistent rate.

It is not surprising that there is a general correlation between settlement and cumulative gas production (compare Figures 6 and 12). A more surprising result, at first sight, is that the least settlement occurred in the wastes that had been placed using only a low compaction method, in Cell 2. In fact, after the second phase of infilling, the overall density of the wastes in Cell 2 was very close to that in the other cells. This result may prompt some re-

examination of the traditional view that a high degree of compaction is needed in order to achieve high densities and prevent excessive settlement.

Leachate quality

Analyses for major parameters in pumped leachate samples from January 1994 to February 1996 are shown in Table 6.

The relationship between leachate quality and gas production rate does not match conventional expectations. In spite of the high gas generation rates in all cells, Cells 5 and 6 were the only two cells producing a fully-stabilized methanogenic leachate by early 1994, with BOD/COD ratios of <0.1 in each case and extremely low sulphate concentrations. Earlier analyses, although unreliable because of the sampling method, suggest that methanogenic conditions may have become established as early as late 1989 (Cell 5) and mid-1990 (Cell 6).

By early 1994 Cells 1 and 2 were each producing gas at a rate of $\sim 10 m^3/t.a$ and Cell 3 at a rate of $\sim 13 m^3/t.a$. These rates are at the high end of the range reported at full-scale landfills and yet all three cells continued to produce high-strength acetogenic leachates. During 1994 and 1995, methanogenic characteristics developed in all three leachates. This can be seen in Table 6, which shows falls in COD, BOD, TOC, SO_4 and BOD/COD ratio in all three cells, although at very different rates. In Cell 3, the transition appeared to be gradual, and may have been stimulated or encouraged by the addition of water to the cell. In Cells 1 and 2, the transition was much more sudden. There is no obvious explanation for this difference in behaviour. Cell 4 appeared already to be going through a gradual transition, similar to that in Cell 3, by the start of 1994, which appeared to be complete by mid 1995.

It remains unclear whether, in late 1993, acetogenic conditions existed throughout the saturated zones in Cells 1 to 4, or simply at the boundary with the unsaturated zone, from which the samples are presumed largely to be derived. Additional piezometers designed to allow 3-D sampling would be needed to determine this. No temporary peak in gas generation rate occurred during the rapid transitions in Cells 1 and 2 when they became methanogenic. This suggests that the observed changes in leachate quality may have been restricted to a relatively thin layer of the saturated zone, thus contributing relatively little to the total gas generation from the cells.

The findings from this study illustrate the possible spatial complexity of conditions in decomposing wastes and the difficulty involved in drawing conclusions from leachate quality data about the status of the decomposition processes throughout the landfill as a whole.

Large differences occurred in the concentrations of conservative parameters between cells that were apparently identical in other respects. For example, Cells 1 and 3 received the same type of wastes, have both produced similar total quantities of gas and have similar

leachate levels, but the chloride and NH_3-N concentrations in Cell 3 are approximately half those in Cell 1. There is no obvious reason why this should be so. It is clear that leachate strength, as measured by conservative parameters, has not been a good indicator of the level of biological activity. Cell 3 has the weakest leachate strength but the second highest gas production rate.

2.5 Potential to Generate Useful Information

Several factors appear to have stimulated gas production when applied independently in separate cells - moisture addition (during and/or after waste emplacement), air injection and possibly pH buffering. It is likely that factors not yet examined at Brogborough (e.g. recirculation, heating, seeding with micro-organisms) would also stimulate gas production, and that the use of several factors in combination could lead to even greater rates of decomposition. The six cells at Brogborough would lend themselves readily to the examination of some further variables and of some variables in combination. Based on the results from perturbations to Cells 3 and 4, it is possible that the effects of further perturbations could be evaluated within two years.

Five areas of useful continuing or additional study can be identified:

- continue operation and monitoring as at present;
- continue operation as at present but carry out more detailed monitoring;
- investigate more operational variables;
- investigate operational variables in combination;
- carry out longer term studies for sustainable landfilling.

These are discussed below.

Continue operation and monitoring as at present.

- The longer term durability of the enhanced rates exhibited since 1993 by Cells 3 and 4 will be further elucidated.

- The cells will continue to provide new information on the shape and range of LFG production curves, in control cells and enhanced cells such as 3 and 4. Within two years it may be possible to establish in which cells rates will continue to increase, level out or begin to decrease, as a function of cumulative gas production and operational variables.

Continue present operations with additional monitoring.

- Leachate levels could be measured monthly in all accessible wells and related to OD and to the cell base levels. This would allow much more reliable interpretation of the water balances of the individual cells, which cannot currently be attempted.

- Additional piezometers could be installed at several depths to allow 3-dimensional sampling of the saturated zone. This would indicate the within-cell variability of leachate quality. In Cells 1, 2 and 3, it would reveal whether acetogenic conditions remain within parts of the saturated zone. This could be of particular relevance to our understanding of landfill processes, in view of the high gas production rates in these cells. Three-dimensional sampling could also indicate whether pumped samples truly represent the full saturated depth or are strongly biased towards the upper layers, which are presumed to have a higher hydraulic conductivity.

- The DNA probe, if sufficiently developed for quantitative work, could be used to measure methanogenic activity in different cells and the results compared with measured methane and gas production rates. A comparison could also be made with other test cells. This work would certainly help to evaluate the usefulness of the DNA probe as a quantitative tool and could also be of direct help in understanding differences in performance between the six Brogborough test cells.

- Analysis of excavated solid wastes could be undertaken at the conclusion of study or on drilled samples. Analyses of samples for calorific value, loss on ignition, cellulose, etc., could be compared with cumulative gas production and with the analyses undertaken earlier in the study. The results would be useful in interpreting or demonstrating the extent of degradation of the wastes. They would also be helpful in assessing the usefulness of solid waste analysis as a tool for landfill completion monitoring. In particular they could provide valuable statistical information on the variability of samples taken from a relatively uniform zone of landfilled waste, whose extent of degradation could be corroborated by cumulative gas production data. There will be very few other opportunities in the UK where this could be done.

Investigate additional variables

It would be necessary always to retain one cell as a control, and Cell 1 appears perfectly suitable for this purpose. Cells 3 and 4 should be left as they are to see how the effects of air and water additions endure. Cell 6 may be unsuitable for additional work because it contains different wastes than all the other cells. Cells 2 and 5 could be made available to study additional variables. Cell 2 has, in effect, been a spare control for the duration of the study, and Cell 5 has served its original purpose. The two additional variables that are most likely to yield useful results are **recirculation** and **temperature**. The addition of water to Cell 3 has shown that the sub-cap herring-bone systems are likely to be effective at re-introducing leachate fairly evenly. The most practical way of examining temperature would probably be to use recirculated leachate to introduce heat into a cell. This could be achieved by pumping abstracted leachate to a small holding tank, heated using either an immersion heater or waste heat from the gas flare. It may, however, prove difficult to effect a large temperature increase within a 2-year period.

Investigate variables in combination

It is probable that the highest achievable rates of gas production would be obtained by optimising several important factors simultaneously. One of these is likely to be shredding of the wastes, and clearly this can no longer be examined at Brogborough. It would, however, be possible to attempt to combine other variables, such as recirculation, heating, air injection and pH control in one cell. It may not be possible to accommodate such a combination without sacrificing some other aspect of continuing study, because of the limited number of cells available.

Longer-term studies

- The cells could be continued for long enough to determine total LFG yields and to establish fully the shape of the LFG production curve under different cell management regimes. It would be very useful to produce data showing how quickly gas production rates may decline as the degradable carbon is depleted. It would also allow assessment of the characteristics of the solid wastes when gas generation is complete, or nearly complete. This information would be particularly helpful in relation to landfill completion.

- One or more cells could be used to provide a large-scale demonstration study of the flushing bioreactor concept. The main barrier to its adoption at full-scale landfills is the cost of leachate treatment at rates equivalent to hydraulic retention times of less than 5 years. For a 15,000m^3 test cell, leachate nitrification at a high flushing rate could be provided at relatively modest cost. The experiment would:

- show whether build-up of excessive dissolved salt concentrations was a problem;

- provide some information on the hydraulics of recirculation;

- confirm denitrification kinetics from smaller scale studies;

- allow the effects of recirculating nitrified leachate on gas production and quality to be quantified;

- demonstrate the flushing out of NH_3-N;

- allow demonstration of a variable flushing rate to optimise utilization of leachate treatment capacity.

Adoption of this suggestion would necessitate the sacrifice of one of the existing cells.

3. LANDFILL 2000 TEST CELLS

3.1 Introduction

Two cells were constructed, in 1990/91, at the Lower Spen Valley landfill, West Yorkshire. The cells were constructed for slightly different objectives than those at Brogborough, and are smaller and shallower, containing approximately 1000t of waste each, with a maximum depth of only 5m. Their purpose was primarily to investigate the practicality of accelerating the stabilization of domestic waste. The design and method of filling and operating the cells were based on a concept of bioreactor cells used in rotation, proposed in the 1980s (Bratley and Khan, 1989) for stabilizing wastes within three years to produce a residue usable as compost. The motivation behind the original concept was the possibility of repeatedly re-using expensively engineered landfill facilities. Gas generation, while clearly an important aspect of accelerated stabilization, was not one of the original objectives behind the project.

The techniques used to accelerate decomposition were the addition of digested sewage sludge and sewage effluent, and the recirculation of leachate. Both cells had a similar quantity (~12%w/w) of sewage sludge added during infilling. Cell 1 subsequently had ~10%v/w of sewage effluent added and leachate was recirculated at a high rate thereafter. In Cell 2, no recirculation was carried out and only a small volume of sewage effluent was added, and at a later stage.

The construction and operation of the cells was funded jointly by West Yorkshire Waste and Yorkshire Water PLC. Monitoring of leachate and gas was funded by the Department of the Environment and carried out by WRc.

The assessment of the Landfill 2000 project for this review consisted of four aspects:

- the strengths and weaknesses of the study;
- knowledge gained from the results up to mid 1995;
- the potential to generate further useful information.

The operation and maintenance of the cells was discontinued by the owners in March 1995 because the project had by then been running for the duration originally intended and budgeted for. No recommendations for further work are therefore included in the review.

3.2 DESCRIPTION OF THE LANDFILL 2000 TEST CELLS

The design and construction of the cells has been described in detail by Reynolds & Blakey, (1992). A schematic and cross-section showing the main features of construction are reproduced in Figures 14 and 15. Each cell measures 36m long x 23m wide, giving a plan area of 828m^2. The cells are extremely shallow, with a lozenge-shaped cross-section, a

maximum waste depth of only 5m and an average waste depth of ~1.4m. Both cells were filled with a mixture of untreated domestic waste and ~12% by weight of dewatered, digested sewage sludge. The wastes were placed in thin layers, with a Dresser 175 bulldozer, using the front blade to spread the sewage sludge and mix it in with the domestic waste. Approximately one year after infilling, sewage effluent was also added to Cell 1 to promote the degradation process.

Cell bases and side-walls were constructed of compacted clay, which was then lined with a 2mm HDPE geomembrane. This was covered by a 200mm protective sand layer, followed by terram and then 300mm of 20mm gravel, with leachate collection pipes. These led to a sump, from which leachate could be abstracted for recirculation.

Following placement of the wastes, the gas collection pipes and leachate recirculation pipes were laid, and the wastes covered with a 200mm layer of pea gravel to assist passive gas collection. The cells were then capped with a 1mm HDPE geomembrane, 200mm sand, and finally 500mm of sub-soil. A schematic representation of the closure details is reproduced in Figure 16.

Chronological highlights in the construction and management of the cells are shown in Table 8 and Figure 18.

The quantities of waste and emplacement densities reported for the two cells were as follows:

		Cell 1	Cell 2
Domestic refuse	(t)	930	980
Sewage sludge	(t)	135	127.5
Total weight	(t)	1065	1108
% sewage sludge		12.6	11.5
Emplacement density	t/m^3	0.94	0.89

The initial construction and filling of the two cells was virtually identical. Subsequently, different management regimes were used to assess their affects on stabilization. Cell 1 had a large volume of sewage effluent added to it and liquor was recirculated continuously, beginning approximately one year after filling. The recirculation regime in Cell 1 consisted of pumping ~$17m^3$ in one hour, every 3 days. In Cell 2, no recirculation was carried out, and only a small volume of sewage effluent was added, following removal of a large volume of leachate, approximately two years after filling.

Gas release from both cells has been by passive venting only, and measurement of gas flow rates only began in 1993 in Cell 2, and 1994 in Cell 1. Gas quality has been measured both

in the vented gas and in four gas probes installed into each cell. Locations of these probes are shown in Figure 17.

Chronological highlights in the monitoring of the cells are shown in Table 9.

3.3 Assessment of the Strengths and Weaknesses of the Landfill 2000 Test Cells Project

The primary objective of the study was to accelerate the stabilization of MSW rather than maximizing energy production. However, because the chosen route for achieving stabilization was methanogenic fermentation, the strengths and weaknesses have been assessed in this review with reference to the same two objectives used earlier to assess the Brogborough project, namely:

(i) to accelerate the **initiation** of methanogenesis;
(ii) to accelerate the **rate** of methane generation.

Choice of variables

The variables included at Landfill 2000 are marked in Table 3 which also shows those examined at Brogborough. With only two cells, there was clearly no opportunity to examine several variables independently. In the event, the three main variables that were examined, namely moisture addition, seeding with methanogens, and recirculation, have emerged from many large and small-scale studies as probably the most cost effective of the eleven variables listed in Table 3. This may be regarded as a strength.

The inclusion of sewage sludge during infilling would have contributed both moisture and methanogens to both cells. The effect of this as a variable could therefore only be assessed in relation to other test cells. The retrospective addition of sewage effluent (one year after cell construction) and the use of recirculation were both applied to Cell 1. It is therefore possible to judge their combined effectiveness against Cell 2, which is a strength, but not to distinguish strictly between the effects of the water addition and the recirculation. This must be regarded as a weakness. Similarly, it cannot be determined whether the use of sewage effluent was important or whether plain water would have had the same effect.

Design and construction of cells

The main strengths and weaknesses are summarized as follows and discussed below:

- cells too shallow to develop optimum temperatures;
- uncertainty over recirculation efficiency in Cell 1;
- uncertainty over control of water ingress and gas egress in both cells;

- uncertain efficiency of passive vs. active gas collection system;
- good mixing of sewage sludge and MSW during filling.

The cells have an average waste depth of only ~1.4m with a maximum of 5m. This is too shallow to insulate the bulk of the wastes from either the effects of fluctuating ambient temperatures or the cooling effect of the underlying ground. This is confirmed by the temperature probe results given in CWM050/96, reproduced here as Figure 19. Waste temperatures fluctuated seasonally between ~7°C and ~17°C with mean values of only ~12°C. The shallower probes exhibited the more extreme fluctuations and responded more directly to seasonal changes in ambient temperature. Other research studies (e.g. Campbell *et al.*, 1986) have shown a direct relationship between gas production rate and temperature, up to 50°C, when other factors are held constant. Commercial waste digestion systems are typically operated at mesophilic (~35°C) or thermophilic (~45-50°C) temperatures.

Leachate was recirculated in Cell 1 using the pipework layout shown schematically in Figure 14. This consisted of open, slotted 90mm pipes running directly down a 1 in 9 slope. This arrangement would have encouraged leachate to short-circuit directly to the basal drainage blanket rather than percolating down through the wastes. This was confirmed in February 1994 when a lithium tracer injected into the recirculation line was detected in the collection sump within 40 minutes. In practice, a significant proportion of the recirculated leachate (perhaps up to 30%, or ~525mm/a) probably did percolate through the wastes. This conclusion is based on longer-term results showing equilibration of the lithium tracer with refuse moisture. Over the long term (~1 year) virtually complete equilibration between recirculating leachate and moisture held in the waste mass occurred. This is discussed later.

Some uncertainty exists over the integrity of the cells, with respect both to water ingress and gas egress. Leachate levels rose steadily in both cells throughout most of the study. Level data from CWM050/96 are reproduced as Figure 20. After removals of leachate in June-August 1993, and the resulting drop in sump leachate levels, both cells recovered rapidly, within two months, to their pre-removal levels. This can be seen clearly in Figure 20. Levels in both cells then continued to increase, but at a slower rate. The initial rapid recoveries were most probably due to draining of leachate from the saturated waste mass after the lowering of levels in the surrounding drainage blanket. The subsequent longer-term rises in both cells must be attributable to a combination of displacement due to compaction/settlement, and possibly ingress of water. Some displacement will almost certainly have occurred, throughout the project, although an unfortunate weakness of the monitoring was that no settlement monitoring was undertaken. However, if displacement were solely responsible for the rises in level, Cell 1 would be expected to have shown a greater rate of rise than Cell 2, because it had leachate recirculation and double the rate of gas production (hence waste degradation) than Cell 2. In practice, Cell 2 exhibited the greater rate of long-term leachate level rise, from ~2.0m in October 1993 to ~2.8m in November 1994, a rise of 0.8m. During the same period the level in Cell 1 rose by only 0.4m from ~1.5m to ~1.9m. These figures under-represent the difference in saturated waste volume changes between the cells, because of the cells' larger plan area at higher

levels. It therefore seems highly likely that there was water ingress into Cell 2. The leachate depth profile from October 1993 to November 1994 (Figure 20) shows the greatest rises in winter months and this would be consistent with rainfall as a source of ingress. If ingress occurred in Cell 2, it could also have occurred in Cell 1, contributing to the rise in leachate level. The waste's effective porosity would have had to fall from ~25% in mid 1992 to ~3% by late 1994 to rule out water ingress as a factor.

There is some evidence that gas was able to escape from both cells into the overlying soils and this would be consistent with leaks in the top cover membrane that could also have allowed water to enter the cells. Thirteen soil gas probes were installed to 30cm depth at ~2m intervals down the centre line of each cell. They were monitored for methane on four occasions, from November 1992 to February 1993. Most had no detectable methane but three probes on each cell did contain methane on three out of four occasions, reaching ~80% above Cell 1 and ~35% above Cell 2.

Leachate quality data for Cell 1 are consistent with there having been ingress of water. Chloride and NH_3-N concentrations are shown in Figure 21. A steady decrease in chloride concentration is evident, which is difficult to explain other than by dilution.

Cumulative gas generation is the most certain measure of the progress of waste stabilization. In order to monitor this reliably it must be reasonably certain that no significant egress of gas occurs other than through the gas flow measuring equipment. A passive venting system was used in the cells and that inevitably increases the risk of uncontrolled egress, because gas pressures inside the cells are likely to be greater than when active gas extraction is used. Attempts were made initially to monitor gas pressures in the exit pipes, using transducers, but the results were erratic and regarded as unreliable. Pressure monitoring was discontinued after June 1993. The results of soil gas monitoring, noted above, suggested that some escape of gas occurred, but the extent cannot be quantified. The results of gas flow measurement must therefore be regarded as possibly erring on the low side.

The thin layer method of waste emplacement is used at a significant proportion of UK landfills. It ensured that the sewage sludge was mixed evenly throughout the MSW in both cells. This would have ensured even distribution of moisture and methanogens and is regarded as a strength in the context of this project.

Monitoring of the cells

The strengths and weaknesses of the monitoring carried out during the study are summarized in Table 10 and discussed below.

Temperature logging was comprehensive, with four probes in both cells, monitored at monthly intervals throughout the study.

Gas quality monitoring was also excellent, with monthly monitoring of quality in the vent pipes and probes in both cells. In addition, the installation and monitoring of probes in the cover soils provided useful information and is regarded as a strength.

Gas flow monitoring comprises both strengths and weaknesses. The absence of regular gas flow monitoring on Cell 1 until the final three months of the project is a significant omission. Even on Cell 2, continuous monitoring was not begun until October 1993, roughly 2.5 years after the start of the study. These omissions mean that comparisons between the performance of the two cells, and comparisons with other studies, are far less reliable and less comprehensive than they might have been. On the positive side, the study led directly to the development of a new 'time of transit' gas flow monitor. This appears to be ideally suited for the modest flows in this type of study and for fluctuating flows from passive venting systems.

No monitoring of leachate quality was carried out on Cell 2 until June 1993, two years after completion of the cells. Even in Cell 1, leachate quality monitoring was only begun when recirculation was started, one year after filling of the cells. In a study of such limited duration, these omissions, and the gas flow omissions, are significant shortcomings. On the other hand, the existence of some leachate analyses from discrete locations within the refuse mass, albeit limited in extent, is a strength of this study because they allow a comparison with the bulk leachate in the sumps. These data came from the gas probes and from the refuse samples obtained at the end of the study. The demonstration of a contrast with the bulk leachate from the drainage sump is a very important outcome of the study because it helps to inform us about the ways in which methanogenic conditions can develop in landfills.

The absence of any settlement monitoring is a weakness. At Brogborough, settlement correlated broadly with cumulative gas production. It would have been instructive to make a comparison with Landfill 2000, where the effects of stabilization might have been increased by the physical effects of waste lubrication and softening brought about by recirculation in Cell 1.

The failure of the gas pressure monitors is also unfortunate. In view of the possibility that gas leakage may have been significant, it would have been useful to have data on the extent and duration of positive pressure within the cells.

3.4 KNOWLEDGE GAINED FROM THE RESULTS

Gas generation

Assessment of the extent to which initiation of methanogenesis, or of gas production, was accelerated in either cell, is inevitably speculative because insufficient gas flow monitoring was carried out. Gas quality data are reproduced from CWM 050/96, as Figures 22-24, showing methane concentrations in the vent pipes and major gas components in the probes.

Leachate COD and BOD are shown in Figure 25.

In each cell, methane concentrations increased sharply to 40-60% in the first 6 months of 1992, both in the main vent pipes and the internal probes. In Cell 1 this occurred slightly earlier than in Cell 2. The time difference between the cells, in the vent pipes (Figure 22), cannot reliably be attributed to recirculation or liquid addition. The change in Cell 1 gas quality was under way before the start of recirculation or liquid addition, and Cell 2 probes underwent very similar, equally rapid, changes at approximately the same time, even though no recirculation was used. The methane concentrations in the Cell 2 vent subsequently increased far more slowly than in Cell 1, but this may have been simply due to gas flow rates being lower, allowing some air ingress in the vent. The change in leachate quality from acetogenic to methanogenic is sometimes taken to indicate the initiation of methanogenesis. However, an often overlooked truism is that in any landfill a significant methanogen population must have already developed before the change in leachate quality can occur. This is evident at Landfill 2000 in Figure 25. COD and BOD exhibited a typical pattern of falling, during a period of ~9 months, to low levels, but this change occurred **after** high methane concentrations had become established. Both COD and BOD were still **increasing** in concentration in Cell 1, up to July 1992, by which time the methane concentration in the vent and probes had already reached ~50%. From July 1992 to April 1993, the leachate COD fell by ~19,000mg/l. Taking a COD:TOC ratio of ~3:1, this is equivalent to a carbon removal rate of ~8,600g/m^3.a (≈22g/m^3.d) in the leachate phase. The contribution of this to overall gas production from the cell is estimated as follows:

$$8{,}600 gC/m^3.a \equiv \frac{8600}{12} \text{ moles gas/m}^3.a$$

$$\equiv \frac{8600}{12} \times \frac{22.4}{1000} \text{ m}^3 \text{ gas/m}^3.a$$

$$\approx 16 \text{ m}^3 \text{ gas/m}^3 \text{ leachate/year}$$

The total moisture content of the cell at this time was estimated in CWM 050/96 as 431m^3.

Using this figure, total gas production = 16 x 431 m^3/a.

= 6896 m^3/a

The net weight of MSW plus sewage sludge in the cell was 1065t.

Therefore, leachate contribution to specific gas generation rate was:

$$= \frac{6896}{1065} \text{ m}^3/t.a$$

= 6.5 m^3/t.a

Four hot wire anemometer (HWA) measurements of gas flow rate were made on Cells 1 and 2 during this period and are shown below, together with results from the time of travel flowmeter at the end of the study:

Date	Cell 1		Cell 2	
	m^3/hr	$m^3/t.a$	m^3/hr	$m^3/t.a$
24.11.92	7.3	60	n.d.	-
7.1.93	6.3	52	3.0	24
24.2.93	4.5	37	0.6	4.7
19.5.93	2.1	17	0.4	3.2
early 1995:		17		8

If the HWA results are taken as correct, the contribution to gas flow from degradation of leachate COD in 1992/93 was minor in comparison to the measured gas flows. This is consistent with observations in smaller scale studies (e.g. Beaven, 1996).

It appears likely from the behaviour of leachate COD that a significant level of methanogenic activity had developed in Cell 1 by July 1992, after 3-4 months of recirculation. The gas probe gas quality data suggest that this activity was not confined to the drainage layer but was distributed throughout the waste mass. The limited gas flow data for late 1992/early 1993, shown above, suggest that water addition and recirculation in March-June 1992 may have led to a short-lived period of unusually high gas production rates similar to those that have been observed in small scale studies (e.g. Campbell *et al.*, 1986; Beaven, 1996).

Although fewer leachate quality and gas flow data are available for Cell 2 during this period they are consistent with a similar behaviour but at a lower rate than in Cell 1. The possibility that such behaviour occurred in relatively large test cells such as those at Landfill 2000 makes it particularly unfortunate that frequent or continuous gas flow monitoring was not undertaken throughout the study.

The gas flow rates in both cells subsided by May 1993 but evidently stabilized in Cell 1 at a level much higher than achieved in conventional landfills or in Cell 2. It is reasonable to attribute the high on-going rates in Cell 1 to the effects of recirculation, since both cells by this time contained similar volumes of leachate.

Results of continuous gas flow monitoring for Cell 2 from October 1993 and for Cell 1 from December 1994 are reproduced in Figure 26. By early 1995 the rate of gas flow from Cell 1 was 18,474m^3/a. For the combined weight of MSW plus sewage sludge of 1,065 tonnes, the specific rate was 17.3m^3/t.a. This is much higher than rates recovered from conventional landfills and is comparable with Cells 3 and 4 at Brogborough. The actual rates of gas generation may even have been somewhat higher, if significant leakage occurred through the cap. The high rate of gas generation is particularly remarkable in view of the low temperatures in both cells (see Figure 19), which averaged only ~12°C. Even in Cell 2, the average rate for the year to February 1995 was equivalent to 8,810m^3/a, or 7.95m^3/t.a

based on the combined weight of MSW and sewage sludge. This is towards the upper end of the range for conventional landfills, most of which have much higher temperatures.

It seems reasonable to conclude that the addition of sewage sludge to both cells led to enhanced gas production, in spite of the low temperatures. It also seems reasonable to conclude that the recirculation of leachate and addition of sewage effluent to Cell 1 further enhanced gas production rates.

The trends in gas production at the end of the study (Figure 26) appear to differ between the two cells, and present an interesting comparison with the Brogborough test cells. For Cell 1, although the continuous data record was only 3 months long, the gas production rate appeared to be constant, and was identical to the rate measured by hot wire anemometer nearly two years earlier. In Cell 2, the rate appeared to be still increasing, as shown by the period July 1994 to February 1995. [Note in Figure 26 that there was a gap in the monitoring record from January-June 1994 and that the line shown for this period is a guestimate]. By the end of this period the rate was approximately $10m^3/t.a$. This behaviour in Cell 2 is similar to that of the Brogborough cells and it is unfortunate that the monitoring could not have been continued, to see if the flow rates would continue to increase.

Waste stabilization

From the measured gas flow rates the wastes would not be expected to have reached a stable non-polluting state by the end of the study. This was confirmed by examination and analysis of solid samples from each cell.

Crude estimates of total gas flow can be made for each cell, with the following assumptions:

- losses via leakage through the caps are ignored;
- gas volumes prior to July 1992 were negligible but increased thereafter;
- gas flow rates changed linearly between flowmeter readings.

Calculations based on these simplifying assumptions are tabulated below. They suggest that by the end of the study Cell 1 had produced $\sim 61m^3/t$ and Cell 2 had produced $\sim 23m^3/t$. In view of the evidence that some leakage of gas did occur, these figures can probably be regarded as under-estimates. Nevertheless, even the higher figure for Cell 1 falls a long way short of expected gas potential, which is usually taken to be in the order of $\sim 200m^3/t$.

The early data are hot-wire anemometer readings and the later data are interpolated from the time of transit flow meter results shown in Figure 26, for dates marking the beginning of continuous monitoring in Cell 2 (20.11.93), Cell 1 (10.12.94) and the end of the study (21.2.95).

Date	Flow Rate (m^3/t.a)		Period days	Flow in Period (m^3/t)	
	Cell 1	Cell 2		Cell 1	Cell 2
01.07.92	0	0			
24.11.92	60	24	146	12	5
07.01.93	52	24	44	7	3
24.02.93	37	4.7	48	6	2
19.05.93	17.3	3.2	84	6	1
20.10.93	17.3	7.95	154	7	2
10.12.94	17.3	7.95	416	20	9
21.02.95	17.3	7.95	73	3	2
Total				61	23

The low estimates of total gas flow are consistent with the results of biochemical methane potential (BMP) tests on solid refuse samples. The samples were excavated on 21st February 1995 and tested for:

- biochemical methane potential (BMP);
- acid-digestible fibre (ADF).
- loss on ignition (LoI);

The results were as follows:

	Cell 1	Cell 2
BMP (m^3LFG/dry tonne)	76.3	161.1
ADF (%wt/wt as received)	13.5	15.5
Loss on ignition (wt/wt % as received)	52	44

These amounts confirm that a high proportion of degradable material remained in each cell. Thus although the treatments did lead to enhanced rates of waste degradation they did not achieve the original objective of stabilizing the waste in three years. If the temperature in the cells had been higher, it is possible that very much faster rates of stabilization would have been achieved, at least in the recirculation cell, closer to those achieved in some laboratory and small scale studies and in refuse digesters. However, this remains a matter for speculation.

Gas quality

The methane concentrations in the gas vented from both cells are shown in Figure 22. In Cell 1 the methane content increased rapidly, after water addition and the start of recirculation, to 50-60% in summer 1992. Thereafter there was no overall change but the concentration fluctuated seasonally. The highest methane concentrations occurred in the winter and the lowest in summer. The ratios of CH_4:CO_2 for the vent gas from both cells

are shown in Figure 27 and indicate that this seasonal behaviour was not simply an artefact due to greater air ingress into the vents in summer. This ratio is a useful indicator because it is not affected by air ingress. The results in Figure 27 show that there was a marked fluctuation in the composition of the gas produced by decomposition of the wastes. The CH_4:CO_2 ratio for Cell 1 was lowest in summer, at just over 1, and highest in winter at 1.5-2.0.

The Cell 2 vent gas initially had a lower CH_4 content (Figure 22) and a lower CH_4:CO_2 ratio (Figure 27) than Cell 1; both during and after the large surge of gas production in the second half of 1992. At that time it exhibited no obvious seasonal fluctuation. The removal of leachate and addition of sewage effluent in July 1993 were quickly followed by a large rise in the CH_4:CO_2 ratio, from ~0.8 to ~1.5 (see Figure 27). The ratio subsequently declined slightly but it remained significantly higher than the levels before manipulation of water volumes in July 1993.

The increase in CH_4:CO_2 ratio in the vent gas in Cell 2 was matched by similar changes in the four probes within the wastes. These are shown in Figures 28 (Cell 1) and 29 (Cell 2). At the same time, hydrogen concentrations in these probes increased dramatically from typical LFG concentrations of a few hundred ppm to unusually high levels of 5,000-15,000ppm. These are shown in Figure 30 along with hydrogen data for Cell 1. The increased levels of hydrogen were sustained for many months in Cell 2. Only a short-lived increase occurred in one of the probes in Cell 1.

It seems likely that the manipulation of liquid in Cell 2 stimulated a change in its biochemistry, towards increased hydrogen production and consequent utilization of H_2/CO_2 to produce methane. This led to the increase in the CH_4:CO_2 ratio. It may be that this altered condition had already been reached in Cell 1, explaining its higher CH_4:CO_2 ratio and absence of any overall change when leachate volumes were manipulated in July 1993. The results suggest that H_2:CO_2 utilization was a significant route for methane generation in the cells, possibly affecting ~10% of the volume of gas produced. It is not possible to attribute increases in CH_4:CO_2 ratio in other studies (e.g. Brogborough) to this route with any confidence, because the low temperatures at Landfill 2000 distinguished the cells from other studies and from real landfills. Several of the H_2/CO_2 utilising bacteria have temperature optima below 30°C whereas the acetoclastic methanogens all have temperature optima above 30°C (Watson-Craik, 1995 personal communication). The low temperatures at Landfill 2000 would therefore favour hydrogen utilizers.

The gas quality data from Cell 2 also suggest that a significant proportion of its gas generation took place within the wastes, rather than being restricted to the methanogenic drainage blanket. This is evident from the sustained elevation of hydrogen levels over many months and by the similarity of CH_4:CO_2 ratios in the gas probes to those in the vent.

In contrast, the vent data for CH_4:CO_2 ratio for Cell 1 were quite different from the gas probe data. These are shown in Figure 28. It is unfortunate that only one of the four probes

remained accessible after July 1993. Up to then, none of the probes exhibited the seasonal fluctuation of CH_4:CO_2 ratio noted in the vent gas. However, after July 1993 the composition in Probe 1 did show a similar fluctuation to that in the vent gas. It appears more likely that in Cell 1 the major proportion of gas was generated in the drainage blanket. That would be consistent with the effect of recirculation, leading to the flushing of acetogenic leachate out of the wastes into a fully-methanogenic zone. [This is discussed in greater detail in the later section on leachate quality and hydraulics.] It is also supported by the phasing of the temperature and CH_4:CO_2 maxima and minima: the vent gas ratios correspond more closely to extremes in ambient air temperature (see Figure 19) than to temperatures within the wastes, which lagged by 2-3 months. If the fluctuations in Cell 1 were indeed due to temperature fluctuations, then the test cells indicate that both temperature changes and manipulation of liquids can lead to significant changes in the biochemistry of decomposition and hence in the composition of gas produced. It is unclear whether the biochemical changes in Cell 2 were accompanied by any change in the rate of waste decomposition, because the gas flow monitoring data were too sparse for the period concerned.

Leachate quality

Results for chloride, NH_3-N, Na and K in the sump leachate in both cells are shown in Figure 21. Results for COD, BOD, pH, iron, sulphate and several parameter ratios are shown in Figures 25, 31 and 32.

In Cell 1 sump leachate there was a steady fall in chloride concentration, from ~1700mg/l to ~950mg/l, over a period of two years. This decline is consistent with there having been ingress of water, a possibility that was also apparent from the behaviour of leachate levels, discussed earlier.

In comparison with chloride, the NH_3-N concentration in Cell 1 fell far less, from ~1050 to ~750mg/l, and the ratio of NH_3-N:Cl rose significantly. This is consistent with continuing release of NH_3-N from waste degradation and suggests that much of the chloride reservoir in the wastes is present in a readily leachable form so that most of it enters the leachate at an early stage. Evidence for this has also come from other studies (e.g. Beaven, 1996).

The change to methanogenic quality in the sump leachate in Cell 1 is clearly seen in Figure 31. It took approximately 9 months, from mid 1992 to Spring 1993, i.e. ~1.5 to 2 years after construction of the cells, and appears to have followed a similar course to that commonly observed in landfills. COD, BOD and iron concentrations all decreased at the same time and at approximately the same rate. However, pH, sulphate and the BOD/COD ratio behaved slightly differently. The rise in pH value slightly preceded the changes in BOD and COD: in July 1992, COD concentrations were at their peak while the pH value had already risen above 7. Although both BOD and COD fell sharply over just an ~9 month period, the BOD:COD ratio fell far more gradually, from a maximum of ~0.7 down to ~0.1 by the end of 1994. A fall in sulphate concentrations to very low levels occurred

roughly 1.5 years later than the other changes. This differs slightly from the Brogborough cells, where the establishment of methanogenic leachate in Cells 1 to 4 was accompanied by SO_4 concentrations falling to very low levels. However, at both sites the fall in SO_4 levels occurred when the BOD/COD ratio fell below ~ 0.2 and this happened more suddenly in the Brogborough cells than at Landfill 2000.

The temporary effects, on sump leachate quality, of liquid level reduction in mid 1993 can be seen in Figures 31 and 32. The lowering of levels in the sump and drainage blanket allowed acetogenic leachate to drain at a higher rate from the waste mass. Once the liquid levels had equilibrated, the drainage rate fell and methanogenic conditions rapidly became re-established in the drainage blanket.

In Cell 2, monitoring of the sump leachate began only in mid 1993 but similar trends are apparent (Figures 21 and 32) to those in Cell 1. Overall, the sump leachate in Cell 2 was slightly more dilute than that in Cell 1. This may indicate a higher rate of ingress of water and is consistent with the higher leachate levels and higher rate of level rise than in Cell 1, discussed earlier.

Some data were also obtained on leachate quality within the waste mass, and they showed that in contrast to the leachate in the sumps and drainage layers, acetogenic leachate conditions prevailed throughout the study. Samples of leachate were obtained from some of the flooded gas probes in January and June 1994 and tested for a very limited range of parameters. Subsequently, in February 1995, leachate was extracted by centrifuging excavated refuse samples from both cells and tested for a more comprehensive suite of determinands. Results from flooded gas probes are shown in Table 11. Results from centrifuged interstitial leachate are shown in Table 12.

Although all the leachates in the waste mass remained acetogenic as late as February 1995, the concentrations of COD in Cell 1 were by then considerably lower than those measured in June 1994. This may indicate that methanogenic leachate quality was becoming established within the wastes in Cell 1. However, sulphate concentrations remained far higher, at several hundred mg/l, than those in the sump leachate, suggesting that sulphate-reducing bacteria were not functioning at all at the prevailing redox potentials. The chloride concentrations within the wastes were far higher in both cells than those in the sump leachates. This may indicate that infiltrating water tended to accumulate predominantly in the drainage layers, as might be expected in the absence of recirculation. However, in view of the long term equilibration implied by the results of lithium tracer addition, discussed below, this is a somewhat surprising observation for Cell 1. The difference between sump and *in situ* leachates also indicates that diffusion and convection processes did not bring about homogeneity of leachate quality.

The interstitial leachates revealed significant differences between the upper and lower layers of waste in both cells. The most significant feature was that ammoniacal nitrogen concentrations were very much **lower** in the bottom samples, whereas all the other

parameters were at **higher** concentrations in the bottom samples. In a pilot-scale study by Beaven (1996) loss of NH_3-N was observed during a period of very rapid methanogenic activity and was attributed to uptake by new cells during a period of rapid growth. It is possible that the differential at Landfill 2000 might also have been due to higher rates of cell growth in the lower layers of the waste. If so, this would be further evidence that significant methanogenic activity took place within the waste mass even while the leachate remained acetogenic.

Hydraulics of recirculation

A lithium tracer test performed in February 1994 provided valuable information on the hydraulic regime in Cell 1, particularly on the extent of short-circuiting around the drainage blanket and the rate of percolation through the refuse.

A 5 litre slug of lithium chloride solution containing 48g Li was injected into the leachate recirculation pipeline on 15th February 1994. It was added while the recirculation pump was running, so mixing and dilution would have been maximised. Samples were subsequently taken from the sump to monitor how soon lithium would be detected and how rapidly it would be diluted by leachate in the cell. The measured lithium concentrations are shown in Figure 33. This also shows the background concentration in the sump leachate before tracer addition, and the concentrations measured in the *in situ* leachate taken from flooded gas probes on 1st March 1994. Several important observations and calculations can be made from these results:

(i) Added lithium was detected in the sump 40 minutes after injection into the recirculation pipeline. This indicates a very rapid flowpath via the re-injection pipes and the drainage blanket. However, WRc observed (Blakey *et al.*, 1996) that it usually took ~3 days for water levels in the sump to recover fully, following each recirculation pumping cycle.

(ii) The maximum concentration detected in the sump was 4mg/l, after 40 minutes. Thereafter, concentrations fell, reaching 2mg/l after 3 days and 1.22mg/l after 13 days.

(iii) Over the longer term, the concentration fell to a level similar to the background (pre-tracer) level and similar to those in the flooded gas probes. This implies that complete equilibration occurred with moisture in the waste mass over a period of less than one year. It is unfortunate that no measurements were made between 13 days and 262 days. These would have allowed more accurate estimation of the rate of equilibration.

(iv) It may be assumed that the gradual dilution in the sump was due to drainage of leachate out of the waste mass. It may also be assumed that recirculating leachate percolated into the top of the waste mass at roughly the same rate. The free leachate

in the drainage system may then be regarded as a completely mixed system (given the rapid appearance of lithium at the sump, and the recovery of water levels within 3 days, this is a reasonable approximation) with a throughput of leachate equal to the rate of drainage from the waste mass. The dilution of lithium observed in the first two weeks after addition can be used to estimate the rate of leachate flow into and out of the waste mass, using the dilution equation:

$$C_t = C_0 \exp [-t/\theta]$$

where,

C_t = concentration at time t
C_0 = initial concentration
t = time
θ = hydraulic retention time

The volumes of leachate involved in mixing with the lithium tracer at various times can be estimated from the measured lithium concentrations as follows:

40 minutes, $C_t = 4mg/l$

$$\therefore \text{volume} = \frac{48{,}000\ mgLi}{4mg/l} = 12{,}000 \text{ litres} = 12m^3$$

1 day, $C_t = 3mg/l$

$$\therefore \text{volume} = \frac{48{,}000\ mgLi}{3mg/l} = 16{,}000 \text{ litres} = 16m^3$$

3 days, $C_t = 2mg/l$

$$\therefore \text{volume} = \frac{48{,}000\ mgLi}{2mg/l} = 24{,}000 \text{ litres} = 24m^3$$

13 days, $C_t = 1.22mg/l$

$$\therefore \text{volume} = \frac{48{,}000\ mgLi}{1.22mg/l} = 39{,}344 \text{ litres} = 39.3m^3$$

For the purpose of calculating leachate drainage rates, the volumes at 1 day and 3 days are taken as approximate estimates of the free leachate volume in the drainage system and sump. The dilution equation is then applied using the concentration after 13 days, to provide two estimates as follows:

Day 1 to Day 13

$\frac{C_t}{C_o} = \frac{1.22mg/l}{3mg/l} = \exp(-12/\theta)$

$\therefore \theta = 13.3$ days

$\therefore$ drainage flow $= 16m^3 \div 13.3$ days

$= 1.2m^3/day$

$= 438m^3/annum$

Day 3 to Day 13

$\frac{C_t}{C_o} = \frac{1.22mg/l}{2mg/l} = \exp(-10/\theta)$

$\therefore \theta = 20.2$ days

$\therefore$ drainage flow $= 24m^3 \div 20.2$ days

$= 1.19m^3/day$

$= 433m^3/annum$

These two estimates are very similar. The plan area of the cells is $828m^2$ each, so the drainage flow estimated above is equivalent to ~525mm/a. The recirculation flow rate varied slightly during the study. A rate of $\sim 17m^3$ every three days was given earlier. Rates up to $21m^3$ every three days were maintained up to late 1993 but declined thereafter due to pump malfunctions and falling pump efficiency. The annual recirculation rates averaged $\sim 2{,}000m^3/a$ during the study and fell from $\sim 2{,}500m^3/a$ initially to $\sim 1{,}500m^3/a$ at the time of the tracer study (Blakey *et al.*, 1996). Thus the percolation of leachate through the waste mass was approximately 30% of the recirculated flow.

(v) The total moisture content (i.e. the Bed Volume) of the wastes in Cell 1 in 1994 was estimated by Blakey *et al.* (1996) to be $431m^3$ after addition of water in 1992. This is approximately 40% wet weight and is a reasonably typical figure. The implied hydraulic retention time within the waste mass would then have been just under one year.

(vi) The leachate drainage rate estimated above is consistent with earlier conclusions that a high proportion of the gas generation in Cell 1 occurred in the drainage blanket. Given that leachate quality in the sump was methanogenic from mid 1993 onwards, it follows that all of the degradable carbon flushed from the wastes must have been converted to landfill gas. Using the 1994 and 1995 values for COD and TOC within the waste mass, the following gas generation rates can be estimated:

1994 Mean *in situ* leachate COD $= \sim 50{,}000$ mg/l

$\therefore$ mean *in situ* leachate TOC $= \sim 17{,}000$ mg/l

$\therefore$ gas flow, at percolation rate of 435 m^3/a is

$$\frac{435\ m^3/a \times 17{,}000g\ TOC/m^3 \times 22.4\ l/mole}{12gTOC/mole \times 1{,}000\ l/m^3} = 13{,}804\ m^3/a$$

$$\simeq 13\ m^3/t.a$$

The measured gas flow rates at this time were $\sim 17 m^3/t.a$, suggesting that the major proportion of the gas may have been generated in the drainage blanket.

1995 Mean interstitial leachate TOC in bottom of cell = 8,000 mg/l
$\therefore$ gas flow at percolation rate of 435 m^3/a, is

$$\frac{435\ m^3/a \times 8{,}000g\ TOC/m^3 \times 22.4\ l/mole}{12g\ TOC/mole \times 1{,}000\ l/m^3} = 6{,}496\ m^3/a$$

$$= 6.1\ m^3/t.a$$

Gas flow rates remained very consistent, at $\sim 17\ m^3/t.a$. The implication is that an increasing proportion was being generated within the waste mass by early 1995.

4. MICROBIOLOGICAL ASPECTS OF THE RESULTS FROM BROGBOROUGH AND LANDFILL 2000

The results described above from Brogborough and Landfill 2000 led to some fundamental questions regarding the microbiology of the test cells. To assist this review, these questions were discussed with Dr Irene Watson-Craik, of the University of Strathclyde, and the outcome is discussed below.

4.1 What is the significance of the proportions of different VFAs in leachate?

The main VFAs produced in the fermentative oxidation of the basic six-carbon units arising from cellulose degradation are those with an even number of carbon atoms, primarily acetate and also butyrate. Higher VFAs, such as valerate, which has an odd number of carbon atoms, are derived mainly from longer chain fatty acids, arising from hydrolysis of lipids. Propionate (or propanoate) is usually taken to be indicative of the accumulation of hydrogen and is a **result** of this accumulation, rather than a **cause** of it. Propionate can be produced from acetate in the presence of excess hydrogen or from the degradation of butyrate. Limited data on the concentrations of VFAs in the sump leachates at Landfill 2000 are shown in Figure 34. In Cell 1, propionate, iso-butyrate, valerate and iso-valerate concentrations continued to increase in mid 1992, at a time when methanogenesis was becoming established, with high gas flow rates, falling acetate and butyrate concentrations, and falling BOD and COD concentrations. Propionate concentrations continued to increase until October 1992, by which time all of the other VFAs had decreased to low levels. An increase in propionate concentrations as a proportion of total VFAs was evident as early as July 1992 and may therefore have some significance as an indicator of incipient methanogenesis. Degradation of propionate is inhibited by hydrogen and requires a low partial pressure of hydrogen. Thus the accumulation of propionate in the third quarter of 1992 may have reflected the presence of elevated hydrogen concentrations at that time. Unfortunately there are no hydrogen data for that period. However, in mid 1993 when a short-lived increase in hydrogen concentration occurred in one of the Cell 1 gas probes there was no evidence of an increase in propionate, relative to acetate, in the sump leachate.

In Cell 2, far fewer VFA analyses were carried out. No results were obtained during the crucial period of July and August 1993 when the leachate COD increased to more than 15,000 mg/l. In September 1993 the propionate concentration exceeded that of acetate, but total measured VFAs were nevertheless at low concentrations (see Figure 34) compared with the leachate BOD of ~2,000mg/l. By early 1994, all the VFAs, including propionate, had fallen to below detection limits and remained so until monitoring ceased, even though elevated hydrogen concentrations persisted in the gas probes. This may mean that the elevated hydrogen occurred only within the wastes and did not occur in the gas produced

within the sump. However, analyses of individual VFAs in the interstitial leachate obtained by centrifuging from refuse samples in early 1995 did not shown any preponderance of propionate (all concentrations in mg/l):

	acetate	propionate	n-butyrate	n-valerate
upper sample	4140	1900	4060	986
lower sample	6950	3230	8770	1420

4.2 How is the production, accumulation and utilization of hydrogen related to that of acetate in the generation of methane?

Methane can be formed from the fermentation of a small number of simple organic compounds, particularly formate, acetate and methanol, or from hydrogen and carbon dioxide. Higher VFAs must first be degraded to acetate before they can be used by methanogens. Acetate, hydrogen and carbon dioxide are all generated during the acidogenic stage of biodegradation. The β-oxidation of long chain fatty acids (produced from hydrolysis of lipids) liberates 2 moles of hydrogen for every mole of acetate generated, but produces no carbon dioxide. Fermentation of carbohydrates on the other hand produces both hydrogen and carbon dioxide, in addition to VFAs. Methanogenesis from acetate produces CO_2, while CO_2 is consumed in the generation of methane from hydrogen.

Typically, in anaerobic digestion systems, it is believed that most of the gas is generated from acetate, and a relatively small proportion from hydrogen and CO_2. Since acetate fermentation produces methane and CO_2 in equal quantities, while the H_2/CO_2 route removes CO_2, the extent to which the CH_4:CO_2 ratio in the gas exceeds 1:1 may give an indication of the relative importance of the two routes at any point in time. Thus the gradual increase in the proportion of methane at both sets of test cells may indicate that the H_2/CO_2 route became gradually more important during the first few years.

The steady state concentration of hydrogen is usually very low in landfill gas - typically a few tens or hundreds of parts per million. An accumulation of higher concentrations, such as occurred in the probes in Cell 2 at Landfill 2000, either means that hydrogen production has been stimulated or that hydrogen utilization has been inhibited. At Landfill 2000 the accumulation of hydrogen was associated with a marked and sustained increase in the ratio of CH_4:CO_2. This suggests that utilization of hydrogen increased significantly so that the cause of the accumulation was most likely to have been an increase in hydrogen generation. Why this should have been stimulated by the manipulation of liquid levels cannot be determined from the monitoring data available and would probably require more detailed microbiological studies to be undertaken. These could be of some value if they lead to the ability to increase the methane content of landfill gas.

All methanogens can utilize H_2/CO_2, whereas only some methanogens can utilize acetate. The H_2/CO_2 route produces more energy than the acetate route, so it may be expected that H_2/CO_2 utilizers might perform better at low temperatures, such as those that prevailed at Landfill 2000. None of the acetoclastic methanogens has temperature optima below 30°C whereas some of the H_2/CO_2 utilizers do.

It is possible that the high temperatures experienced in the early stages at many landfills may kill off the psychrophilic (low temperature) methanogens, so that the populations that developed at Landfill 2000 could be quite different from those at some of the larger, hotter full-scale landfills.

Given that all methanogens can utilize H_2/CO_2 it is possible that the key to the fluctuations in H_2 concentration and in CH_4:CO_2 ratio at both sets of test cells lies in the characteristics and species distribution of the acidogenic bacteria rather than the methanogenic bacteria. It may be that further research into these bacteria would be more fruitful than into the methanogens, which are usually not the rate-limiting factor in landfill stabilization or gas production.

4.3 What determines the ratio of CH_4:CO_2 in landfill gas?

The ratio is governed by two main factors:

- population distribution between acetate utilizers and H_2/CO_2 utilizers as discussed above;

- changing nature of the substrate: more reduced compounds produce a higher percentage of methane.

The second of these factors is likely to occur at all landfills and would presumably be independent of operating conditions. A general trend with time would therefore be expected, such as that which occurred in most of the Brogborough test cells. A strong correlation between CH_4:CO_2 ratio and waste age, up to 25 years was reported in a study of 16 Australian landfills (Bateman, 1993).

Substrate changes do not, however, explain the behaviour of Cell 2 at Landfill 2000 following the manipulation of liquid levels, or the high initial CH_4 concentration in Cell 5 at Brogborough, or the seasonal behaviour of the CH_4:CO_2 ratio in Cell 1 at Landfill 2000. These changes appear more likely to be a result of changes in the behaviour of bacterial populations. If this is the case, then some degree of influence may be achievable over gas quality. It would be beneficial to explore in more detail the reasons for the observed behaviour and the practicality of exercising any control. For example, rapid changes in leachate level are easy to achieve in a test cell but may be far more problematic to achieve at a full-scale landfill. If low temperature were shown to be important for a high CH_4:CO_2

ratio, that would favour shallow waste depths, at least during the period of most active degradation.

4.4 What is the physical distribution of methanogens within landfills?

There is ample evidence from several sources that methanogens and other bacteria are mobile within the leachate present in landfilled wastes. Research at CAMR (Luton *et al.*, 1995) into the use of the DNA probe found that leachate was a good source of methanogenic DNA. In samples from the Brogborough test cells, they estimated methanogen numbers to be 10^3-10^4 per gramme of solid material, but 10^6-10^8 per ml of leachate. In lysimeter studies in Australia, Chugh *et al.* (1995) found that leachate from a mature methanogenic lysimeter was a very effective inoculum to accelerate the establishment of methanogenesis in a new lysimeter. In UK studies of the clogging of leachate drainage media (Paksy *et al.*, 1996), columns of various media were inoculated by passing leachate through them. They quickly developed the capacity to generate gas from a synthetic acetogenic leachate, and subsequent loss of drainable porosity was attributed partly to the growth of biomass. Leachate may also contain significant populations of other organisms in addition to methanogens. Kromann *et al.* (1995) found that the organisms present in eight different leachates were able to degrade a range of halogenated hydrocarbons. The greatest degradation activity was found in the leachates with the highest level of methanogenic activity. Similar observations were made by Paksy *et al.* (1996) who recorded degradation of pentachlorophenol in leachate-inoculated methanogenic drainage media.

There is equally strong evidence that methanogens and other bacteria tend to attach themselves readily to smooth surfaces, forming biofilms. Watson-Craik and Jones (1995) operated continuous culture vessels fed with butyrate as sole carbon source. A vessel packed with glass slides developed a higher level of methanogenic activity than one with no packing and suffered no loss of activity when the washout rate was increased. In the vessel with no packing the higher washout rate led to loss of suspended organisms and a drastic fall in activity. In related experiments, they found that methanogenic bacteria readily formed extensive biofilms on a variety of smooth materials including glass, polyethylene, polyterephthalate (PET) and cellophane. Most of these materials would be regarded as biologically inert. On the other hand, fibrous materials that might be regarded as potential substrates in landfills exhibited very little colonization by methanogens. These included cotton, newspaper and polyester fabric. In both the Landfill 2000 study and the experiments of Paksy *et al.* (1996) gravel drainage media readily formed methanogenic biofilms.

The tendency of methanogens to attach to smooth surfaces in preference to complex surfaces can lead to prima facie evidence of physical separation of methanogenesis from acidogenesis in landfills with drainage layers. This was the case at Landfill 2000, where leachate in the drainage layer became methanogenic while that in the waste layer remained acetogenic. However, this separation may be more apparent than real. Most wastes contain numerous

smooth surfaces as well as fibrous substrates. Landfill 2000 showed that significant gas production took place in the waste mass, and in Cell 2 it may have constituted the major proportion of gas generation. In many studies and full-scale landfills, methanogenic leachate has developed within the waste layers especially where saturated conditions exist. This became the case at all of the Brogborough cells. In one of the experiments of Paksy *et al.* (1996), drainage layers in a $35m^3$ skip were overlain by a layer of domestic waste. Monitoring results from different levels in the waste showed that volatile fatty acids in applied synthetic leachate were very largely removed in the refuse, before the leachate reached the drainage layers.

One of the reasons for the difference that sometimes occurs in the leachate characteristics between the waste and drainage layers is that in the drainage layers there can be no production of organic acids, only consumption. They are therefore more likely to appear methanogenic than the waste layers, where both production and consumption occur simultaneously. Whilst it could be that methanogenesis is initiated within the drainage layers, the responsible organisms must have originated within the wastes and many are therefore likely to be retained on smooth surfaces in the waste layers. It is highly likely, however, that drainage layers may have an important polishing effect on the quality of leachate abstracted for treatment while it remains acetogenic within the waste mass. Nevertheless, the simple observation of acetogenic leachate in the waste and methanogenic leachate in a drainage layer can not be taken as indicating that methanogenesis is restricted to the drainage layers. An often repeated view among microbiologists is that the key groups of micro-organisms are most likely to grow in very close associations with each other and that spatial separation is unlikely.

5. USEFULNESS IN VALIDATING LFG PRODUCTION/ EMISSION MODELS

Many models have been developed for predictions of gas production over the lifetime of individual landfills. This is distinct from modelling national or global production of landfill gas, for which a steady state is usually assumed and is likely to be reasonable assumption. Several constant rate models exist and have been reviewed by Gendebien *et al.* (1992) for the European Commission. This discussion concerns gas production at individual landfills, and for these a steady state can not be assumed.

Numerous non-steady state models have been developed and many are available for use on a PC. Reviews have been conducted by Pacey and Augenstein (1990) of USA models and by Sterritt (1995) of models available for PC in the UK. Pacey and Augenstein (1990) noted three key characteristics that may be used to distinguish different models, namely:

- the ultimate gas yield,
- the timescale for gas generation,
- the profile of the gas generation curve.

The results from Brogborough and Landfill 2000 can make little useful contribution to the consideration of ultimate yield or the full timescale for gas generation because neither study has been taken to completion. However, both projects are highly relevant to the important question of the profile of gas generation.

Most of the available models describe the kinetics or profile of gas generation by assuming an exponential decay in production rate after the peak rate has been reached. Many models assume that the peak rate occurs in year 1, immediately after initial deposit of the waste, while a minority include a linear, exponential or hyperbolic function to describe the initial (usually assumed to be rapid) build-up of gas generation. Few models include a lag period of zero gas generation.

In most of these cases the lag and rise periods, if considered, are relatively short compared with the total period of gas generation and account for a small proportion of total gas flow. Thus, the majority of models predict highest flows very early in the life of the site, declining thereafter.

There is some support, from field data, for models based simply on exponential decline, with no lag or rise period. Coops *et al.* (1995) carried out regression analysis on gas recovery data from nine Dutch landfills of known ages. Data from up to four different years at some of the sites generated a total of 18 data points. The best fit was obtained from a first order (i.e. exponential decline) model, with no lag or rise period, which categorized waste components as being of fast, medium or slow degradability. A slightly poorer, but still satisfactory, fit was obtained from a single phase first order model in which all the waste was

characterized by a single value for degradability. Similar findings were reported from an Australian study reported by Bateman (1993). He used up to 18 data points from landfills up to 20 years old to calibrate the MGM model of EMCON Associates in the USA (Pacey and Augenstein, 1990). The model fit produced by regression analysis showed gas production increasing linearly during the first year after waste placement, and declining logarithmically thereafter. However, in this case all of the data were obtained from pumping tests on a single well in each of the landfills studied. They were not based on measured total gas production at any of the landfills and did not include any time-series data for individual landfills.

In contrast to typical model profiles and the results from regression analysis at different landfills, referred to above, the time series data from individual Brogborough test cells have shown a completely different profile, to date. Weekly mean flow rates in each cell are shown in Figure 36. They, together with the cumulative flow data in Figure 6, show that the gas flow rates were increasing in all cells up to six years since waste deposit was completed, and were still increasing in two cells at 8-9 years since waste deposit was completed. If the date of completion of infilling is taken as the end of 1988, back-extrapolation of Figure 36 suggests that there was probably no lag period. The rate of increase has been very approximately linear. Somewhat different profiles have been reported for large-scale test cells in Helsingborg, Sweden, of a similar size to Brogborough, described in Section 6.2 of this report. They showed approximately constant gas flow over periods of several years.

These differences in behaviour are of such a magnitude and duration that it is necessary to consider whether the available models or these large-scale test cells better simulate the behaviour of wastes in landfills. It is also necessary to consider the reasons for various types of gas flow profile.

Models based on exponentially declining flow rates are based on an assumption, whether explicit or implicit, of first order kinetics, i.e. they simulate a case where gas flow is directly proportional to, and solely dependent upon, the available food supply. As the food supply is depleted, so the rate of gas generation falls. In real landfills, as currently operated, this situation is unlikely to be reached for many years. The Brogborough and Landfill 2000 test cell results, as well as many other experimental studies, have shown that gas flow rates are usually limited by many other factors, of which moisture content, moisture movement, bacterial numbers, pH and temperature appear to be the most important. Of these, moisture content and moisture movement appear to be able to have a dominant effect, outweighing most of the other variables. None of the readily available models takes these factors into account, other than to the extent that they allow for professional judgement in selecting generation times and lag times, and only a few models allow even this degree of flexibility.

That these variables, rather than substrate availability, are in fact limiting, is well illustrated by the contrast between results from the Brogborough test cells and results from small-scale studies where these environmental factors have been optimised. For example in the 500 litre

lysimeters reported by Beaven (1996), domestic waste was sorted, shredded and brought to a moisture content in excess of field capacity at the start of the study. Leachate recirculation and pH control then induced gas flow profiles typically characterized by a lag of ~1-2 years, rapid logarithmic growth phase and rapid exponential decline phase. In these lysimeters it would appear that after peak flows had been reached, the flow rates were indeed limited by the availability of substrate. It should be noted that even in these optimised studies, 15-50% of the ultimate gas yield was liberated by the time peak flow rates were reached. This is in contrast to the typical predictions of many of the models. Results qualitatively similar to those of Beaven have been reported by other workers (e.g. Lee *et al.*, 1993).

Given this contrast between models, optimised laboratory-scale reactors and the Brogborough and Swedish test cells (see Section 6), it is interesting to consider the gas flow profiles of the Landfill 2000 test cells. Although gas flow measurements were sparse up to October 1993, the available data are shown graphically in Figure 37 together with data from the lysimeters of Lee *et al.*, (1993) and Beaven, (1996). For the purpose of this graph it has been assumed that gas flow was negligible up to mid 1992, when the methane concentration began to increase rapidly in both cells. The profile for Cell 1 appears to be more like the typical model predictions than either the Brogborough cells or laboratory lysimeters. This may be attributable to the inclusion of sewage sludge (in each cell) and sewage effluent, and leachate recirculation, which provided both moisture and bacteria, and moisture movement. It is likely that both cells, but Cell 1 in particular, were much closer to optimising environmental conditions than most full-scale landfills.

In the Brogborough test cells, the increasing gas flow rates suggest that conditions for gas generation have improved very gradually over several years. The key factors are likely to have been a gradually increasing moisture content (rising leachate level) and the growth *in situ* of suitable bacteria.

The status of gas generation models can perhaps be likened to that of water balance calculations: they are recognized as not being very accurate but there is little choice other than to use what is available. There is a clear need to re-examine gas modelling. The results from Brogborough and Landfill 2000 show that models must take into account variables that are now known to have a direct and dominant impact on gas generation, particularly moisture content and moisture movement. In view of current efforts to accelerate the stabilization of landfills, it is important that models attempt to predict the results of specific management strategies such as leachate recirculation. For optimum management of the landfill as a whole it may be undesirable to accelerate the generation of gas too rapidly. It may be of greater economic advantage to avoid an early peak of gas production in order to ensure maximum efficiency of collection and utilization.

Total yields, and eventual timescales, for gas generation remain almost completely unmeasured at real landfills or large test cells. It would be of great benefit for test cells such as Brogborough to be continued until complete.

6. COMPARISON WITH OTHER LARGE-SCALE TEST CELL STUDIES

6.1 Test Cells at Mountain View, California, USA

6.1.1 Introduction

Six large-scale (~8000t; ~13,500m^3) test cells were constructed at the Mountain View landfill, near San Francisco, California, in 1981. Construction was completed, and monitoring began, on 1st June 1981. The cells were then monitored and operated for over 4 years, until mid October 1985.

Their purpose was to investigate the effects of four different factors in enhancing gas production in landfills, namely:

moisture addition;
seeding with digested sewage sludge;
buffering with calcium carbonate;
leachate recirculation.

6.1.2 Description

The design and construction of the cells has been described by Pacey and Van Heuit, (1983) and by Halvadakis *et al.*, (1988). Each measured 30m x 30m x 15m deep, giving a volume of 13,500m^3. The walls and bases were constructed from clay. The filled cells were covered with a pea gravel layer to facilitate gas collection and water distribution, and sealed with a hypalon geomembrane. A single leachate abstraction well was installed to the base, in the corner of each cell. Gas extraction was mainly passive, with a slight positive pressure being maintained at all times beneath the geomebrane cover. Centrifugal blowers were used "as necessary" to assist gas extraction but positive pressure was still maintained.

Details of cell wall construction and geomembrane liner sealing are not known, but it is reported [Pacey, 1989] that ingress of water to the cells occurred to varying degrees. Pacey noted that it is therefore possible that gas leakage would have occurred. This would undoubtedly have been encouraged by the maintenance of a positive gas pressure and the reliance on predominantly passive gas venting.

The input details of the six cells are shown in Table 13 This shows that where sewage sludge was added, the quantity varied from 5% to 14% of total solid waste inputs. Two levels of water addition were used - a low level at ~3% of total solids, and a high level at ~22% of total solids.

The initial density of the wastes after emplacement was relatively low, varying from ~570 to 670kg/m^3.

6.1.3 Monitoring

No details have yet been obtained of gas flow monitoring techniques or frequency. Leachate sampling was said to be undertaken at intervals but no results are given in the sources accessed so far. Temperature was recorded, but no data given.

Solid samples were obtained from four of the six cells (A,B,D and F) at the end of the study and analysed for a range of parameters including biochemical methane potential (BMP). Either one or two auger holes were drilled per cell. Twenty-eight samples were taken from each auger hole for chemical analysis and twelve samples for BMP testing.

A grid of nine settlement monuments was placed across the surface of each cell, to allow settlement to be surveyed. The frequency with which this was done is not known, but data for settlement at the end of the study have been reported (Pacey, 1989).

6.1.4 Results

Results at the end of the ~4 year study are summarized in Table 14. Detailed gas flow data during the period have not been obtained and are in any case likely to be of little value. There is circumstantial evidence that leakage occurred from the cells, so that cumulative gas flow does not reliably indicate the real extent of decomposition. It was reported (Pacey, 1989) that gas flow rates from several cells fell to below detectable limits for prolonged periods of time and then resumed at detectable levels. This is unlikely to reflect the real behaviour of the wastes and is more likely to indicate egress of gas by routes other than through the flow meters. Comparison of the recovered gas volumes and the BMP test results, on the refuse remaining, also suggests that for many cells a significant proportion of the initial gas potential had been lost, if it is assumed that this would be in the range 200-400m^3/t. If it is assumed that the BMP and chemical test results are reliable (the large number of samples encourages this belief), then it is clear that Cell A (leachate recirculation) underwent the greatest degree of degradation. It had the lowest remaining cellulose, COD, volatile solids and methane potential. It was also reported (Pacey, 1989) to have the highest temperature of any cell. The BMP test results indicated that perhaps less than 10% of the original methane potential remained in Cell A, and that perhaps 90% degradation had occurred in just over 4 years.

The difference in BMP between Cell A and Cells B, D and F was in the range 70-100m^3 CH_4/t dry refuse. At 50% v/v methane (actual values not reported), this equates to a difference in gas potential of 140-200m^3/t. Over 4.37 years, this is a difference in gas production **rate**, of 32-46m^3/t.a. Given that a rate of 19m^3/t.a was recorded from Cell D, it may be postulated that the actual rate of gas production from Cell A ranged from (19+32) to (19+46) m^3/t.a, that is 51-65m^3/t.a. Although a somewhat speculative estimate, this is

an exceptionally high rate, which had previously only been obtained in laboratory-scale studies. The main difference in the treatment of Cell A and Cell B (which finally had a similar BMP to that of the control) was the addition of a large quantity of **water** and the **recirculation** of leachate similar to Cell 1 at Landfill 2000. It is not possible to distinguish which of these two factors may have been the more important because solid samples were not examined from Cell C, which had the same water addition as Cell A, but did not have leachate recirculation. The gas production rate calculated above is similar to the peak rate recorded for Cell 1 at Landfill 2000.

It is also notable that even in the control Cell, Cell F, the measured gas collection rates greatly exceeded typical reported LFG recovery rates from full-scale landfills.

The addition of digested sludge and calcium carbonate may have been effective in promoting early establishment of methanogenesis. The comparison between Cell A and Cell B shows, however, that these factors were not themselves responsible for the unusually high rates of decomposition that apparently occurred in Cell A but not in Cell B.

The study provides strong evidence that a high moisture content and/or leachate recirculation are necessary to achieve the highest possible rates of decomposition.

6.2 Test Cells at Helsingborg, Sweden

6.2.1 Introduction

Four large-scale (13,500t) test cells were constructed at the Filborna landfill, operated by NSR, near Helsingborg, Sweden, in 1989. Filling with waste began in March 1990, and was completed by April 1991. Results have been reported up to February 1994 i.e. ~3 years since filling (Nilsson *et al.*, 1995; Meijer and Nilsson, 1995; Meijer *et al.*, 1994).

The purpose of the study was to stimulate faster waste degradation, to produce higher rates of gas production. Three stimulation factors were investigated and compared with a control cell:

Cell 1: Control cell
Cell 2: 5% water added during infilling
Cell 3: ~1% coal ash added during infilling, as a pH-buffering medium
Cell 4: Large volumes of air injected after infilling and capping.

6.2.2 Cell design, construction and operation

The design and construction of the cells has been described in detail by Meijer *et al.*, (1993). Each measured 40m x 40m x ~9m deep with a volume of ~15,000m^3. The four cells were

constructed in a square formation with common dividing walls, on an area of old landfill. The outer walls were of clay and the cell dividing walls were also of clay, constructed using a 'Christmas tree' technique. The base liner between the old and new wastes was clay, and leachate collection pipes were laid, leading to tipping buckets for flow measurement.

In all four cells, a pre-composting layer of ~1m of uncompacted MSW was placed, during March 1990 and left uncovered for ~3 months. Filling of the cells then took place from June 1990 to April 1991, with wastes comprising 83% crude MSW and 17% "organic industrial waste" (no further details available). Wastes were placed in four ~2m lifts using a Caterpillar 836C compactor. No daily cover was used and a density of ~0.9 t/m^3 was reported. In the water addition cell (Cell 2) the water was added by sprinkler to the top of each lift, during emplacement. In Cell 3, the coal ash (total quantity 80t or ~0.6% of cell contents) was added to each lift during emplacement.

After filling, the cells were covered with identical caps, consisting of 700mm clay and 300mm topsoil. Horizontal drains for gas extraction were incorporated in two lifts, and four vertical gas extraction wells per cell were installed after filling. Active gas extraction was used.

Air was injected into Cell 2 over a 2-month period from mid-June to mid-August 1992, i.e. more than one year after completion of infilling. The intention was that the injection of air would raise the temperature, thus stimulating faster degradation. A total of 30,200m^3 of air was injected via the four vertical wells, one at a time. This was a much larger addition than in Brogborough Cell 4, which had ~12,000m^3 injected into a similar quantity of waste.

6.2.3 Monitoring

Continuous gas flow monitoring was undertaken from August 1991 onwards. The methane content of the gas was also monitored continuously from this point onwards.

Temperature monitoring was undertaken in probes located at six depths in each cell. No monitoring of leachate level was carried out so the development of any saturated zone within the wastes can not be determined.

Leachate volumes draining from the cells were measured in tipping troughs but the results may be subject to some error because settlement of the cell bases was reported and not all leachate may have been collected. For the first five months of 1993 no leachate volume data were available.

Leachate quality has been measured both in the cell drainage and in pairs of lysimeters in the base of each cell. Only limited data on leachate quality have been published so far. Solid samples have been recovered from three depths within each cell on several occasions and results for pH, moisture content, VFA concentration and have been published. Settlement monitoring was undertaken.

6.2.4 Results

To date (published data up to early 1994), none of the 'treatments' has led to increased rates of gas generation compared with the reference cell, which has in fact been the most productive of the four cells. Cumulative gas volumes during the period of continuous measurement from roughly August 1991 to February 1994, a period of ~2.5 years, were:

	volume (m^3)	m^3/t	$m^3/t.a$
Cell 1 (control)	450,000	33	13.2
Cell 2 (5% H_2O)	290,000	21.5	8.6
Cell 3 (~1% ash)	225,000	16.7	6.7
Cell 4 (air injection)	260,000	19.3	7.7

The gas volume data above were taken from a graphical presentation of data given by Meijer *et al.* (1994) which is reproduced as Figure 38. It should be noted that some confusion exists in the published reports and papers over whether the graph data refer to gas or methane. It is clear from data elsewhere in the reports that the figures are for total gas volume, not methane. The same graph appears in Nilsson *et al.*, (1995), in which the volumes are also erroneously shown as methane rather than gas.

The pattern of gas production is highly relevant to modelling of gas generation. The rates have so far remained almost constant. This is clear from Figure 38. A slight increase occurred in Cell 4 following air injection but it was not sustained for more than six months. This behaviour contrasts with the protracted increase in rates at the Brogborough test cells.

The rates of gas generation are largely within the typical range for existing landfills, particularly given the high collection efficiency from most test cells. Thus, while the composted layer may have accelerated the initiation of methanogenesis, it does not appear to have led to unusually high rates of gas generation.

The absence of any sustained improvement in Cell 4 is of particular interest in view of the sustained increase that evidently followed from a smaller injection of air at Brogborough. As at Brogborough, any increase in temperature was negligible compared with the seasonal variations and fluctuations that occurred in all of the Filborna cells. These results are consistent with the explanation that the Brogborough Cell 4 increase may have been due mainly to the air forcing leachate into a higher proportion of the unsaturated waste, rather than a direct effect of temporary aerobic conditions. At Filborna, with leachate being drained by gravity, it is likely that there was very little saturated zone and hence little opportunity for the air to have a similar effect. This explanation would also be consistent with the gradual increase in gas production rate in all cells at Brogborough, where leachate

levels have risen steadily throughout the study, so that an ever-decreasing proportion of the wastes is moisture-limited.

Temperatures within the Filborna cells have been similar to those at Brogborough. At depths down to ~1.5m they have exhibited a strongly seasonal pattern with fluctuations from ~5 to 25°C. At 2m and below, the seasonal fluctuation has been less (~5°C) and temperatures have mostly been in the range 20-25°C.

Collected leachate volumes from March 1990 to December 1993 have been:

Cell	Leachate (mm)
1	119.9
2	144.5
3	171.3
4	45.0

Some doubt must exist as to whether all of the leachate is collected, particularly in view of the anomalously low figure for Cell 4. However, the volumes are generally quite low even allowing for the missing 5 months of 1993 data, and are consistent with the use of a clay cap on the cells. To assist free drainage within the wastes, no daily cover was used. Solid samples, recovered at regular intervals from three depths in the cells, have shown no evidence of any long-term increase in the moisture content of the wastes:

	Moisture content (% wet weight)			
Cell	25.5.91	23.11.92	25.11.93	27.5.94
1	38	36	45	38
2	37	36	47	-
3	42	42	43	-
4	52	40	45	-

As at Brogborough and Landfill 2000 there is evidence that acetogenic leachate has persisted within the body of the wastes while the leachate draining from the base is methanogenic, although only limited data have been published. Since approximately March 1992, the leachate draining via the tipping troughs has had a pH in the range 7 to 8 in all four cells. However, solid wastes obtained by drilling have had VFA concentrations consistently in the range 10-40g/kg and pH values typically below 7 and sometimes below 6.

6.3 Test Cells at Malmö, Sweden

6.3.1 Introduction

Six identical test cells (6,000t each) were constructed at a landfill operated by SYSAV at Spillepeng, Malmö, Sweden, in 1988. Filling with waste began in October 1988 and was completed by October 1989. Results have been reported up to October 1993 (gas) and March 1994 (leachate) (Nilsson *et al.*, 1991; Nilsson *et al.*, 1993; Nilsson *et al.*, 1994; Nilsson *et al.*, 1995).

The objective was to enable the optimisation of methane production by studying the mechanisms that control methane production, leachate quality and the degradation of the solid wastes. The factors addressed were primarily the composition of the wastes. Leachate recirculation has also been examined in one of the cells:

Cell 1: 30% MSW + 70% non-hazardous industrial and commercial waste
Cell 2: As Cell 1, but including 5% grease trap sludge
Cell 3: High organic, moist wastes from MSW sorting plants, canteens and restaurants
Cell 4: 100% MSW
Cell 5: 95% MSW + 5% grease trap sludge
Cell 6: 100% MSW with leachate recirculation.

The MSW and industrial wastes were used in their crude, unpulverized form.

6.3.2 Cell design, construction and management

The design and construction of the cells has been described in detail by Nilsson *et al.*, (1991). The cells are rectangular in plan and are constructed in line, side by side, on top of an area of old waste. Each cell has a base area measuring ~35m x ~35m. The top surface slopes at ~12-15% and to achieve this the depth of waste varies from 9m down to 2m. The waste depth is thus relatively shallow. The cell bases are of compacted clay, overlain by a plastic (no further details discovered) liner. However, this does not constitute a composite liner because the plastic has a 200mm sand layer above and below it. Leachate drainage is facilitated by a single drain pipe per cell, laid in the upper sand layer. The cells were completed with a 500mm clay cap, overlain by 300mm of top-soil which was seeded with grass.

The wastes were emplaced using identical techniques in all six cells, although the exact methods have not been discovered. The emplaced densities in Cells 1-3 were lower than in Cells 4-6. Volumes, weights and densities were:

Cell	Volume (m^3)	Weight (t)	Density (t/m^3)
1	7,400	3,400	0.46
2	6,800	3,400	0.50
3	7,600	3,500	0.46
4	8,000	5,200	0.65
5	8,400	5,000	0.60
6	7,600	5,250	0.70

In the cells containing mainly MSW a higher density was achieved than in those containing mainly industrial/commercial waste.

No pre-composting layer was used, although in Cells 1-3 there was a pause during infilling, of several months during winter 1988/89. It is thought that no daily cover was used in any of the cells.

Gas abstraction was facilitated by horizontal drains consisting of tyres and drain pipes, placed at two levels in each cell, in a radial pattern leading to a central well in each cell. Active gas extraction and flow monitoring began in August 1990, approximately one year after the completion of infilling.

In Cell 6 leachate recirculation was effected via two sub-cap injection trenches, containing pipes in free-draining media (specification unknown). These were placed perpendicular to the slope and run almost the full width of each cell. Continuous recirculation began in May 1991, approximately 18 months after completion of infilling. No record of the quantity or rates of recirculation has been discovered.

6.3.3 Monitoring

Gas flow is measured at least weekly and methane content every three weeks. More detailed analysis of major gas components is carried out every 6-8 weeks.

Leachate is analysed every 6-8 weeks also, and the leachate drainage volume is recorded every three weeks.

Solid waste samples are obtained annually by drilling. Eight samples per cell are obtained by sub-sampling from two drillholes at four different levels.

Settlement is monitored every 3 months at a single reference marker in each cell.

6.3.4 Results

All six cells began producing gas almost immediately and the methane content reached 50% or more within six months of the completion of waste emplacement in each cell. The methane content continued to increase in all cells and had reached ~60% by the start of 1992. Thereafter there was some evidence of seasonal fluctuations similar to those observed at Landfill 2000. The methane concentration appeared to be highest in the winter and lowest in the summer, with a seasonal range from ~55% to ~65%. Up to the most recent reported data (late 1993) there was no evidence of any significant difference in the quality of the gas generated in any of the cells.

The methane production rates in the six cells up to the 4th quarter of 1993 (~4 years after emplacement) are shown in Figure 39. Cells 1 and 2, containing only 30% MSW have reached the highest gas generation rates and have produced the highest total gas quantities. None of the 'treatments' (i.e. addition of grease trap sludge; leachate recirculation) has led to any increase in gas production compared with reference cells. Of the three basic waste mixes used, the high-organic (Cell 3) and MSW (Cells 4-6) wastes have behaved very similarly and have produced less gas than the mixes containing 70% industrial/commercial waste. Gas flow data prior to January 1991 are not available. From back-extrapolation of the graphs in Figure 39, it may be inferred that in all cells the gas generation rate increased at an accelerating rate during late 1989/1990, then increased at a constant rate during 1991, levelling off to more or less steady rates by mid to late 1991. In Cells 3, 5 and 6 there is possible evidence of a very gradual decline in rate since the end of 1991. So, gas flow rates continued to increase for ~2-2.5 years after emplacement then levelled off. This behaviour is mid-way between that of the Filborna cells (constant flows since less than 6 months after placement) and the Brogborough cells (flows increasing up to 6-9 years after emplacement).

The steady gas flow rates in Cells 3-6 are on the order of $7m^3$ CH_4/t.a (wet weight), equivalent to LFG flows of ~$12m^3$/t.a. For Cells 1 and 2, the corresponding rates are ~$12m^3CH_4$/t.a and ~$20m^3$LFG/t.a. These flows are significantly higher than at typical landfills and higher than at the Filborna test cells and most of the Brogborough test cells. It is unclear why Cells 1 and 2 should have such high flow rates, nor why recirculation in Cell 6 should apparently have had no effect. However, no data have been obtained on the volumes of leachate recirculated, so the significance of this negative result for Cell 6 is difficult to assess.

Temperature data showed that Cells 4-6 went through a typical initial aerobic composting phase, reaching 40-50°C, while Cells 1-3 did not. This may be because the filling of Cells 1-3 spanned a winter period, while that in Cells 4-6 took place entirely during Spring-Autumn of 1989. The loss of organic matter during the composting phase may be one reason why the gas volumes and flow rates in Cells 4-6 were lower than in Cells 1 and 2. However, that does not explain why the flows from Cell 3 were lower than from Cells 1 and 2, since none of these three cells had an initial composting phase. In all of the cells

temperatures have decreased gradually. Although showing significant seasonal fluctuations, the temperatures in Cells 1-3 have fallen from ~30°C in mid 1989 to ~20°C in mid 1993. Cells 4-6 have undergone a similar change but remain approximately 5°C warmer than Cells 1-3. These cells provide another instance where gas flow rate appears not be related to temperature.

Leachate flow and quality data have provided useful information on the behaviour of the cells. In spite of being clay-capped, the volumes of leachate have increased over time in five of the six cells and in 1993, four years since capping, were approximately as follows:

Cell	Leachate (mm)
1	80
2	133
3	57
4	67
5	10
6	79

As at Filborna, the volumes exhibit a large variation between cells and the possibility that collection is not fully effective in all cells must be considered likely. In particular, the result for Cell 5 is only approximately one third of that collected in 1992 and appears anomalous, given that all other cells produced larger volumes than in 1992.

The patterns of leachate production have been highly seasonal, with most leachate being generated in the winter. Leachate quality has also shown a marked seasonal pattern. BOD and COD concentrations, and the BOD/COD ratio have been at their highest at times of peak flow and the quality has fluctuated from largely methanogenic in periods of low flow, to largely acetogenic in periods of high flow. In considering the reasons for this, Åkesson and Nilsson (1996) have proposed an explanation which has many parallels with the observations discussed earlier at Landfill 2000. They propose either a horizontal stratification mode, or a pore-scale model in which the bulk of the waste produces gas but contains acetogenic leachate, i.e. its rate of gas generation is currently limited by the activity of the methanogen population. Meanwhile, in the bottom sand layer, at low leachate flow rates, methanogenic activity is sufficient to remove most of the degradable organic matter, producing a methanogenic type of leachate. When higher flow rates flush larger volumes of acetogenic leachate into this layer, the capacity of its methanogen population is exceeded, leading to the higher organic content observed in the collected leachate. This model is highly plausible, both for the Spillepeng and Landfill 2000 test cells. Equally, however, there are many examples of landfills with saturated zones of many metres depth which are fully methanogenic. It remains unclear whether, and how quickly, fully methanogenic conditions will become established in the unsaturated wastes, and what factors control this. In the Spillepeng cells, moisture from annual solid waste samples has shown a continuing decline in COD concentration in the most productive cells, Cells 1 and 2. In 1990, interstitial COD

concentrations ranged from ~20-40,000mg/l in these two cells. By 1993 the range was ~4-12,000mg/l, so it may be that the whole of the waste mass will eventually become methanogenic. The interstitial COD concentrations in the other cells are higher, typically in the range 10-20,000mg/l, although they too are showing some overall decrease with time. A similar trend was observed at Landfill 2000.

Without data on the rates of recirculation in Cell 6, no useful conclusion can be made about its apparent failure to stimulate increased gas generation. Moisture content data (Nilsson *et al.*, 1994) show that this cell has had a similar moisture content to the other cells to date (ranging from 38-48% in 1993) and it may be that considerably higher rates of recirculation are necessary to achieve the enhancement observed in other studies.

6.4 Test Cells at Stockholm, Sweden

6.4.1 Introduction

Two large-scale (10-12,000t) test cells were constructed at the Högbytorp landfill, operated by Ragn-Sells Ltd, near Stockholm, Sweden, in 1991. Filling with waste took place from September 1991 until the end of June 1992. The cells were filled with predominantly (85%) industrial waste, the balance (15%) being MSW. The experiment is younger than the other Swedish test cell studies and only limited results have been published so far (Karlsson, 1993).

The main purpose of the cells is to examine the effect of compaction on the generation of landfill gas. One cell was only loosely compacted while in the other a high compactive effort was applied.

6.4.2 Design and construction

The design and construction of the cells has been described by Karlsson (1993).

The cells are approximately square, with a base area of ~40m x ~40m and are constructed of clay. The depth of waste is approximately 10m in each, and the volumes and densities achieved were:

	Cell 1 (compacted)	Cell 2 (loose)
volume (m^3)	16,500	15,400
weight (t)	12,100	9,700
density (t/m^3)	0.73	0.63

In Cell 1, wastes were placed in 0.25m lifts each of which received at least 10 passes of a compactor. In Cell 2, the waste was placed in 4m lifts and very little compaction was used.

Horizontal gas collection systems were placed on the cell bases and at 4m and 8m above the cell bases. Their design ensured that each level could be monitored and controlled individually. Above 8m, a further 1m of waste was placed. This was then capped with a 1m layer of clay mixed with sewage sludge.

During infilling, the temperature in the loosely-packed cell rose so high (75°C) that a risk of fire was feared. Water was therefore added until the temperature fell to 60°C. In order to ensure comparability, the same quantity of water was added to Cell 1. The amount of water added has not been reported yet, but it appears that the moisture content of the wastes may have been enhanced to a similar degree to that in Brogborough Cell 5, and perhaps the Landfill 2000 cells. No information on leachate levels or waste moisture contents has been obtained yet.

In addition to a main collection pipe for leachate drainage, each cell was equipped with seven separate ~2m^2 lysimeters in the base to study spatial variations. In addition, four lysimeters were placed just under the cap in each cell to monitor the ingress of water. Four permanent settlement markers were installed in each cell.

Gas flows have been measured with a vane anemometer. Methane concentration has been determined using an infra-red type meter.

6.4.3 Results

Only results for gas flow and methane content have been published so far, up to October 1993. This spans the period from ~2 months after completion of infilling to a little over one year, and up to two years since the first wastes were deposited.

In both cells, gas extraction rates have been altered, at intervals of 2-3 months, and adjusted in the light of their effect on methane concentrations.

Both cells have exhibited similar behaviour, producing relatively high gas flows from the beginning of the monitoring period i.e. within two months of the completion of infilling. By the end of the monitoring period the flows and quality appeared to have been reasonably stable for several months and were approximately as follows:

	Gas Flow (m^3/t.a)	CH_4 (%)
Cell 1 (high compaction)	10.9	~45
Cell 2 (low compaction)	10.8	30-40

The gas flow rates are at the upper end of those recovered at full-scale landfills and were reached very early in the life of the cells. Continued monitoring will be necessary to determine whether these flows will increase or decrease. The cell with the more highly compacted wastes had a higher specific rate of methane production than Cell 2, even though

the specific gas generation rates were virtually the same. The methane contents were as yet relatively low in both cells.

The densities achieved in either cell were not particularly high and this may be a result of the characteristics of the industrial wastes that formed the greater part of the cell contents. It is also noticeable that the difference in densities between the cells was not large, given the difference in compactive effort that was applied. This has some parallels with the Brogborough study, where similar initial densities were achieved and the eventual density in Cell 2 at Brogborough was very similar to that in the other cells, in spite of a low-density tipping method.

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7. DISCUSSION

7.1 The Brogborough and Landfill 2000 test cells have confirmed, at a large-scale, results from many earlier bench-scale studies showing that it is possible to accelerate the rate of waste decomposition, using simple, inexpensive techniques. The successful techniques included both the manipulation of the waste mixture during emplacement and the active management of the filled cells:

- at Brogborough, the addition of moisture in the form of sewage sludge (Cell 5) and the inclusion of a high proportion of non-hazardous industrial/commercial waste (Cell 6) both accelerated the initiation of landfill gas production;

- at Landfill 2000 the inclusion of appropriate bacteria, in sewage sludge, and the addition of moisture, as sewage sludge and sewage effluent, helped in the early establishment of methane generation and in promoting high rates of degradation, even at atypically low temperatures (10-15°C);

- at Brogborough, the retrospective addition of water, or injection of air, both led to a large, sustained, increase in the rate of gas production. It appears quite probable that the effectiveness of air injection was mainly due to its having forced leachate into previously dry layers of waste;

- at Landfill 2000, recirculation of leachate through the waste at a hydraulic retention time of approximately one year led to a large increase in gas generation rate, from ~8m^3/t.a to 17m^3/t.a in otherwise identical cells;

- low density tipping techniques at Brogborough made little difference compared with a control cell and certainly did not enhance gas production or accelerate the initiation of methane generation.

The test cells are large enough that it is safe to assume similar results would be achieved in full-scale landfills.

7.2 The findings from the Brogborough and Landfill 2000 cells are largely consistent with results from large-scale studies in other countries:

- at Mountainview (see section 6.1) in the USA, the most complete degradation over an ~4.5 year period occurred in a cell with massive water addition and leachate recirculation. Remaining gas potential was just 22m^3CH_4/t dry solids, compared with 92-120 m^3CH_4/t dry solids remaining in cells without leachate recirculation;

- although recirculation at the Malmö project in Sweden (see section 6.3) has evidently had no effect yet compared with a control cell, no details have been found of the rate of recirculation and this may be an important factor;

- at both the Malmö (section 6.3) and Helsingborg (section 6.2) projects in Sweden, cells with a significant proportion of non-hazardous industrial/commercial wastes produced higher rates of gas generation, at an earlier stage, than similarly operated cells containing only MSW; this is similar to the observation in Cell 6 at Brogborough. The eventual total yield of gas from such cells may be different than from MSW and the gas production rate at Brogborough Cell 6 levelled off while the rates in other cells continued to increase;

- at the Stockholm cells in Sweden, low density tipping has so far produced similar density and similar specific gas generation rates to a cell tipped using highly compacted thin layers.

7.3 The Brogborough and Landfill 2000 cells have not incorporated all of the important determinants of high degradation rates (such as elevated temperature) in a single cell and even the enhanced gas production rates in various large-scale cells (typically $\sim 20m^3$ LFG/t.a) remain far below the peak rates achieved in optimised small-scale studies (e.g. $800m^3$/t.a, Beaven, 1996). There is evidence that rates of $\sim 60m^3$/t.a may have occurred briefly at Mountain View and in the Landfill 2000 recirculation cell, but the flow monitoring frequency at the time was too low to regard this as a reliable conclusion. Nevertheless, an important point can be made regarding these high rates. It may be possible to reach rates well in excess of $20m^3$/t.a in full-scale landfills by employing several different factors in combination (i.e. moisture addition, leachate recirculation and heating to high temperatures). However, the closer that conditions are brought to the optimum, the higher the maximum specific gas production rate will be, the sooner it will be reached, and the quicker the gas production rate will decline. The total duration of gas production is also likely to be shorter, behaving more like conventional models, peaking and decaying rapidly. Even though these rapid decay rates would be partly smoothed by the spreading of infilling over several years, gas production could fall to very low levels long before the other main task of landfill completion, namely contaminant flushing, had been progressed very far. This may not be the most economical approach to the overall task of landfill stabilization.

7.4 The Brogborough and Landfill 2000 cells, together with several other studies discussed in this review, have shown that the duration and profiles of gas generation are far more dependent upon environmental conditions than on waste composition. There is therefore a need to modify the approach used in the modelling of gas production, since most models in current use allow for differences in waste composition, whereas none include moisture content, recirculation and temperature as variables. Under optimised laboratory conditions, profiles are often similar to the

rapid or instantaneous growth and rapid exponential decay curves used in most gas models. Initial conditions in most landfills are nowhere near optimal and this has led to quite different profiles. At Brogborough, gas generation rates were still increasing after more than six years. At the Helsingborg cells (Figure 38), rates reached a steady value very quickly soon after filling, and have remained virtually constant since then. In the Malmö test cells (Figure 39), rates can be deduced to have gone through a logarithmic and then linear growth phase over a period of ~2 years and have remained more or less constant for the subsequent 2-3 years. Of the large-scale test cells only Cell 1 at Landfill 2000 has provided any evidence of a profile that is similar to model profiles and the data are sparse, rendering this a rather tentative conclusion. This was also the only UK or European cell that has incorporated both a high moisture content and a high rate of recirculation.

To assist attempts to improve gas modelling, it would be of great value to collate gas extraction data over periods of many years at individual landfills. Several sources of such data must now exist within the UK, Europe and the USA, where landfill gas exploitation schemes have been in place since the early 1980s. A review of time series data from such sites would be an informative and relatively straightforward exercise. It would also be very useful to continue monitoring existing test cells for as long as possible, to confirm profiles, duration and yields. It is unfortunate that the Landfill 2000 test cells were discontinued at such an early stage.

7.5 Temperature did not, at first sight, appear to be an important determinant of gas generation rate in any of the large-scale test cells. At Landfill 2000, very high rates were achieved at temperatures below 15°C. At Brogborough, there was no correlation between temperature and gas generation rate. The same may be said of the Swedish cells. However, results from small-scale studies show that temperature is definitely an important parameter, when other factors are held constant. In a bench-scale study reported by Campbell *et al.*, (1986), gas production was investigated in 1kg reactors, operated in a saturated condition with leachate recirculation and pH control. With these other factors optimised, there was an almost linear relationship between gas generation rate and temperature between 10 and 50°C from almost zero at 10°C to ~31m^3/t.a at 50°C. Similar results were found in a review of data from nine studies of methane fermentation from a variety of solid waste materials (Ashare *et al.*, 1977). These data showed an approximately 50-fold increase between 10°C and 55°C. Other work on the anaerobic digestion of refuse has shown that far higher rates were achievable under thermophilic (55°C) conditions than under the more typical mesophilic (37°C) conditions (Cecchi *et al.*, 1993).

The absence of any marked temperature effects in large-scale test cells may be due to the variations in other factors and the fact that most of these factors were at sub-optimal levels and therefore were rate-controlling. As more effort is applied to optimising factors such as moisture content and recirculation, it is quite possible that the higher gas generation rates will then be found to be temperature-limited.

7.6 Data from the test cells have provided useful information on the evolution of the methane content of landfill gas and the possibilities of manipulating it. In most lysimeters, test cells and landfills, CH_4:CO_2 ratio rises with time, stabilizing at ~1.5. This gradual increase was observed in all of the Brogborough cells and both of the Landfill 2000 cells. The same trend has also been reported in data from Australian landfills up to 25 years old (Bateman, 1993). Some long-term increase may be inevitable when starting with mixed wastes, as the less readily-degradable compounds are thought to be in a more chemically reduced form, which would favour higher methane production. There was, however, also some evidence from Landfill 2000 that different biochemical pathways may be encouraged, even in identical wastes, by control of the environmental conditions. In the case of Landfill 2000, it appeared that the prevailing low temperatures may have favoured H_2/CO_2 producing and utilizing bacteria, and methane concentrations were higher in winter than in summer. Similar fluctuations were apparent in the six test cells at Malmö, Sweden, which were also relatively shallow. To develop this possibility it would be necessary to consider in more detail the various biochemical pathways that affect the CH_4:CO_2 ratio in landfill gas and to attempt to manipulate them at laboratory scale using a single substrate, before considering how manipulation might be achieved at landfills.

7.7 The large-scale test cell studies have helped in resolving the question of stratification or physical separation of acetogenic and methanogenic activity in landfills, which has been the subject of discussion for many years.

That methanogenic activity develops in the initially inert environment of basal drainage layers is beyond dispute. The experimental study of Paksy *et al.*, (1996) confirmed this, as did the data from Landfill 2000, where the *in situ* leachate remained acetogenic, while the collected leachate became fully methanogenic at an early stage. Similarly, in the Helsingborg and Malmö test cell studies in Sweden, leachate draining from the cell bases was typically methanogenic, while that obtained from excavated solid waste was consistently acetogenic.

The occurrence and extent of methanogenic activity within the unsaturated wastes themselves has been harder to estimate. The data from Landfill 2000 have shown that methane generation must have been occurring in the wastes even while the *in situ* leachate was acetogenic. Firstly, from mass balance calculations it was clear that the measured gas flows from Cell 1 were greater than would result from the estimated flow of acetogenic leachate into the methanogenic drainage zone. In 1994, the drainage zone could have been responsible for the major proportion of gas production, i.e. ~14m^3/t.a out of a total flow of ~17m^3/t.a. This is probably within experimental error. However, by 1995 *in situ* COD concentrations were much lower and the drainage layer could only have generated approximately 6m^3/t.a, while total gas generation remained at 17 m^3/t.a. The greater proportion must therefore have been generated within the wastes themselves. Additional evidence comes from Cell 2 where a rapid rise in the CH_4:CO_2 ratio in the *in situ* gas probes in July 1993 was

matched by an identical rise in the ratio in the vent gas from the whole cell. The absence of recirculation in Cell 2 means that the flow of leachate into its drainage blanket must have been low and it would not have been enough to generate the measured gas flows from the cell. A conclusion from these observations is that high rates of methanogenesis can occur within unsaturated wastes while the moisture in those wastes retains the characteristics of a high-strength acetogenic leachate. With time, the leachate quality in the unsaturated wastes may become fully methanogenic. The fall in COD between 1994 and 1995 in Cell 1 at Landfill 2000 suggests this process may have been under way. In a drainage study in a $35m^3$ container, reported by Paksy *et al.*, (1996), methanogenesis appeared to be fully established because a synthetic acetogenic leachate added to the top of the waste layer had become fully methanogenic before it reached the drainage layer.

The role of drainage layers in converting acetogenic leachate to methanogenic leachate may be important for leachate management, even if it is only a temporary situation. At the Malmö test cells, high seasonal flows of acetogenic leachate exceeded the capacity of the drainage layer to convert the organic content to gas. Design of treatment facilities to deal with fluctuations between acetogenic and methanogenic leachate is more problematic than for a consistently methanogenic leachate. This concern would favour the maintenance of a deeper saturated zone, or alternatively the use of a pre-composting basal waste layer to maximize the level of methanogenic activity in the base of the landfill.

Where leachate is sampled from a saturated zone of several metres using vertical leachate wells, as at Brogborough, even pumped samples are likely to be derived largely from the upper layers of the saturated zone, because they will be more transmissive than the lower layers. When such samples go through a rapid transition from acetogenic to methanogenic quality, as they did at Brogborough at different times, it does not necessarily mean that the whole saturated zone has undergone the same rapid transition. Methanogenic conditions could have been increasing at depth for a long time, without being detected in the leachate that is sampled. In order to monitor any stratification that may develop it would be necessary to have monitoring locations at specific depths.

8. CONCLUSIONS

8.1 The Brogborough and Landfill 2000 test cells have provided very valuable information on the acceleration of landfill degradation processes.

8.2 Initiation of landfill gas generation may be accelerated by:

- initial addition of moisture, as sewage sludge or sewage effluent;
- use of a pre-composted waste layer;
- leachate recirculation or inoculation with methanogenic leachate;
- incorporation of a significant proportion of non-hazardous waste that is less bioreactive than MSW.

8.3 Using these techniques, significant rates of LFG generation should be achievable within less than 1-2 years of waste placement, possibly within just a few months.

8.4 Rates of LFG production on the order of $20m^3/t.a$, i.e. approximately double the highest rates typically recorded for conventional landfills, have been achieved by simple techniques such as high-rate (retention time ~1 year) leachate recirculation and retrospective moisture addition. Air injection has also achieved a similar enhancement but the reason for its effect is not known it may therefore not be relied upon.

8.5 No large-scale test cell in the UK or Europe has yet achieved the peak levels of gas generation that have been reported for some laboratory-scale trials. The implication is that optimisation of all relevant factors has still not been achieved.

8.6 At the Mountainview test cells in California, analysis of solid waste residues after 4.5 years suggested that gas generation rates on the order of $50\text{-}65m^3/t.a$ may have been achieved in a cell with moisture addition and leachate recirculation. The difference between this cell and test cells in Europe may have been the higher temperatures in California.

8.7 Gas generation rates were still increasing in the Brogborough cells, 6 years after waste placement and in some cells 9 years after waste placement. This is contrary to expectations from models, which predict an early peak, followed by exponential decay.

8.8 The Brogborough cells provide an opportunity to generate further valuable data on gas generation profiles and yields by continuing monitoring for as long as possible.

8.9 Methane generation from acetogenic leachate percolating into basal drainage layers can be a high proportion of total gas production.

8.10 High rates of LFG production can also occur in unsaturated wastes that contain acetogenic leachate.

8.11 H_2/CO_2 utilization may be an important route for gas generation, leading to enrichment of the methane content of LFG. Results at Landfill 2000 suggested that up to 10% of the LFG production may have been via this route.

8.12 H_2/CO_2 utilization may be partly determined by temperature and perhaps other factors. It may offer a means whereby conditions could be manipulated to increase the methane content of landfill gas. Further specialized laboratory-scale research would be needed to make progress in this area.

8.13 None of the large-scale test cells has yet generated any data on the ultimate yield of LFG because none has reached the point where gas generation has ceased. Much longer periods of monitoring will be needed at existing test cells if any of them are to produce yield or time-scale data.

8.14 Total yields and eventual timescales for gas generation remain almost completely unmeasured at real landfills or large-scale test cells.

8.15 None of the existing large-scale test cells, either in the UK or abroad, has investigated accelerated contaminant flushing. To date, this aspect has only been investigated in bench or pilot-scale studies. Large-scale test cells have been set up exclusively to examine enhancement of degradation processes.

8.16 It is clear from all of the large-scale test cells that they must be regarded as long-term projects. It would be virtually impossible to achieve the type of objectives that have been set for most of them within the 2 to 3 year duration of conventional research contracts.

9. RECOMMENDATIONS

9.1 The Brogborough Test Cells

The Brogborough cells now provide a well-engineered, well documented test facility in which landfill management techniques can be investigated at a scale large enough to allow the direct transfer of results to full-scale landfills. Their use should be continued as long as possible. Some cells should be continued to pursue the objectives that led to their original construction and determine the profiles and timescales for gas generation. At least one cell should be used to demonstrate the flushing bioreactor concept by incorporating a leachate recirculation and nitrification facility.

Another cell should be used to investigate the extent to which elevated temperatures (up to 50°C) could enhance waste stabilization rates.

Routine monitoring of all cells should continue and should be improved and expanded to include:

- surveying of all wells every 6 months;
- leachate levels in all accessible wells every month;
- quarterly monitoring of pumped leachate samples;
- temperature measurement of pumped leachate and extracted gas (at the well-head);
- use of the DNA probe to measure methanogenic activity.

9.2 Other Work

Gas extraction data from large-scale long-established UK LFG utilization schemes, such as Aveley I, should be collated and reviewed to help the development of more realistic gas generation models. Similar data from other countries should also be sought.

Studies should be undertaken into the manipulation of the biochemical pathways of waste degradation, particularly into the stimulation of hydrogen production to increase the CH_4:CO_2 ratio in landfill gas.

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Table 1. Chronology: Management of Brogborough Test Cells

1986	Contract starts
8/86-1/88	Cell construction
3/87-1/88	Initial filling, to 10m
by 1/88	Capping completed
7/88	Cap removed
7/88-10/88	Phase 2 infilling to ~20m
18/11/88-21/12/88	Wells A + B, Mk I drilled
3/89-5/89	Cells re-capped
2/90	Cap cracking and leaking gas in places
5/90	Further deterioration in cap integrity noted
6/90	Gas extraction and flaring commissioned
3/91	Some leachate pumping from Cell 5.
10/91	Cap re-worked and re-seeded
27-28/4/92	First air injection, Cell 4 (563m^3 air (???520m^3)) via B well at 130m^3/h
2/7/92	First water addition, Cell 3 (98.5m^3) via top herringbone at 6.2m^3/h
2/93	Aborted 2nd. air injection, Cell 4 (244m^3 injected)
20-23/4/93	Leachate addition, Cell 3 (21m^3)
2-6/8/93	Second air injection, Cell 4 (11,101m^3)
21-25/2/94	Water addition to Cell 3 (231m^3 via top herringbone system)

Table 2. Chronology: Monitoring of Brogborough Test Cells

?/87	Bailed leachate sampling begins
12/88-1/89	Gas probes at "5, 10 & 15m" installed
12/88	Gas quality monitoring begins
18/11/88-21/12/88	Wells A + B, Mk I drilled (pre-capping)
5/89	Cells capped
6/89	1st. Gas flow meters installed
7/8/89-14/9/89	Wells A + B Mk II drilled (through cap) 125mm dia.
9/89	Gas probes replaced
12/9/89	First leachate level data (~1yr since filling, 4 months since capping)
1/91	New wells A + B drilled in Cell 5 (Mk III) 210mm dia.
8/91	Wells C installed (300mm dia., 6mm slots no screen)
22/8/91	First leachate level data, wells C
9/91	Turbine-type gas flowmeters installed
5/92	Semi-pumped leachate samples. Waterras installed May '92
10/92-1/93	Data logger and Servomec gas analyser installed
1/93	Venturi meter, Cell 2
9/93	Venturi meter, Cell 1
10/93	Venturi meter, Cells 3-6
11/93	Hourly gas flow recording initiated
1/94	Pumped leachate sampling begins

Table 3. Choice of variables examined in the Brogborough test cells

SELECTED	**Cell**
control	1 (2,3,4)
density	2
mix with inerts/buffer materials	6
moisture addition during infilling	5
retrospective air injection	4
retrospective water addition	3
NOT SELECTED	
pre-composting layer	
shredded waste	
seeding with methanogens	
pH control	possible
temperature	possible
leachate recirculation	possible

Table 4. Strengths and weaknesses in the construction and management of the Brogborough test cells

STRENGTHS

20 METRE WASTE DEPTH

3 YEAR DELAY IN START OF AIR AND WATER ADDITIONS

APPARENT INTERNAL HYDRAULIC CONTINUITY

- results of water injection in Cell 3
- level rise similar at middle and ends of cell
- leachate recirculation may be effective

HYDRAULIC SEPARATION OF INDIVIDUAL CELLS

- head differences between cells
- rates of rise only as expected for moderate cap
- no obvious gas escapes from cracks between cell boundaries

PROBLEM AREAS

ABSENCE OF LEACHATE COLLECTION/ABSTRACTION LAYER

UNCERTAINTY OF GAS COLLECTION EFFICIENCY

- dependence on weekly adjustment of valve settings
- importance of well characteristics?
- effects of differential settlement and distortion of pipelines

POSSIBLE DETERIORATION OF CAP

- risk of excessive rise in leachate levels

Table 5. Critical aspects of the monitoring of the Brogborough test cells

GAS

- gas flow measurement crucial, but subject to considerable uncertainty
- many changes in methods used, but same on each cell
- hourly readings only since late 1993
- volumes not temperature corrected?
- results internally consistent within cells, so valid for comparisons

LEACHATE

LEVELS

- dipped frequently but never related to O.D.
- gaps in usable data
- conflicting implied cell base levels in various reports

QUALITY

- representative pumped samples only since early 1994
- uncertainty regarding quality stratification within saturated zone

TEMPERATURE

- only static probes monitored
- neither pumped leachate nor extracted gas are monitored
- uncertain accuracy: all rise simultaneously late 93/early 94

SETTLEMENT

- good data

REFUSE

- no analyses of waste at start of study
- samples at 6 and 18m following completion of infilling
- may be possible to assess loss of organic matter

Table 6. Leachate quality in pumped samples from the Brogborough test cells

date	pH	cond	Temp	Cl	Alk	NH3-N	COD	TOC	BOD	SO4
CELL 1										
25/01/94	6.2	33.2	22.3	3210	16300	2610	91400	30200	68600	1790
08/02/94	6	31.9	23	3170	17100	2600	112728	29900	83700	1890
08/03/94	5.9	17.6	24	3340	17500	2810	91900	30600	71900	1950
06/04/94	6.1	15.5	28	3230	16900	2510	104900	32300	70500	1840
04/05/94	6	34.6	21.5	3200	17600	2900	96000	33100	72300	1710
04/10/94										
01/03/95	7.3	15.3	21.2	1920	9500	1650	11000	3400	6540	141
06/07/95	7.5		31.2	2580	9810	2140	12000	4000	6940	136
08/11/95	7.7		30.5	2760	11200	2420	8630	2620	4200	70
29/02/96	7.6	20	27.5	2810	12600	2560	12800	4510	7670	170
mean:	**6.7**	**24.0**	**25.5**	**2913**	**14279**	**2467**	**60151**	**18959**	**43594**	**1077**
CELL 2										
25/01/94	7.4	17.3	23.4	2170	10200	1270	12000	4170	8720	230
08/02/94	7.2	21.4	24.4	2540	7840	1580	14500	4610	8530	170
08/03/94	7.1	18.3	27.3	3150	8390	1570	12900	4340	8630	220
06/04/94	7.5	16.4	27	2870	9190	1620	13300	4390	8890	230
04/05/94	7.3	26.6	25	2910	9680	1770	14300	4930	9530	230
04/10/94	7.4	18.4	19.5	2800	5650	1760	17100	5330	10200	280
01/03/95	7.3	14.4	21.4	2250	10400	1470	5800	1900	2730	42
06/07/95	7.4	15.9	29.4	2560	9000	1740	7480	2260	3660	97
08/11/95	7.5	19	27.3	2800	9160	1940	9260	3090	5200	114
29/02/96	7.4	20	24.1	2220	7600	1410	4200	1590	1870	26
mean:	**7.4**	**18.8**	**24.9**	**2627**	**8711**	**1613**	**11084**	**3661**	**6796**	**164**
CELL 3										
25/01/94	7.1	16.5	22.6	1530	7970	1190	23900	8240	18500	460
08/02/94	7	15.8	24	1660	8680	1650	20100	6510	12600	320
08/03/94	6.2	9.5	14.3	900	5210	630	18900	6500	14500	770
06/04/94	7.2	8.1	19	1020	5960	785	7490	2870	6380	65
04/05/94	7.1	12.7	22	1020	6090	849	7410	1710	4100	68
04/10/94	7.5	14	22.2	1355	6760	1130	3030	980	910	40
01/03/95	7	7.3	16.7	850	6100	700	1940	567	398	30
06/07/95	7.6		33.1	2000	9800	1740	3130	972	360	10
08/11/95	7.6	17	29.4	1980	8710	1680	3160	984	222	10
29/02/96	7.5	20	31.1	1925	7910	1440	2900	872	137	10
mean:	**7.2**	**13.4**	**23.4**	**1424**	**7319**	**1179**	**9196**	**3021**	**5811**	**178**
CELL 4										
25/01/94	7.8	23.8	24.3	2780	10200	1820	9410	2620	4860	180
08/02/94	7.7	26.5	24.4	2920	11400	2330	6930	2370	3210	105
08/03/94	7.4	23.6	25.1	2910	11100	1830	7630	1930	3360	66
06/04/94	7.8	20.9	29	2940	11500	2010	5270	1410	1850	10
04/05/94	7.9		30.1	3060	13600	2040	4480	1390	1740	10
04/10/94	7.8	20	27.4	2994	13700	2330	4700	1310	1330	12
01/03/95	7.5	17.2	25.3	2550	8825	1300	3000	830	525	21
06/07/95	7.8		33.1	2670	9560	1540	2480	734	268	10
08/11/95	7.6	19	33.6	2710	8520	1480	2750	739	158	10
29/02/96	7.4	20	34.9	2540	8690	1320	2530	735	188	10
mean:	**7.7**	**21.4**	**28.7**	**2807**	**10710**	**1800**	**4918**	**1407**	**1749**	**43**
CELL 5										
25/01/94	7.8	25.4	26.6	2570	13000	2060	4360	1230	373	<5
08/02/94	7.8	26.4	30.7	2630	11800	2440	4220	1260	233	<5
08/03/94	7.3		31.5	2420	11800	2040	3720	1090	317	<10
06/04/94	7.8	19.9	36	2750	11500	1980	3670	1200	376	<10
04/05/94	7.5	27.2	35.9	2680	11500	2180	4240	1230	271	<10
04/10/94	7.9	20	29.6	2550	10650	2110	4780	1285	256	<10
01/03/95	7.5	15.6	21.5	1600	8400	1270	2400	720	222	<10
06/07/95	7.6		30.2	2330	10200	1960	3450	1090	1960	<10
08/11/95	7.8	19	33.2	2280	9450	2050	3800	985	330	<10
29/02/96	7.6	20	38.8	2370	10000	1930	3510	1210	260	<10
mean:	**7.7**	**21.7**	**31.4**	**2418**	**10830**	**2002**	**3815**	**1128**	**460**	**0**
CELL 6										
25/01/94	7.6	14.6	25.3	1680	8060	1040	2300	747	202	5.5
08/02/94	7.3	14.7	29.1	1700	8930	940	2430	837	167	36
08/03/94	7.2	12.8	30.5	1600	6150	1010	2390	710	136	125
06/04/94	7.5	9.3	29.2	1540	6390	1010	1950	622	93	10
04/05/94	7.3	15.1	29.9	1640	6550	1030	2420	772	167	10
04/10/94	7.5	15.3	25	1620	6330	1040	2720	752	110	10
01/03/95	7.3	13.6	27.6	1310	6780	1025	2430	756	168	10
06/07/95	7.4		33.7	1840	7380	1330	2830	918	154	10
08/11/95	7.6	11	28.2	1880	6960	1380	3480	1170	140	13
29/02/96	7.4	18	32.4	1680	6220	2470	2790	836	148	140
mean:	**7.4**	**13.8**	**29.1**	**1649**	**6975**	**1228**	**2574**	**812**	**149**	**37**

[concentrations in mg/l; conductivity in mS/cm; temperature in Celsius]

Table 7. KEY RESULTS FROM THE BROGBOROUGH TEST CELLS

1. Cells behave individually, wide range within replicates.

2. None of the initial treatments led to unusually high rates of decomposition.

3. Two initial treatments led to early establishment of methanogenesis.

4. Retrospective addition of air or water has led to unusually high rates up to $22m^3/t.a.$

5. All cells, including controls were still getting faster, 6 years after infilling finished.

6. Some cells are still getting faster, 8-9 years after infilling finished.

7. A high proportion of the initial gas potential remains within all the cells.

8. Cells 1 and 2 were producing $\sim 10m^3/t.a$ even while their leachates were still fully acetogenic.

9. Temperature, as recorded, has not been a good indicator of activity.

10. The methane concentration increased gradually over 5+ years in all cells.

11. The study will not provide information about gas yields within next two years but can provide additional extremely valuable information about achievable production rates.

Table 8. Chronological highlights in the construction and operation of the Landfill 2000 test cells

3/91	Cell base construction competed.
4/91	HDPE liners laid in both cells
17/4/91 - 25/4/91	Cell 1 filled
29/4/91 - 2/5/91	Cell 2 filled
19/3/92 - 22/5/92	119m^3 sewage effluent added to Cell 1
19/3/92	Recirculation begun in Cell 1
24/6/93 - 20/7/93	107m^3 leachate removed from Cell 2
20/7/93 - 3/8/93	37m^3 sewage effluent added to top of Cell 2
20/7/93 - 22/7/93	65m^3 leachate removed from Cell 1 17m^3 sewage effluent added to base of Cell 1
3/95	Project terminated

Table 9. Chronological highlights in the monitoring of the Landfill 2000 test cells

4/91 - 5/91	Four gas/temperature probes installed in each cell.
6/91	Gas composition and temperature logging begin in probes and vent gas from both cells.
19/3/92	Existing leachate in Cell 1 sampled prior to addition of sewage effluent.
	Monthly leachate monitoring in Cell 1 begins.
24/11/92 - 19/5/93	3 - 4 hot wire anemometer gas flow readings per cell using Solomat HWA.
1/93	Monthly HWA readings begin in Cell 2.
6/93	Leachate monitoring in Cell 2 begins.
10/93	Continuous gas flow monitoring in Cell 2 begins.
2/94	Lithium tracer study begun in Cell 1. Interstitial liquid from Cell 1 gas probes analysed.
12/94	Continuous gas flow monitoring in Cell 1 begins.
2/95	Refuse samples excavated from both cells for analysis, including interstitial leachate analysis.
3/95	Project terminated.

Table 10. Strengths and weaknesses in the monitoring of the Landfill 2000 test cells

Strengths

Comprehensive temperature logging
Comprehensive gas quality monitoring
Development of 'time of transit' gas flow meter
Some leachate monitoring within the waste mass

Weaknesses

Little gas flow monitoring until late in the study
No settlement monitoring
No leachate monitoring until two years after waste placement
Failure of gas pressure monitors

Table 11. Leachate quality in samples from flooded gas probes at Landfill 2000

	pH		conductivity (μS/cm)		COD (mg/l)
	27.1.94	9.6.94	27.1.94	9.6.94	28.2.94
Cell 1					
probe 1	-	-	-	-	-
probe 2	6.4	6.5	19,400	18,300	49,900
probe 3	5.9	5.9	~28,000	15,700	72,000
probe 4	6.6	6.7	18,800	14,300	36,800
sump	7.2	7.1	9,950	-	-
Cell 2					
probe 5	-	-	-	-	-
probe 6	-	-	-	-	-
probe 7	-	-	-	-	-
probe 8	5.7	5.9	19,300	12,800	-
sump	6.94	-	6,170	-	-

Note: probe locations are shown in Figure 17.

Table 12. Leachate quality in interstitial water centrifuged from waste samples excavated in February 1995 at Landfill 2000

	Cell 1		Cell 2	
	top	bottom	top	bottom
chloride	1,260	1,410	1,130	1,970
NH_3-N	1,140	656	1,460	817
COD	16,700	22,600	27,400	64,900
BOD	10,200	17,700	22,000	42,500
TOC	3,480	7,890	10,200	19,300
SO_4	229	436	800	1,280
Na	748	962	865	1,530
K	539	781	687	1,310
Fe	4.9	163	26	65
BOD/COD ratio	0.61	0.78	0.80	0.65
Na/K ratio	1.39	1.23	1.26	1.17
NH_3-N:Cl ratio	0.90	0.46	1.29	0.41

1. Concentrations in mg/l.
2. 'Top' samples taken from 1.35-1.50m depth.
   'Bottom' samples taken from 1.50-3.00m depth.

Table 13. Summary of input details of Mountain View test cells

Cell	Additions to MSW Content			Total solids in cell (tonnes)	In place density (kg/m^3)
A (recirculation)	buffer	sludge (14% of total)	Water (1906m^3)	8479	628
B	buffer	sludge (11% of total)	-	9093	674
C	buffer	sludge (6% of total)	water (1906m^3)	7711	571
D	buffer	-	water (264m^3)	8989	665
E	-	sludge (5% of total)	water (267m^3)	7844	581
F (control)	-	-	-	8448	626

Table 14. Summary of results from Mountain View test cells

	Cell					
	A	B	C	D	E	F
Measured gas flow						
total: '000m^3	314	275	337	748	238	631
specific: m^3/t solid wastes	37	30	44	83	30	75
rate: m^3/t.a	8.5	6.9	10.0	19.0	6.9	17.1
Average settlement						
m	2.04	2.19	2.32	1.28	2.35	1.86
%	13.4	14.4	15.2	8.4	15.4	12.2
Residual solids analysis (mean of all samples from each cell)						
BMP m^{3}CH$_4$/t dry solids	22	98	-	120	-	92
COD g/kg dry solids	130	220	-	440		268
Volatile Solids% dry solids	32	43		51		44
Cellulose% dry solids	16.3	25.6		32.8		26.6
Lignin % dry solids	13.4	14.0		13.6		14.2
Cellulose:Lignin ratio	1.2	1.8		2.4		1.9

N.B. measured gas flow rates refer to whole (undried) weight

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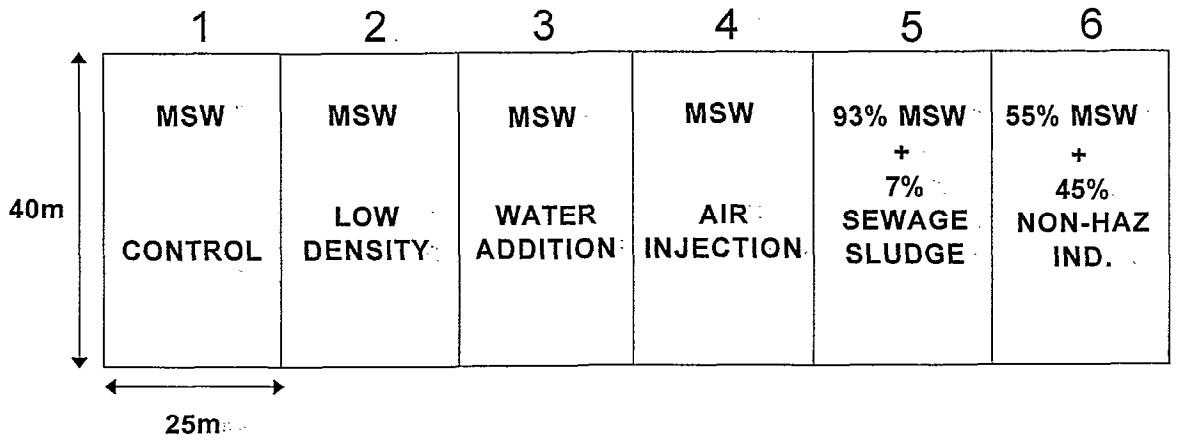
Brogborough Test Cells

Landfill 2000 Test Cells

General



LAYOUT OF BROGBOROUGH TEST CELLS

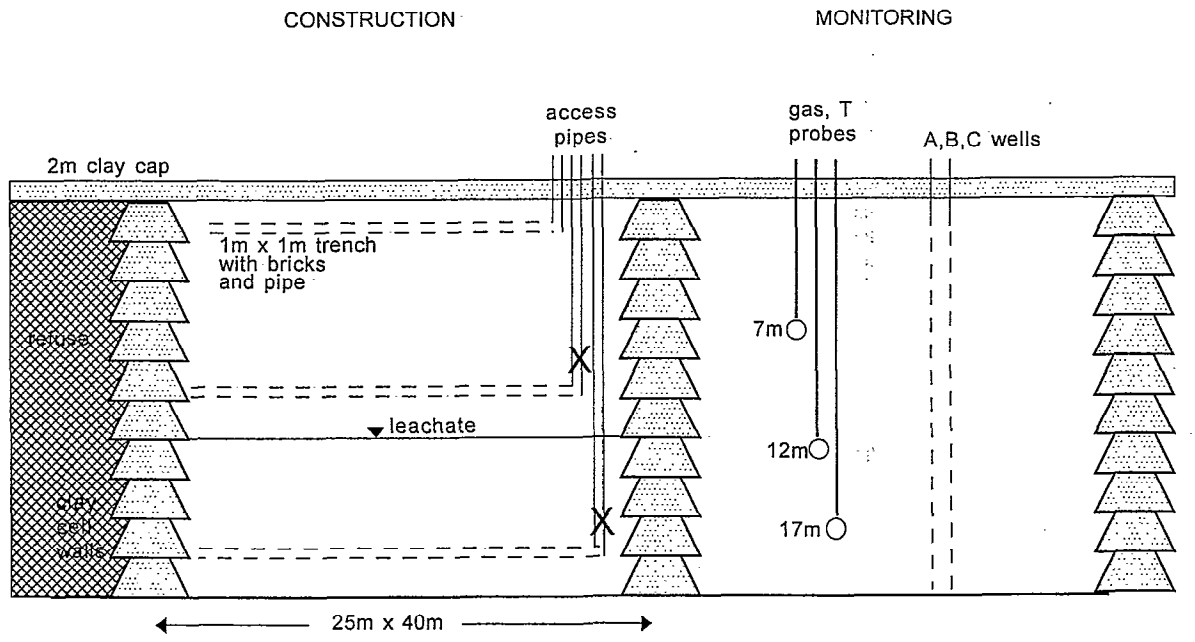
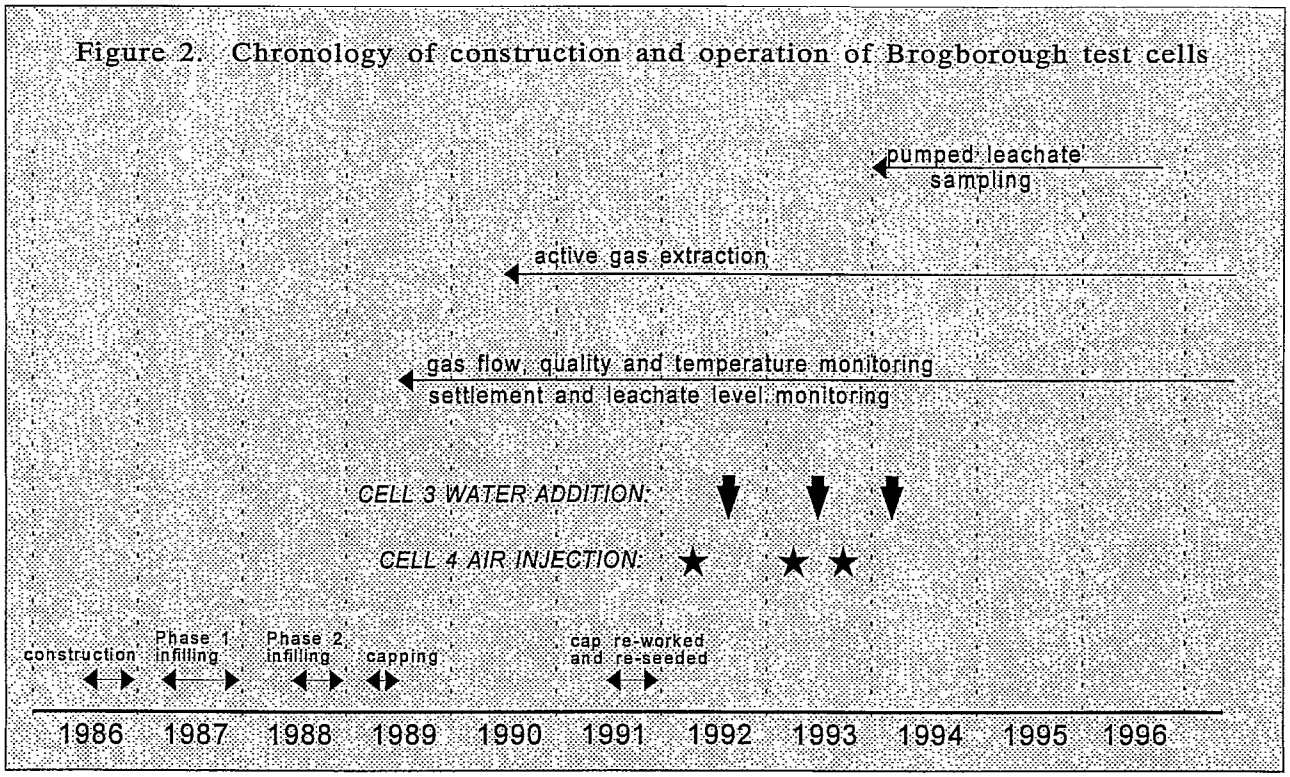


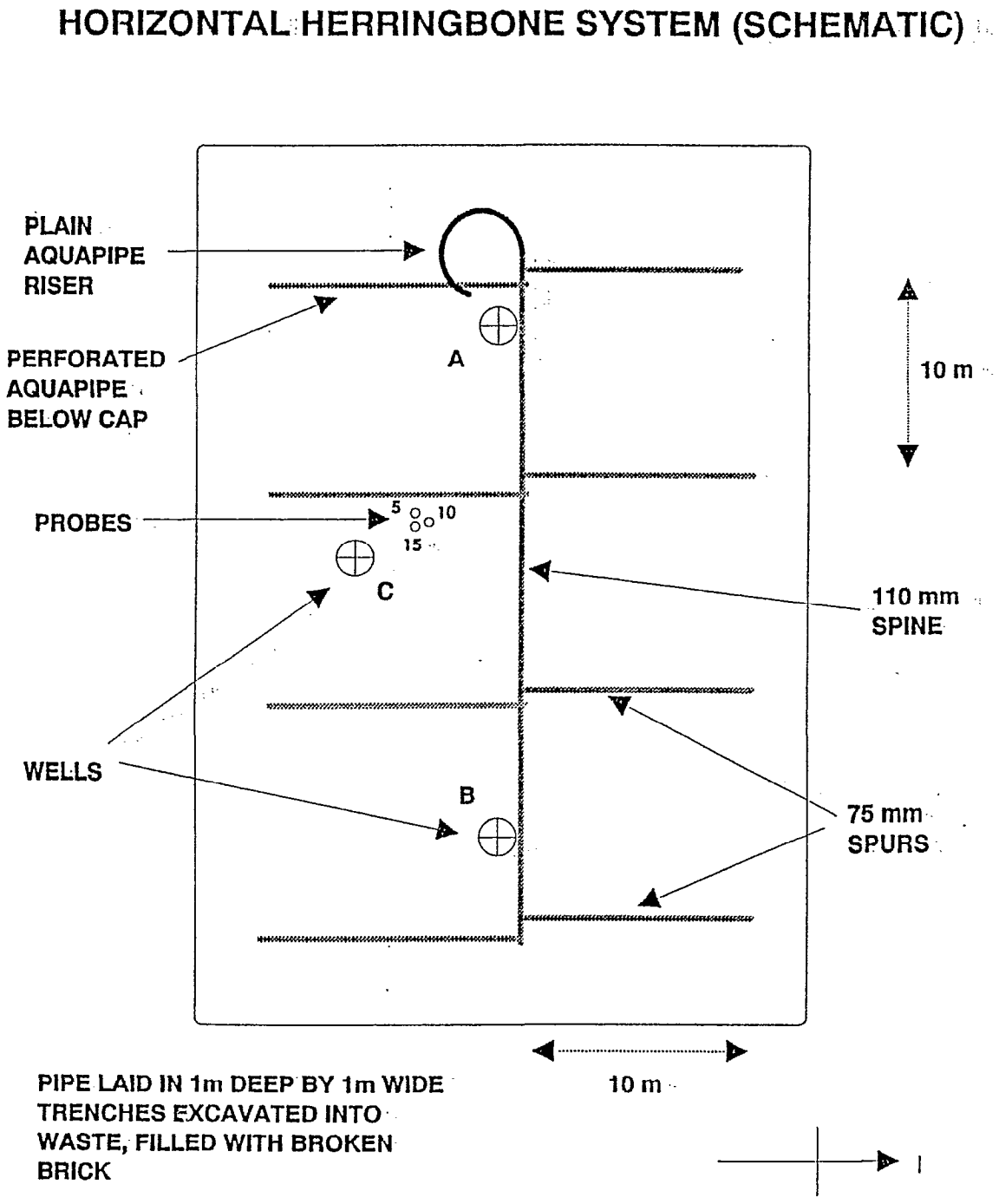
Figure 1. Layout and schematic construction details of Brogborough test cells

Figure 2. Chronology of construction and operation of Brogborough test cells



CELL 1	CRUDE MSW	control
CELL 2	CRUDE MSW	low density
CELL 3	CRUDE MSW	water addition
CELL 4	CRUDE MSW	air injection
CELL 5	CRUDE MSW (93%) AND PRIMARY SEWAGE SLUDGE (7%)	water addition
CELL 6	CRUDE MSW (55%) NON-HAZARDOUS INDUSTRIAL WASTE (45%)	pH buffering

FIGURE 3. TYPICAL LAYOUT OF MONITORING AND EXTRACTION WELLS. GAS/TEMPERATURE PROBES AND HERRINGBONE TRENCH SYSTEM



[From AEA/CS/18311002/Progress Report 2, July 1993]

Figure 4. Brogborough test cells
Dissipation of liquid injection, Cell 3

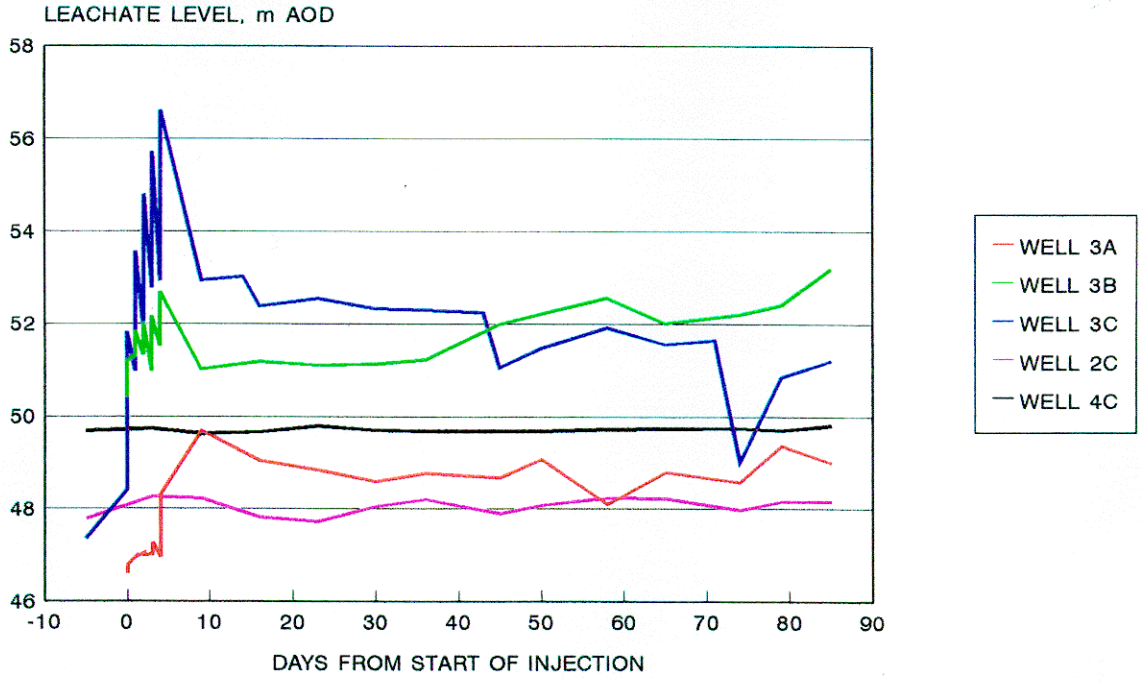


Figure 5. Brogborough test cells
Leachate depths in type B and C wells

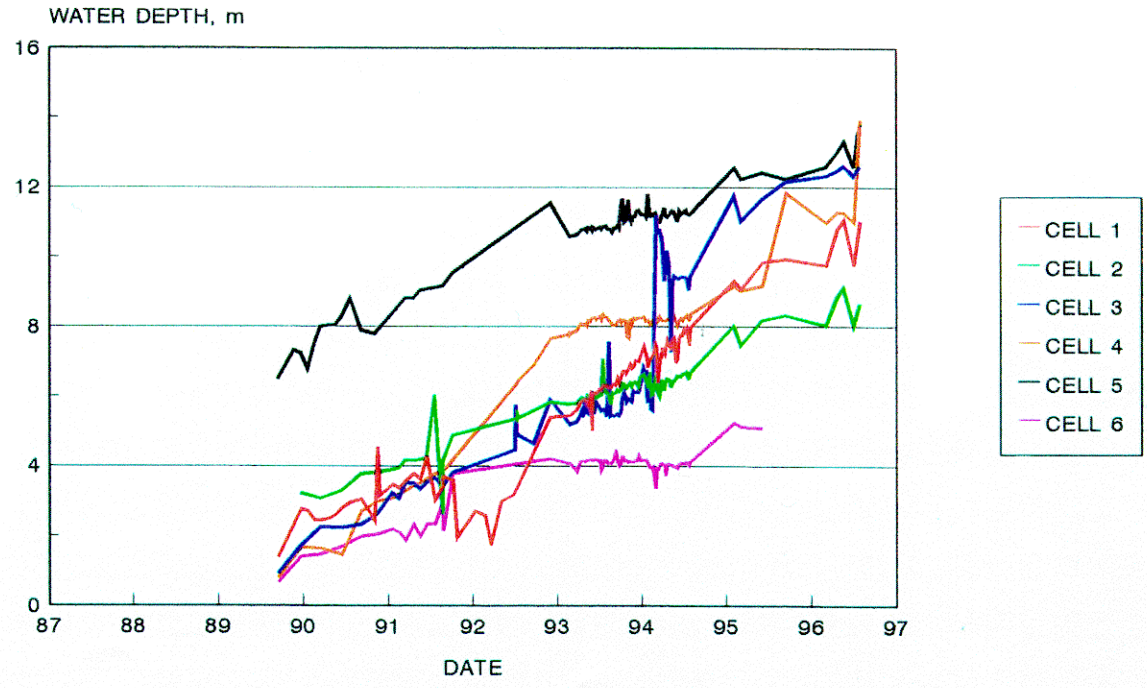


Figure 6. Cumulative gas flow at Brogborough test cells

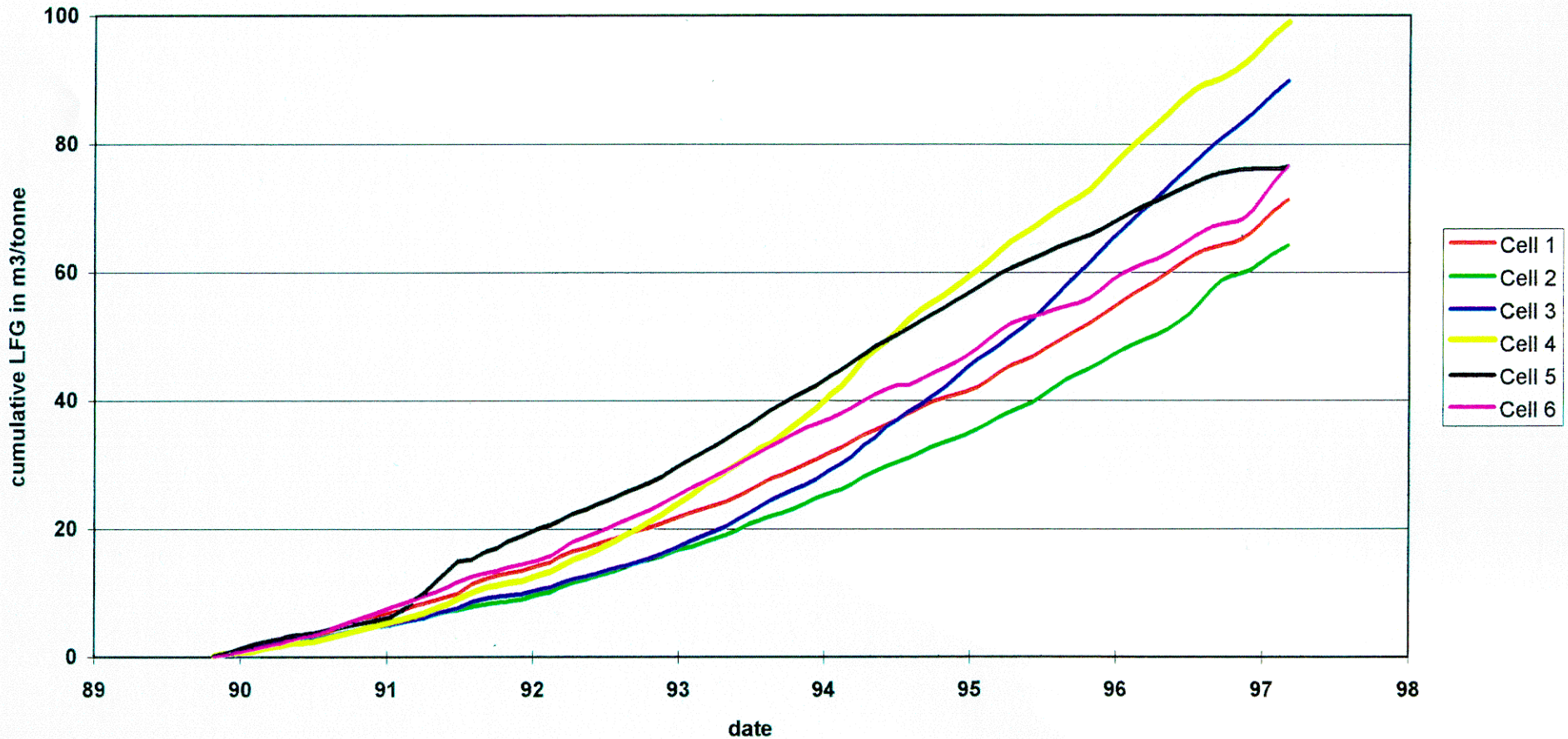


Figure 7. Brogborough Test Cells
Leachate temperature in pumped samples

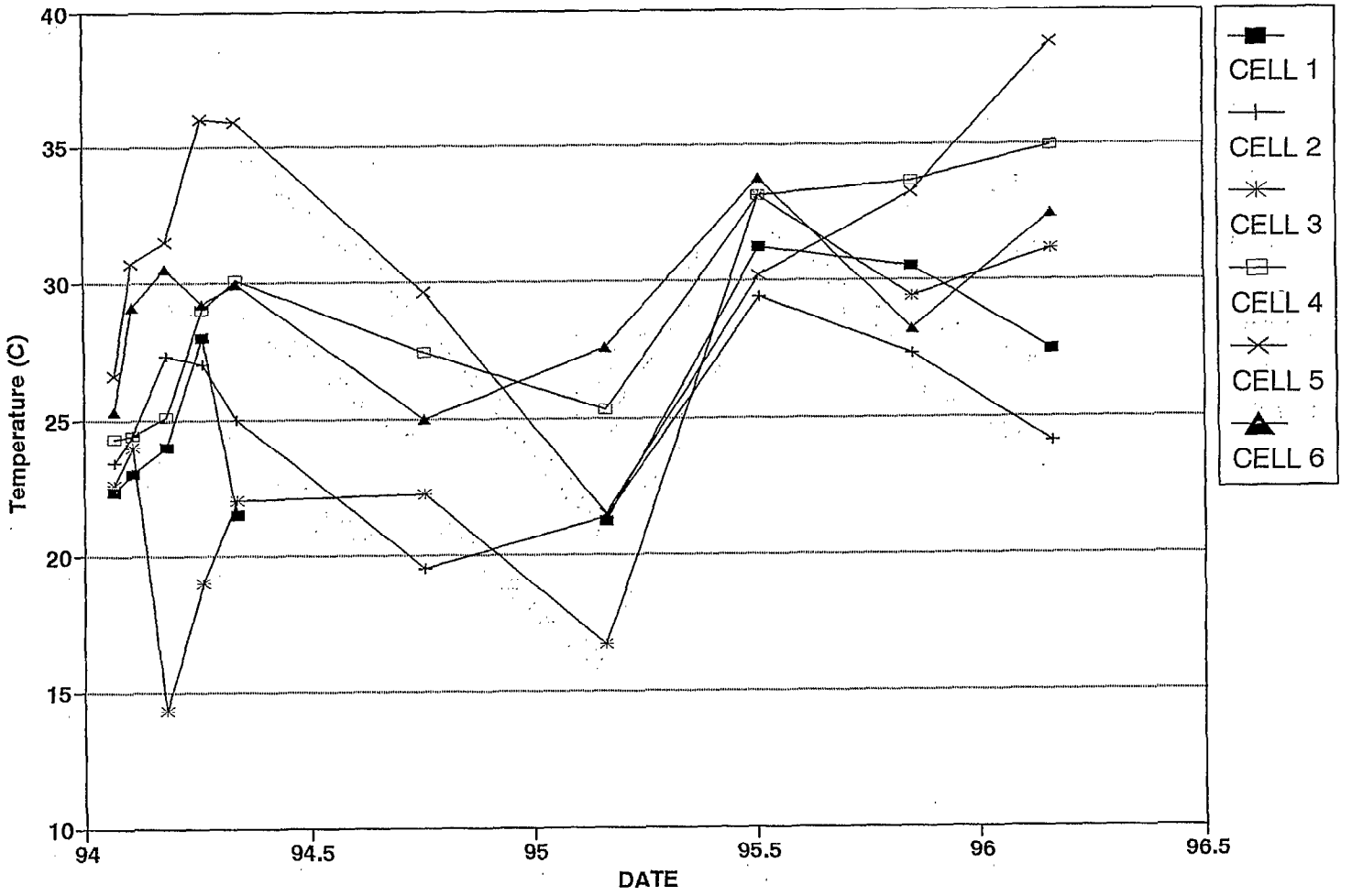


Figure 8. Temperature in 7m probes

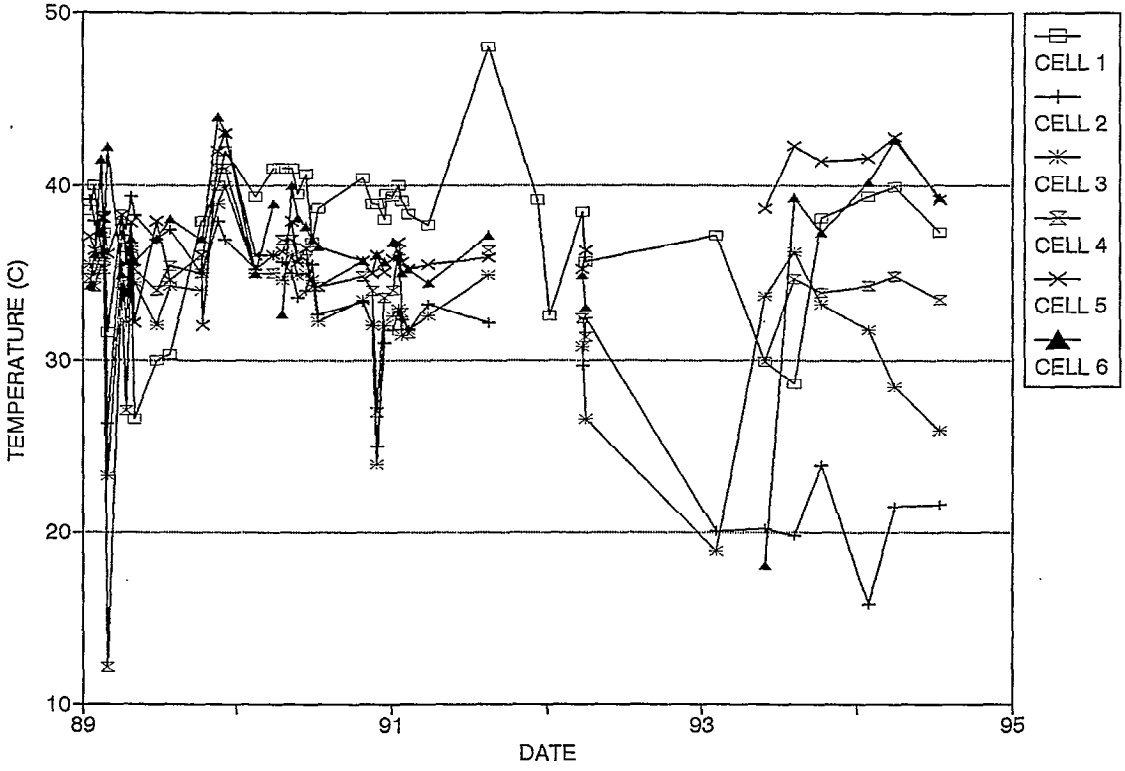


Figure 9. Temperature in 12m probes

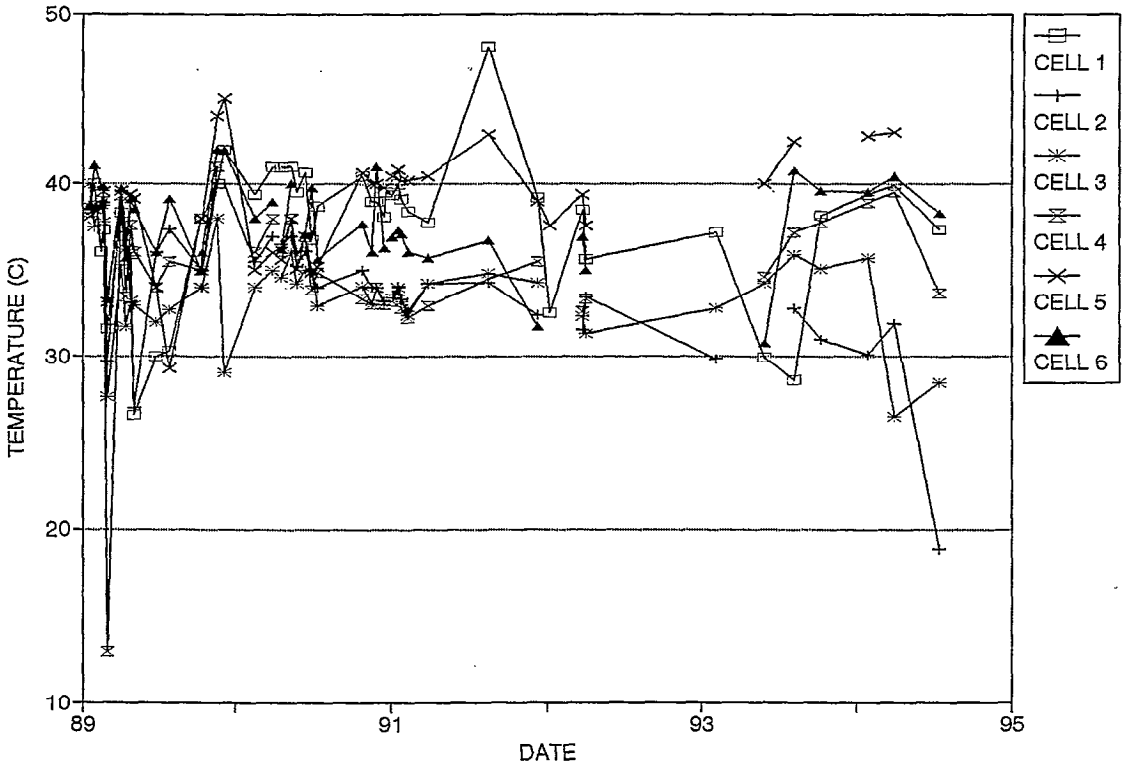


Figure 10. Temperature in 17m probes

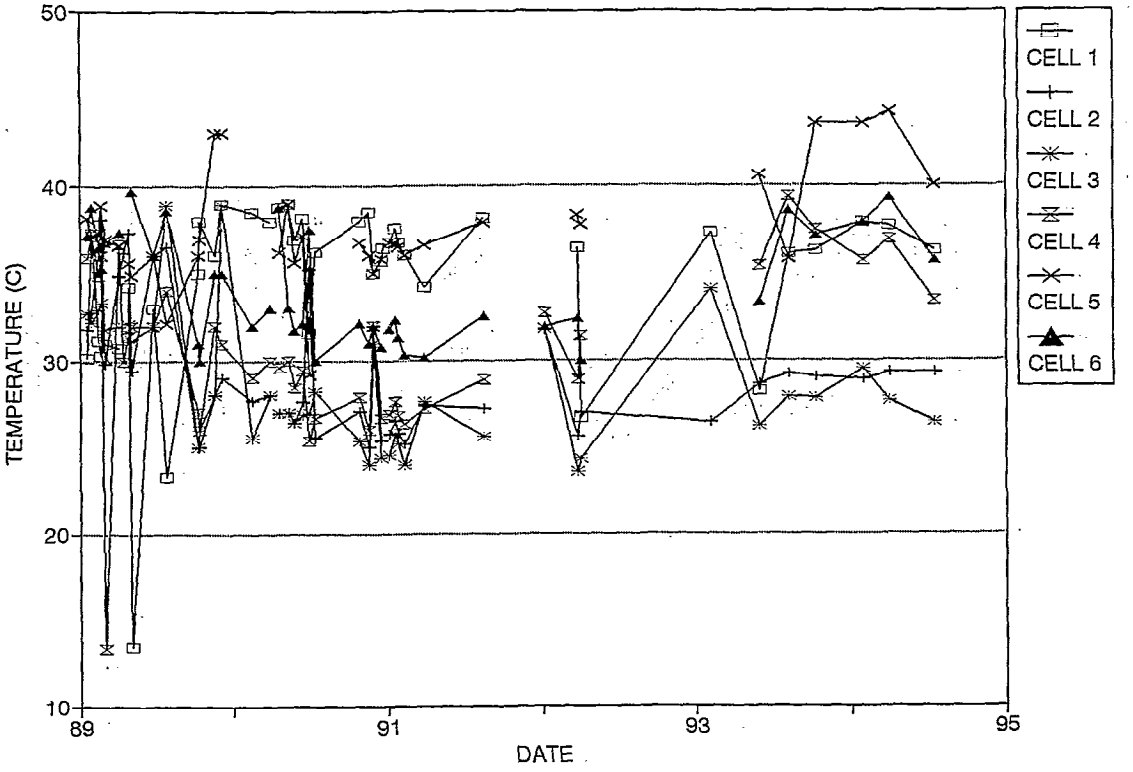


Figure 11. Mean temperature, all probes

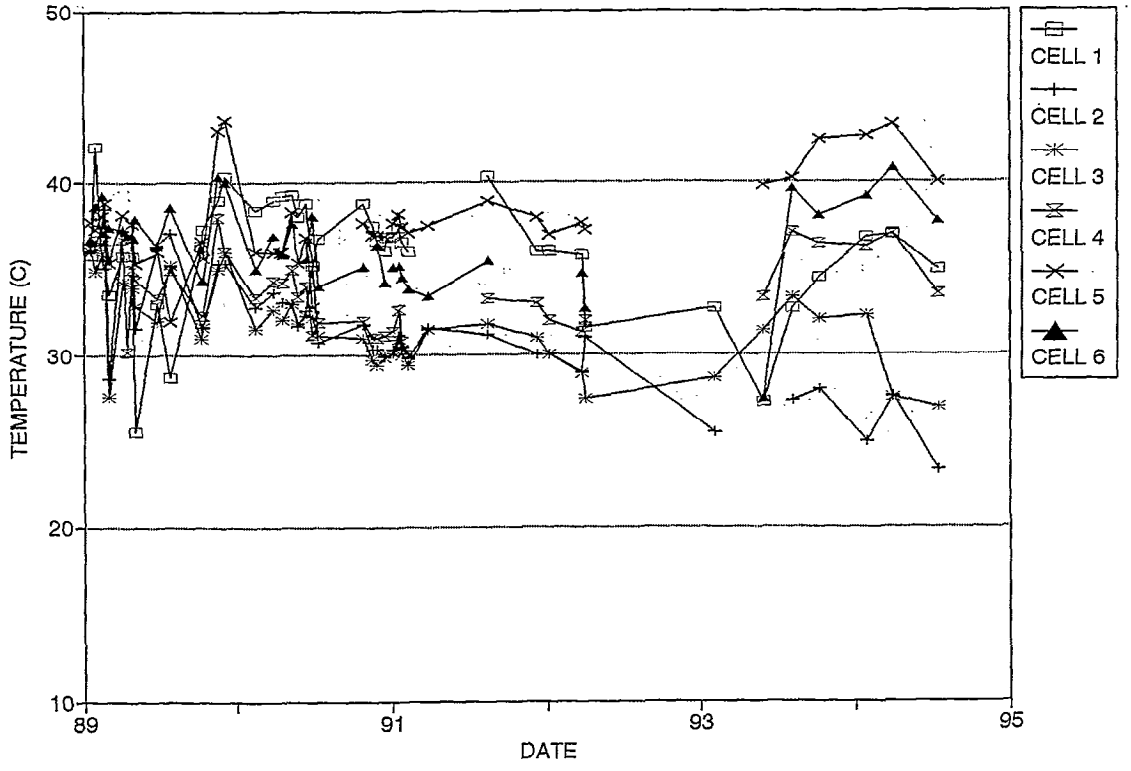


Figure 12. Brogborough test cells
Cumulative settlement since 1989

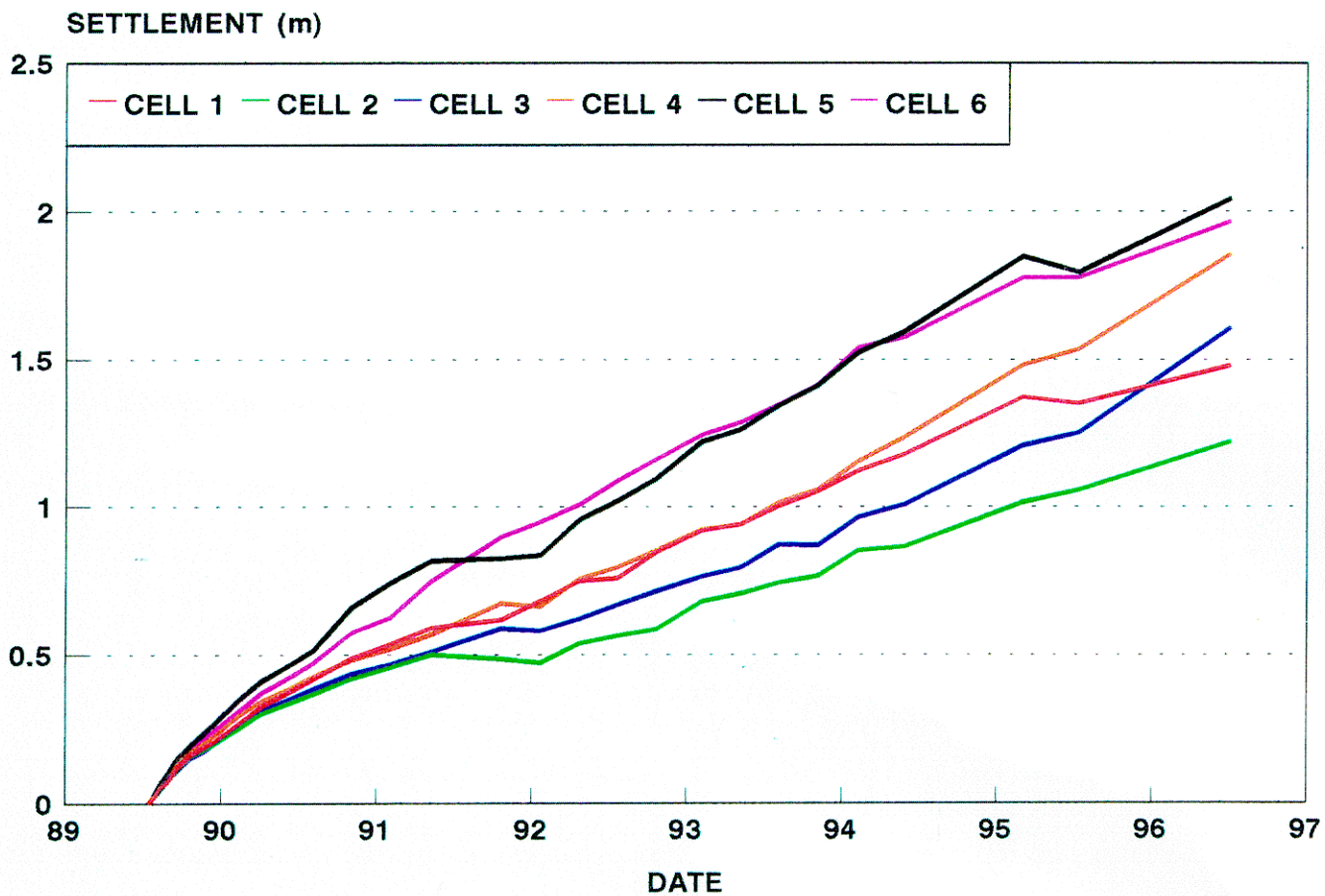


Figure 13. Methane concentration in gas extracted from Brogborough test cells

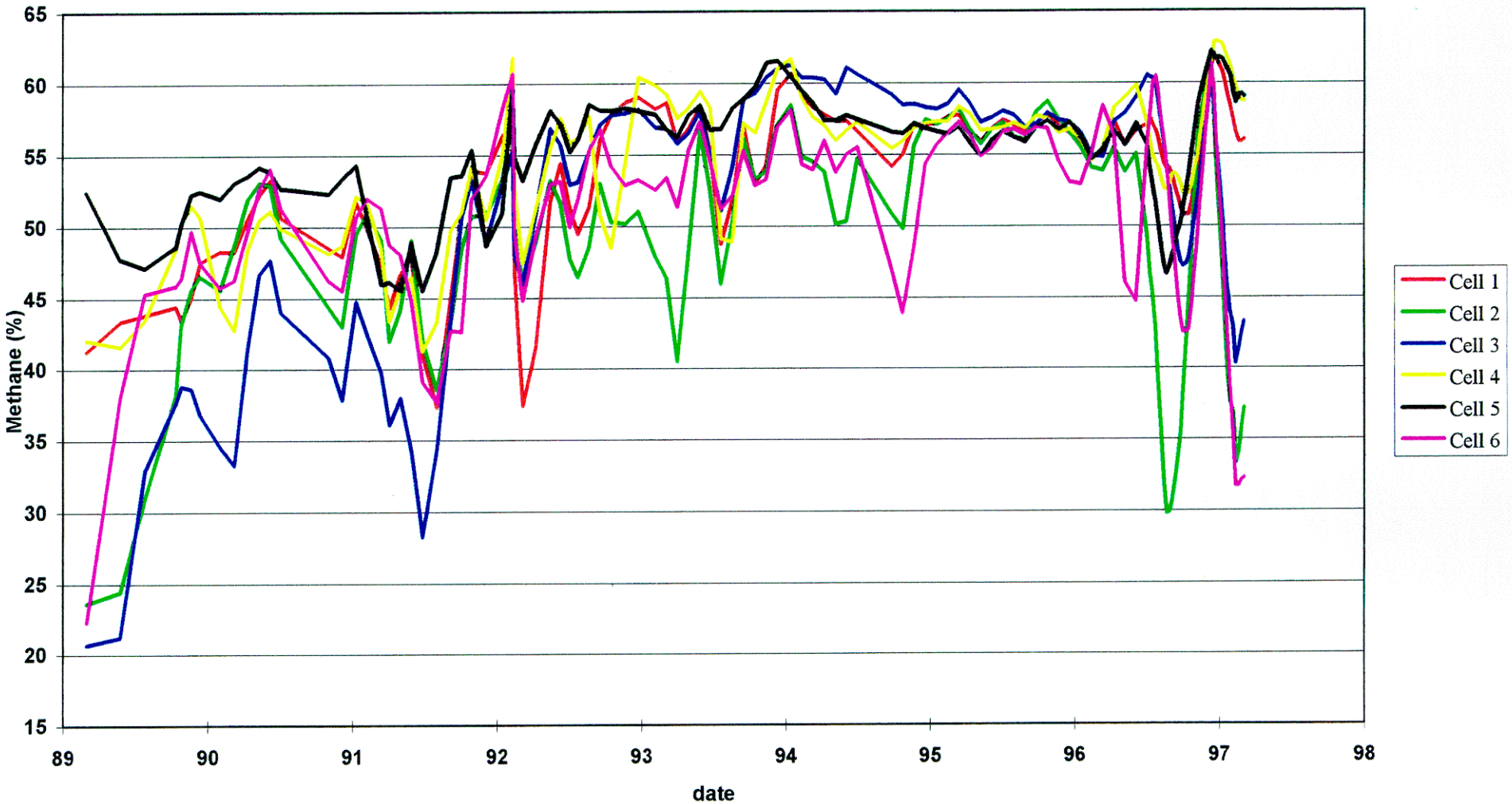


Figure 14. Schematic layout showing gas collection and leachate recirculation pipes (after Blakey *et al.*, 1996)

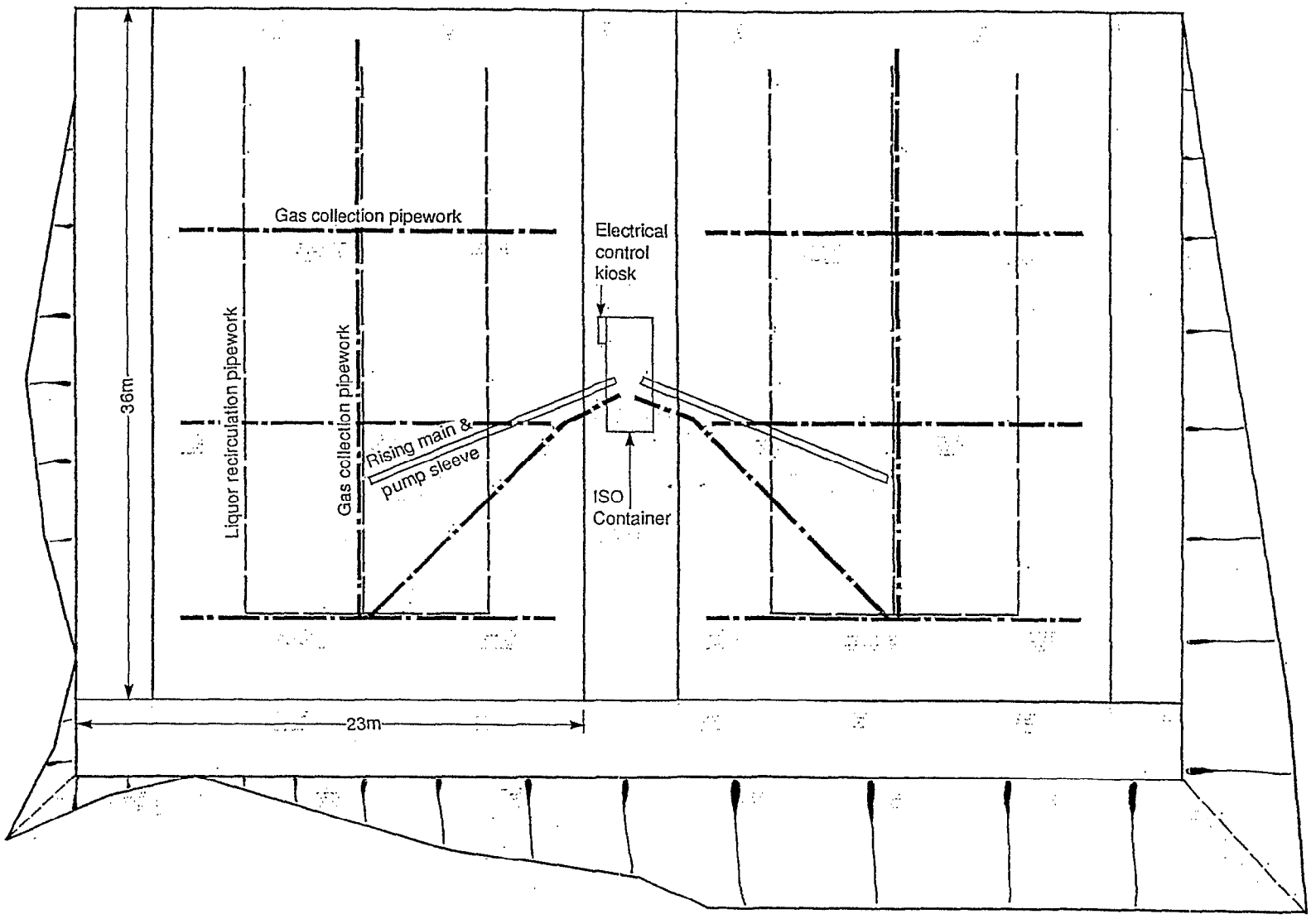


Figure 15. Cross-sections showing construction details (after Blakey *et al.*, 1996)

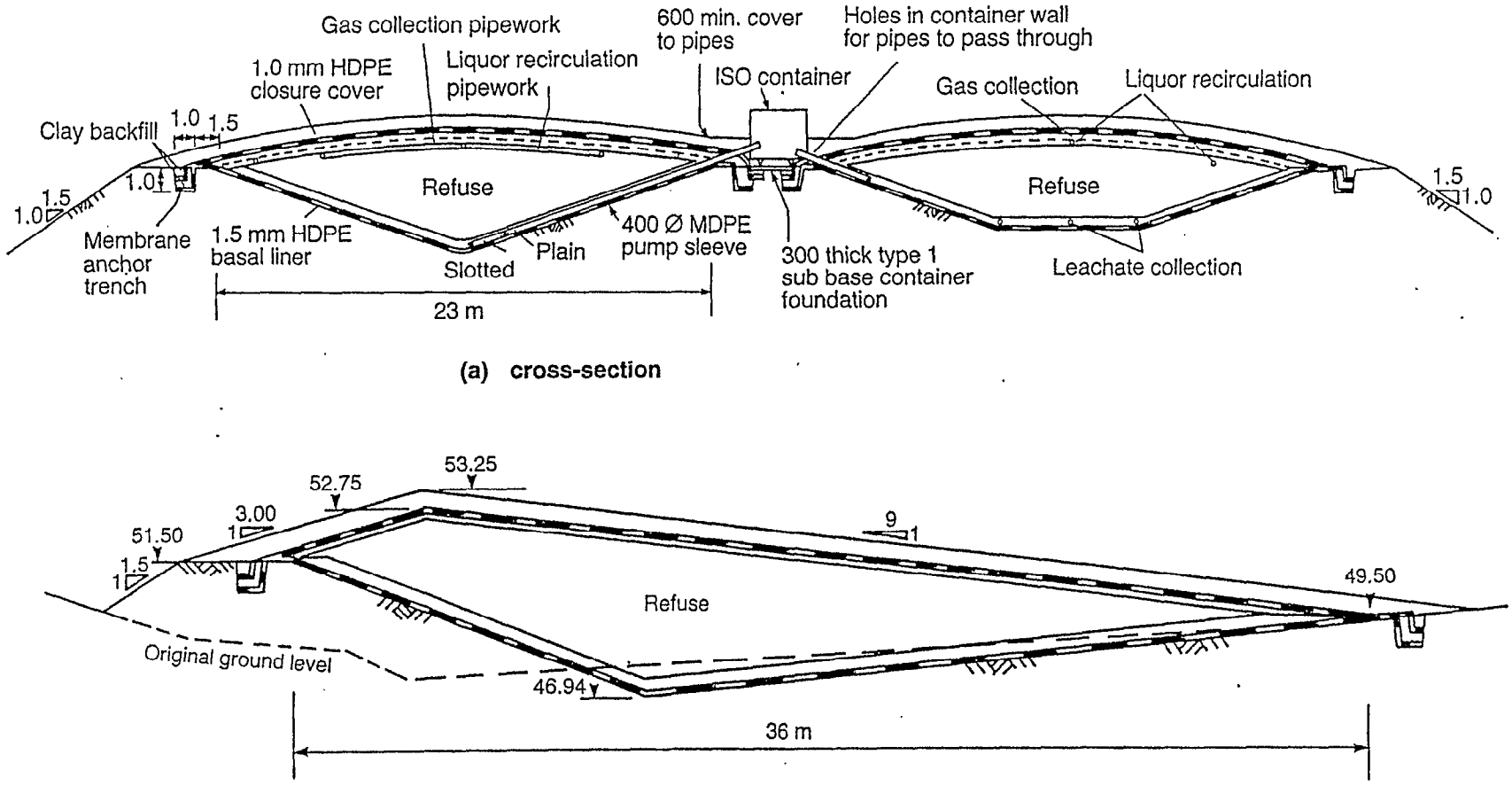


Figure 16. Schematic cross-sections showing closure details (after Blakey *et al.*, 1996)

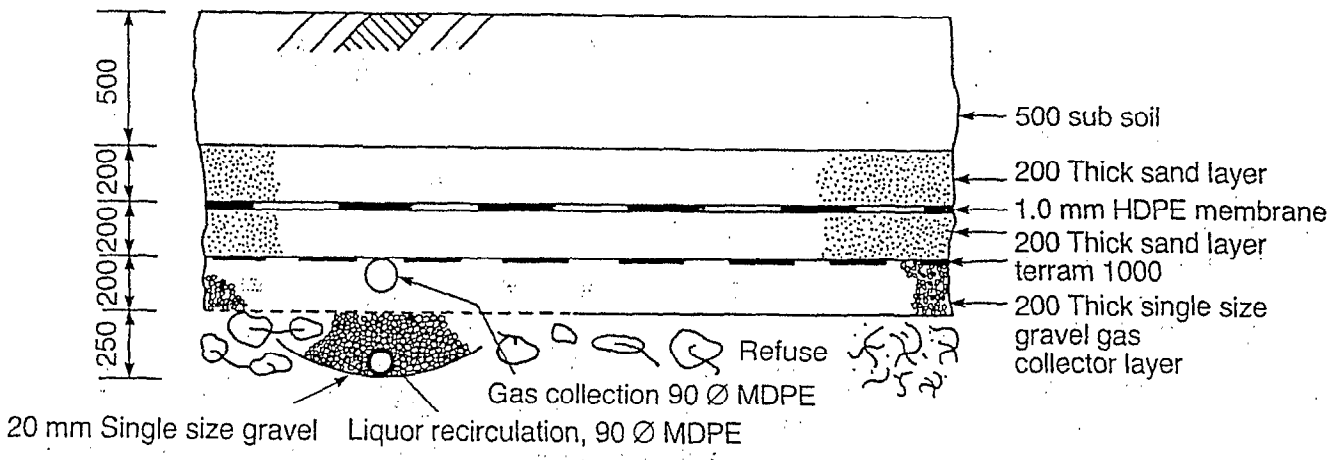
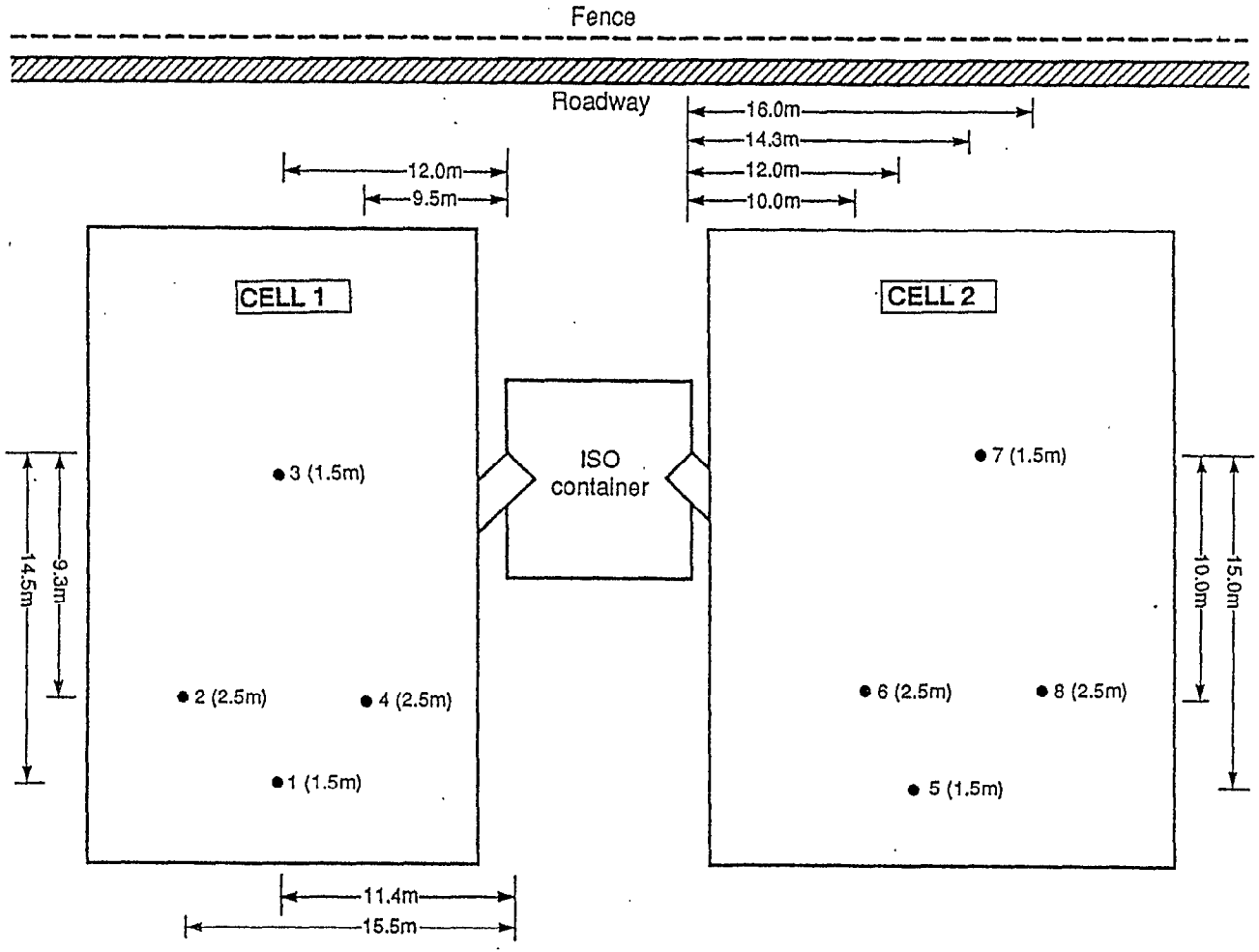


Figure 17. Locations of gas probes in test cells (after Blakey *et al.*, 1996)



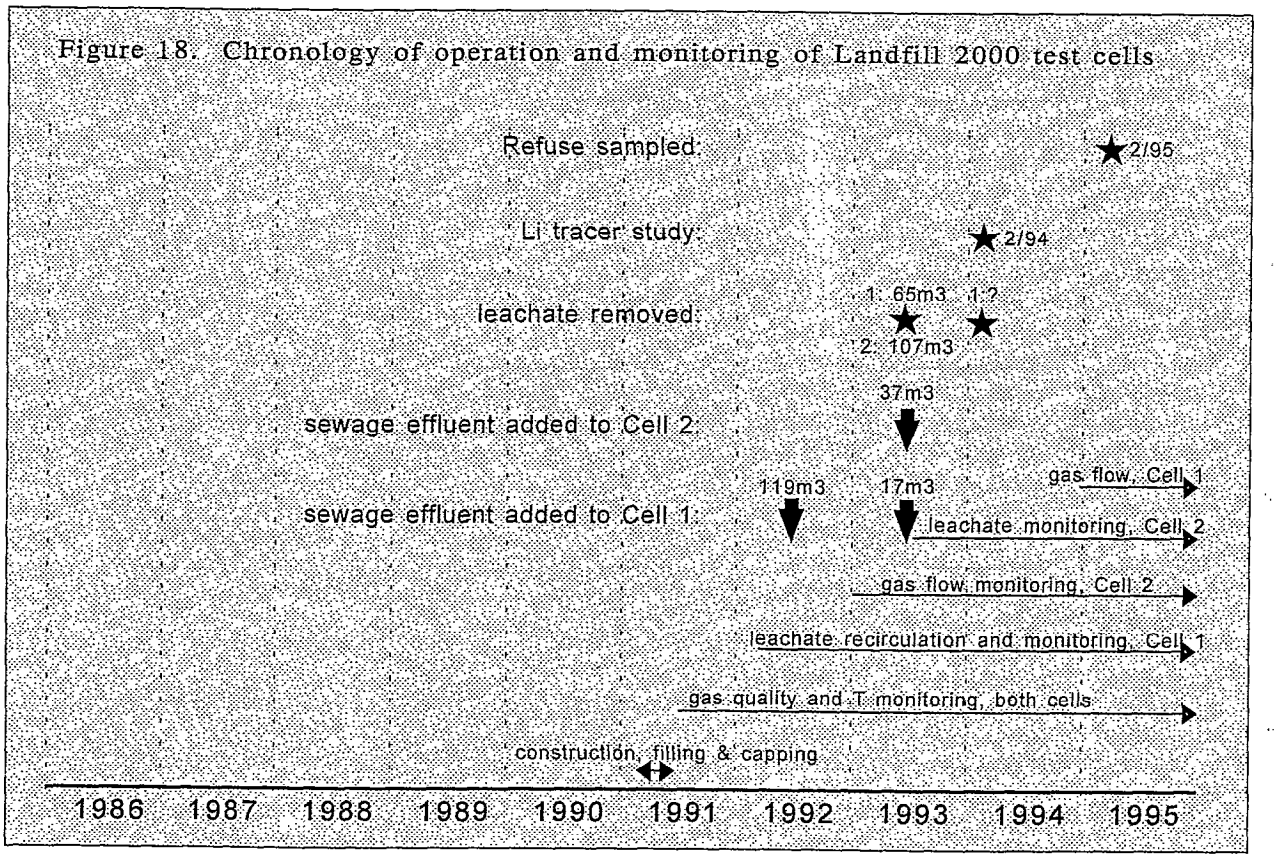


Figure 18. Chronology of operation and monitoring of Landfill 2000 test cells

Figure 19. Temperature variations in the test cells and ambient air (after Blakey *et al.*, 1996)

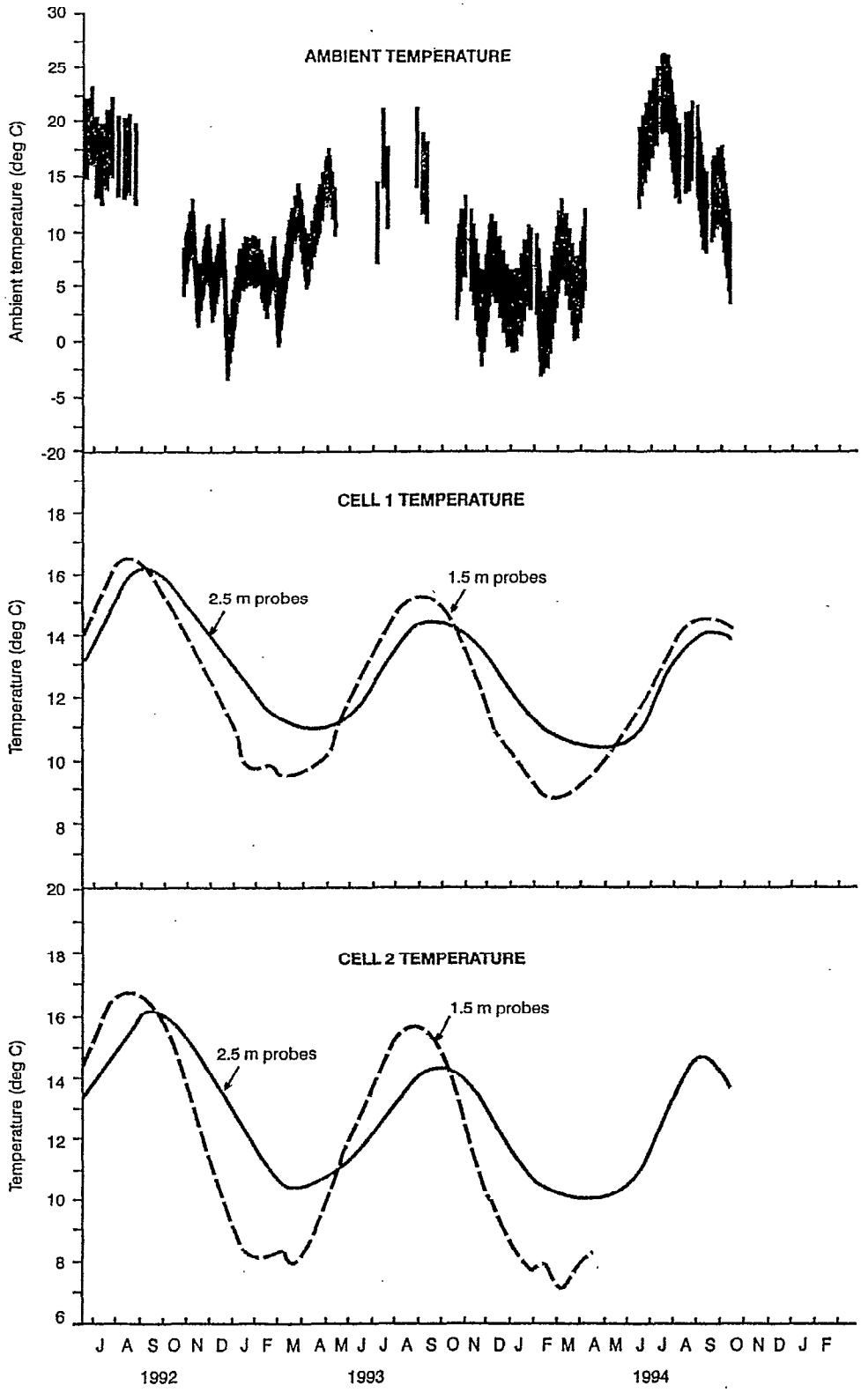


Figure 20. Leachate level changes in the test cells (after Blakey *et al.*, 1996)

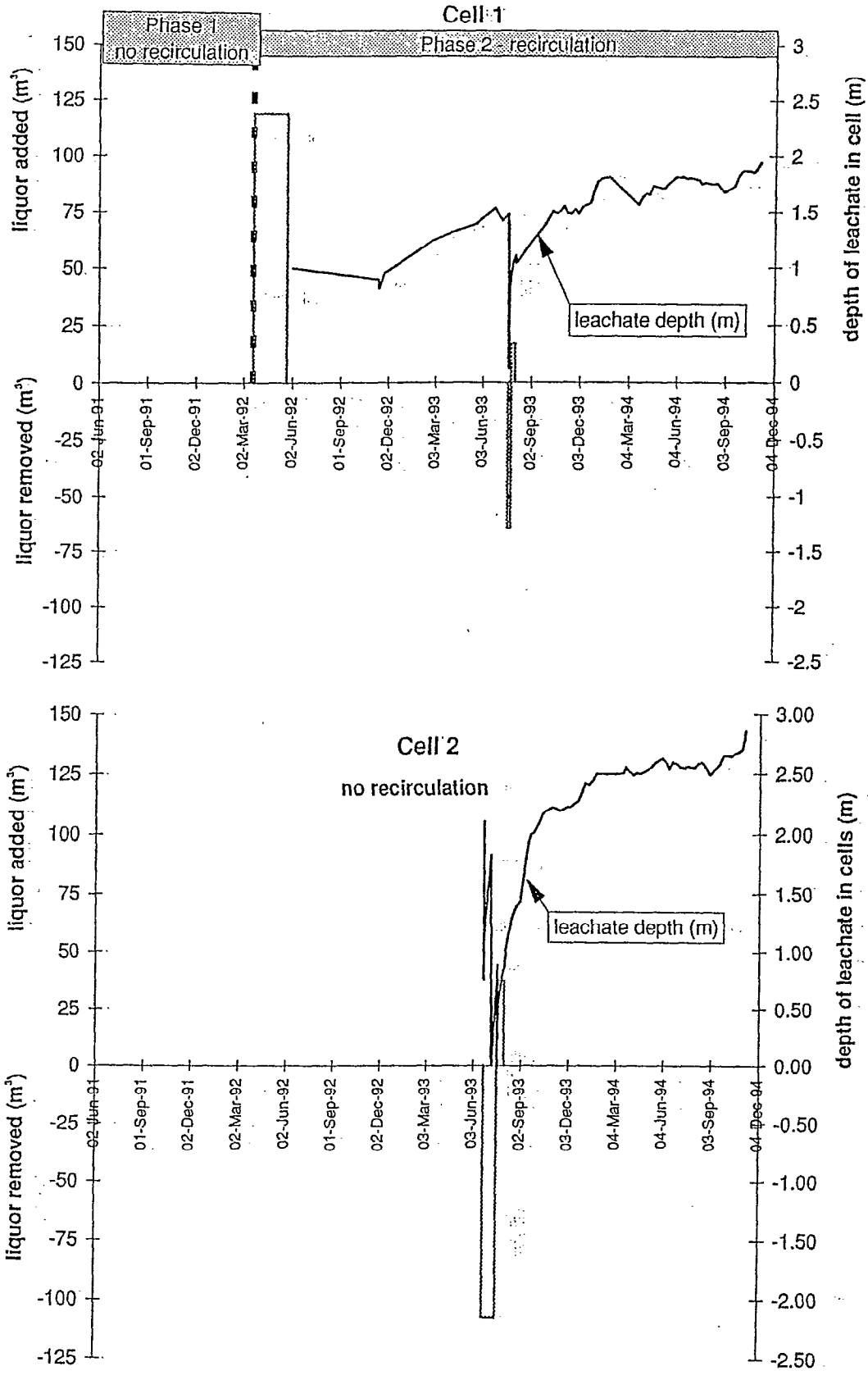


Figure 21a Cell 1 sump leachate quality
major inorganic parameters

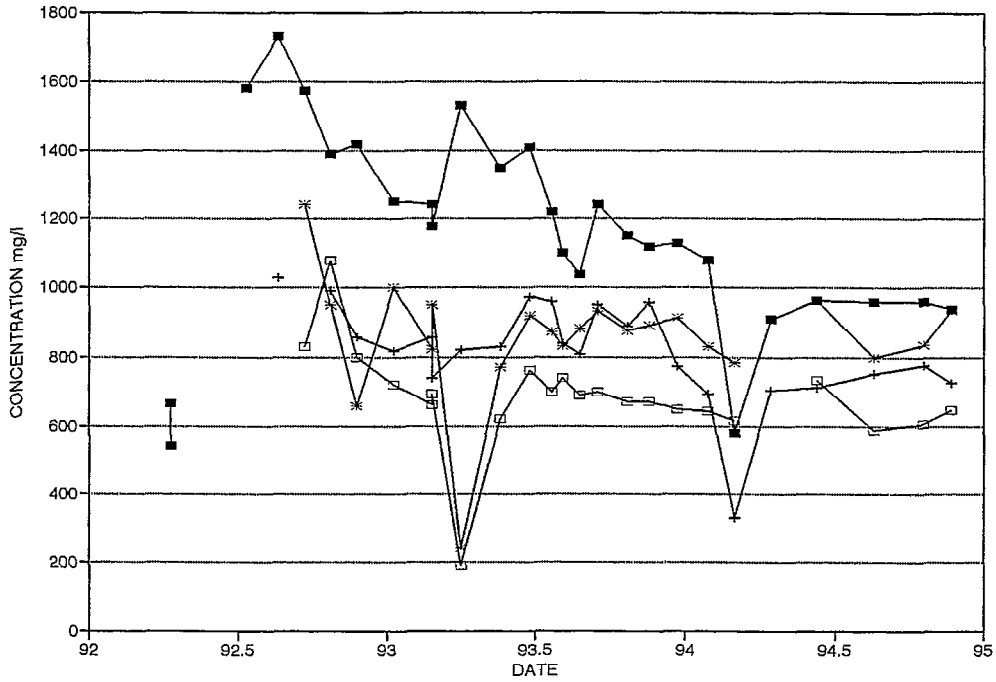


Figure 21b Cell 2 sump leachate quality
major inorganic parameters

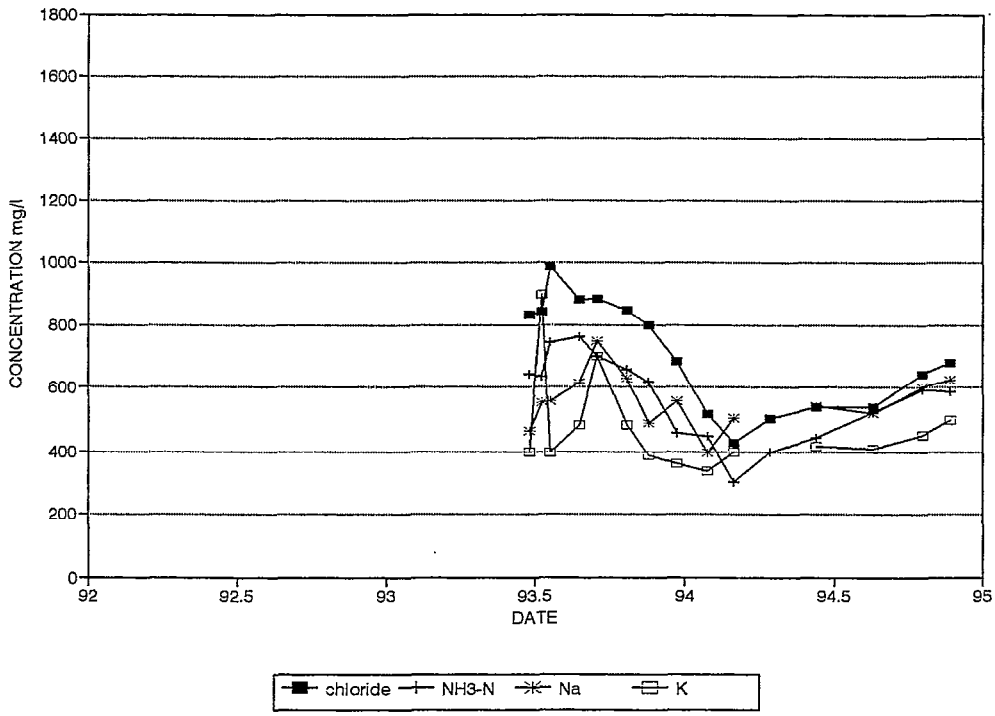


Figure 22. Methane concentrations in the gas vent pipes of the test cells (after Blakey *et al.*, 1996)

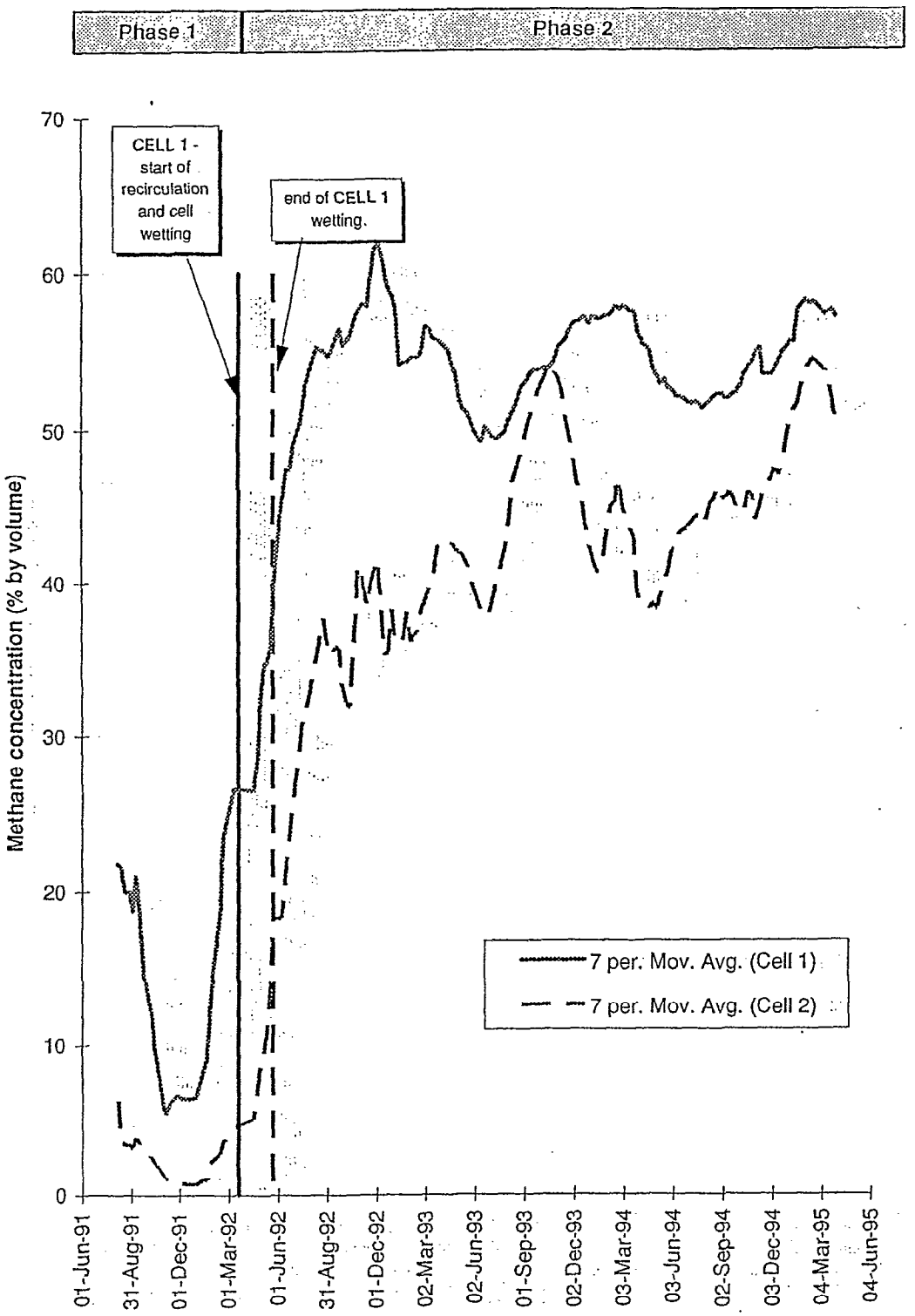


Figure 23. Gas composition in the probes of Cell 1 (after Blakey *et al.*, 1996)

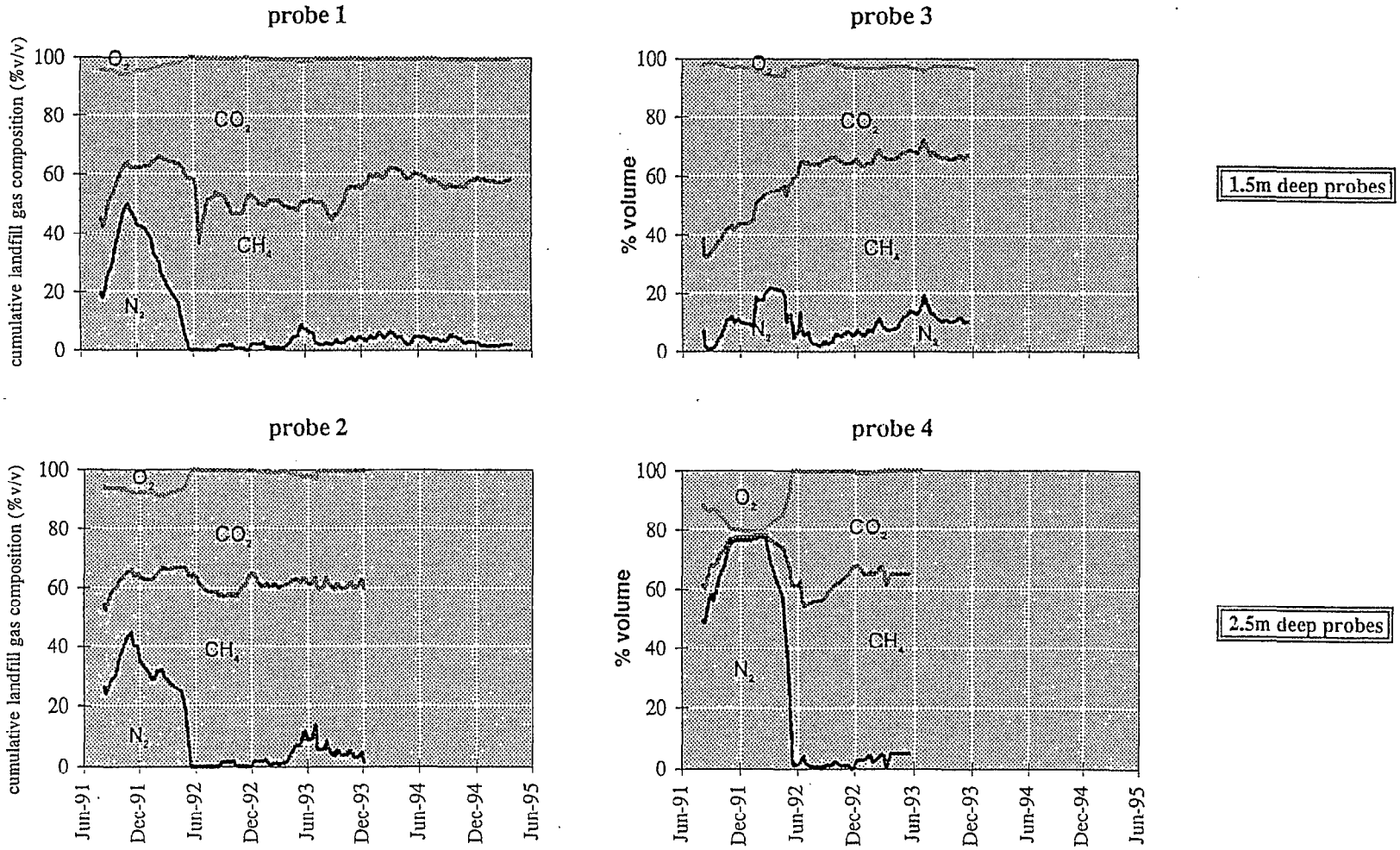


Figure 24. Gas composition in the probes of Cell 2 (after Blakey *et al.*, 1996)

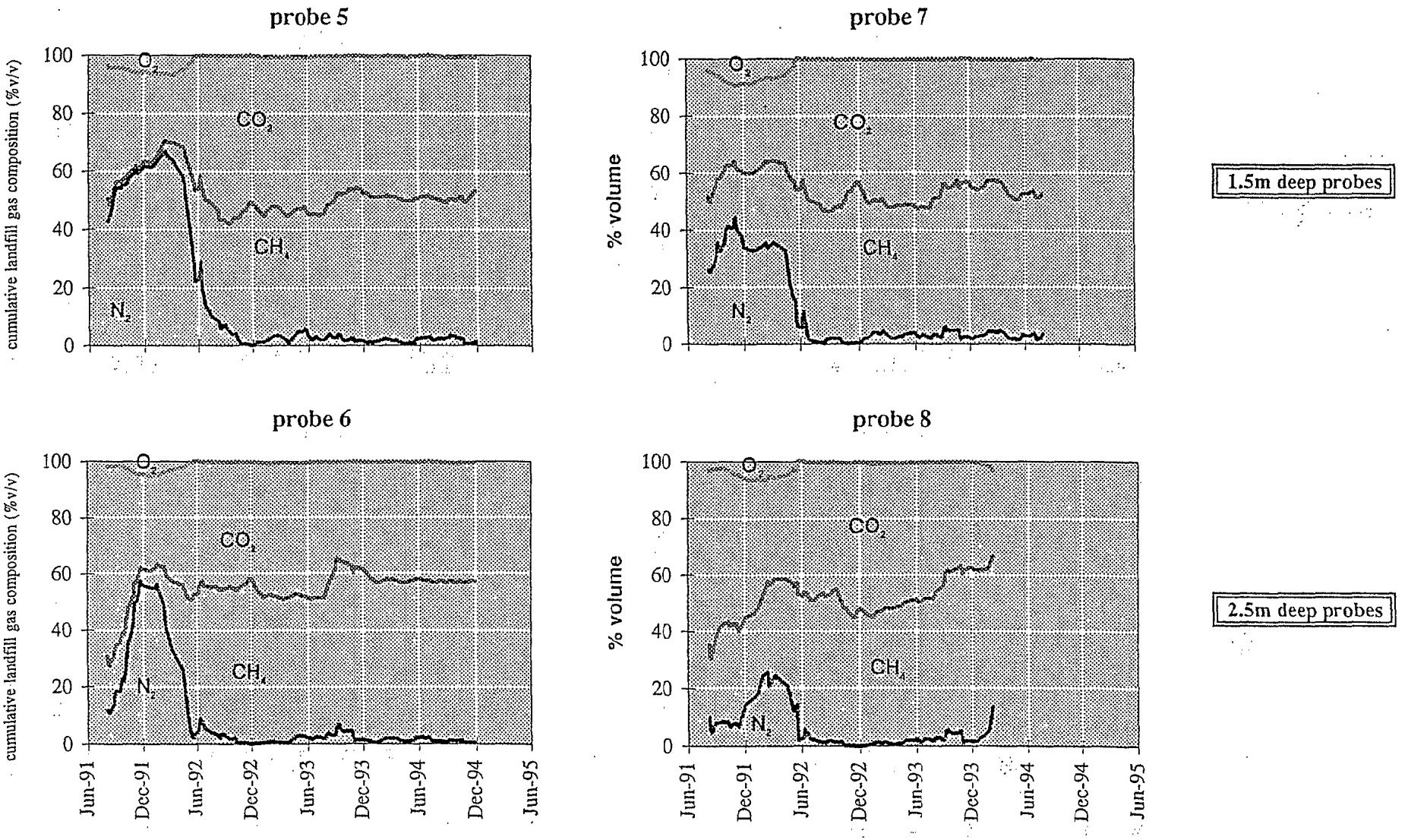


Figure 25. Leachate COD and BOD in Landfill 2000 test cell sumps (after Blakey *et al.*, 1996)

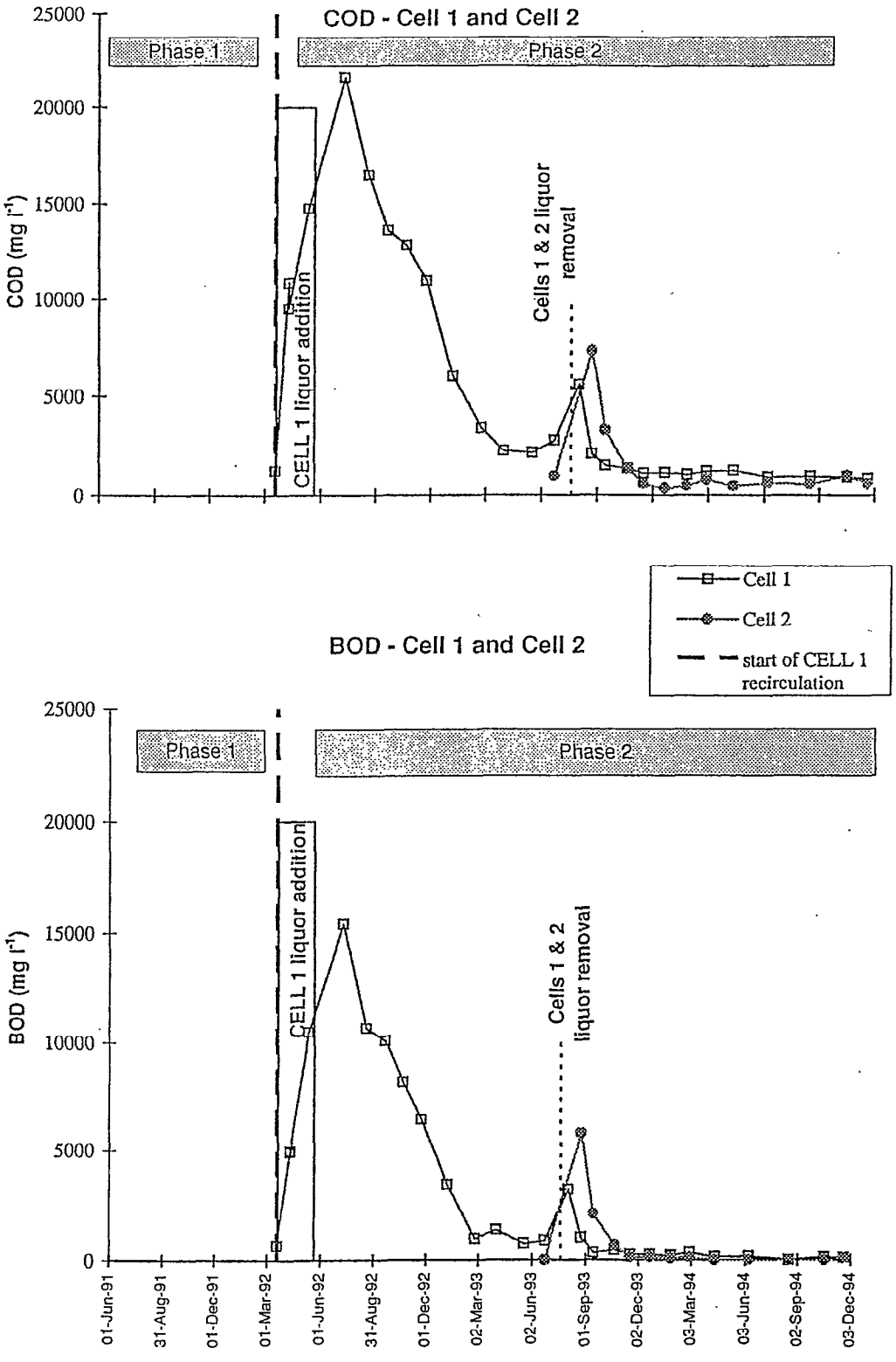


Figure 26. Cumulative gas flow measurements from time-of-transit meters (after Blakey *et al.*, 1996)

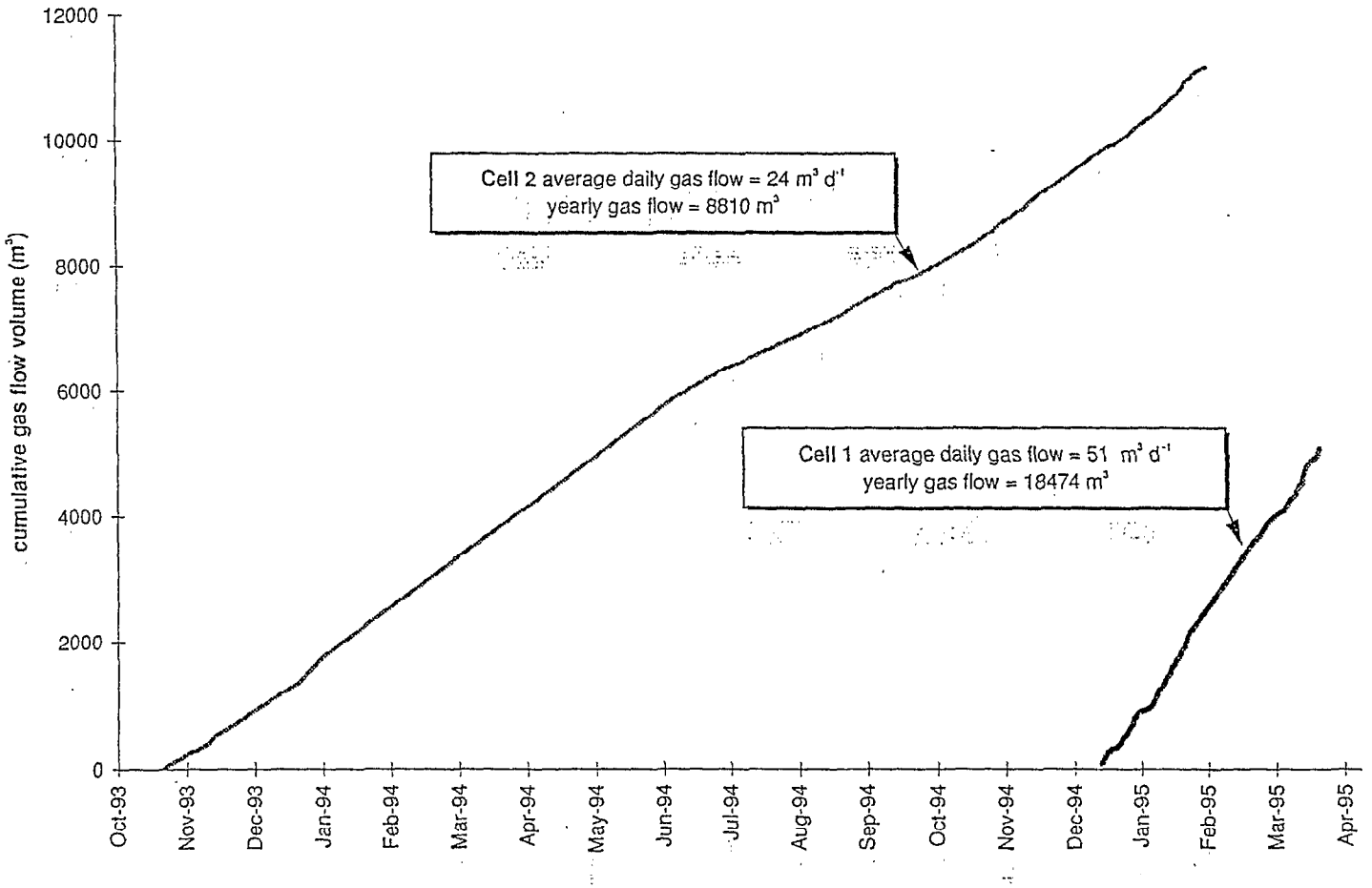


Figure 27. Vent gas composition:
CH4:CO2 ratios from Cells 1 and 2.

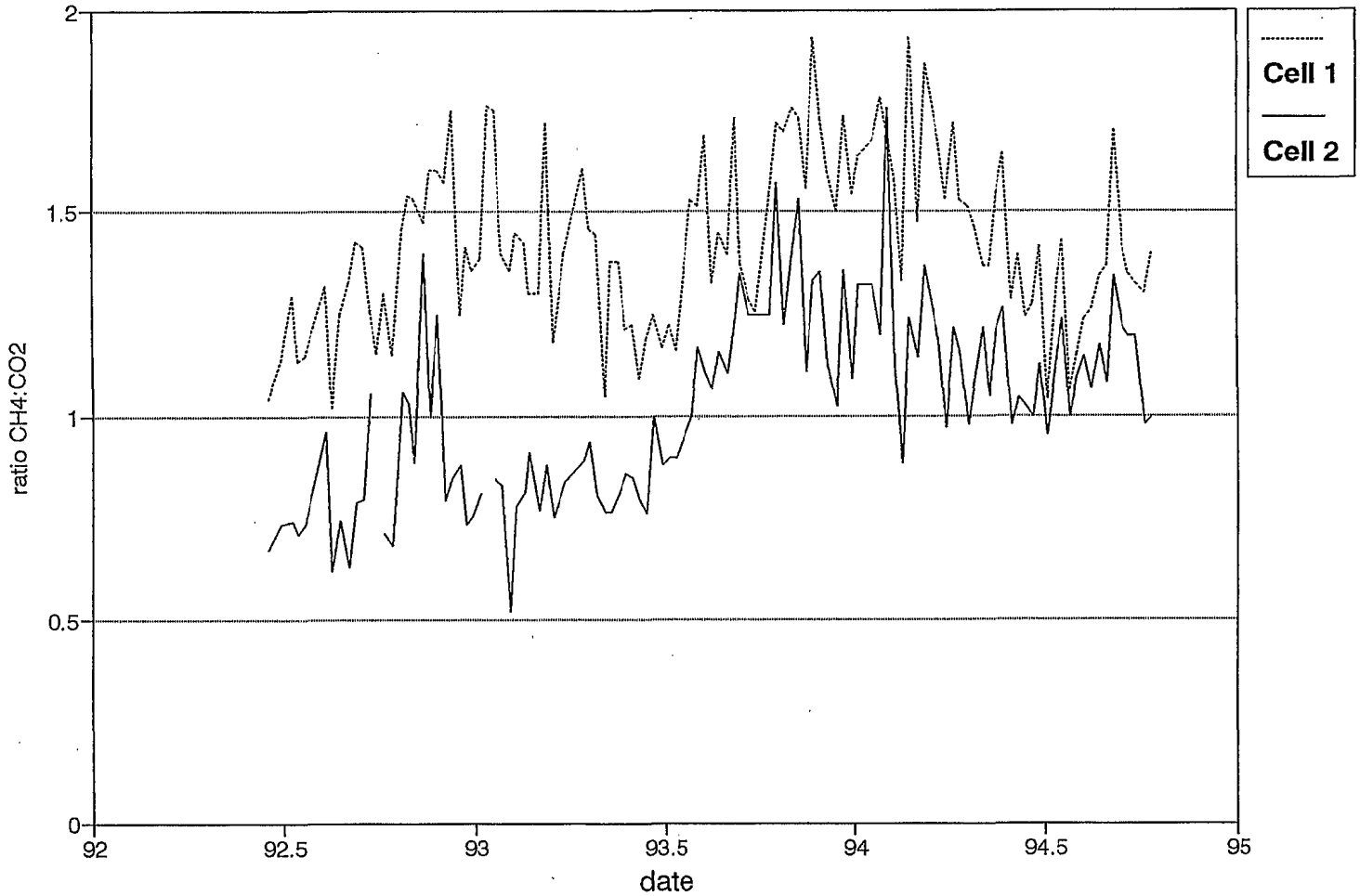


Figure 28. Cell 1 gas probe data
CH4:CO2 ratio; 2-point moving average.

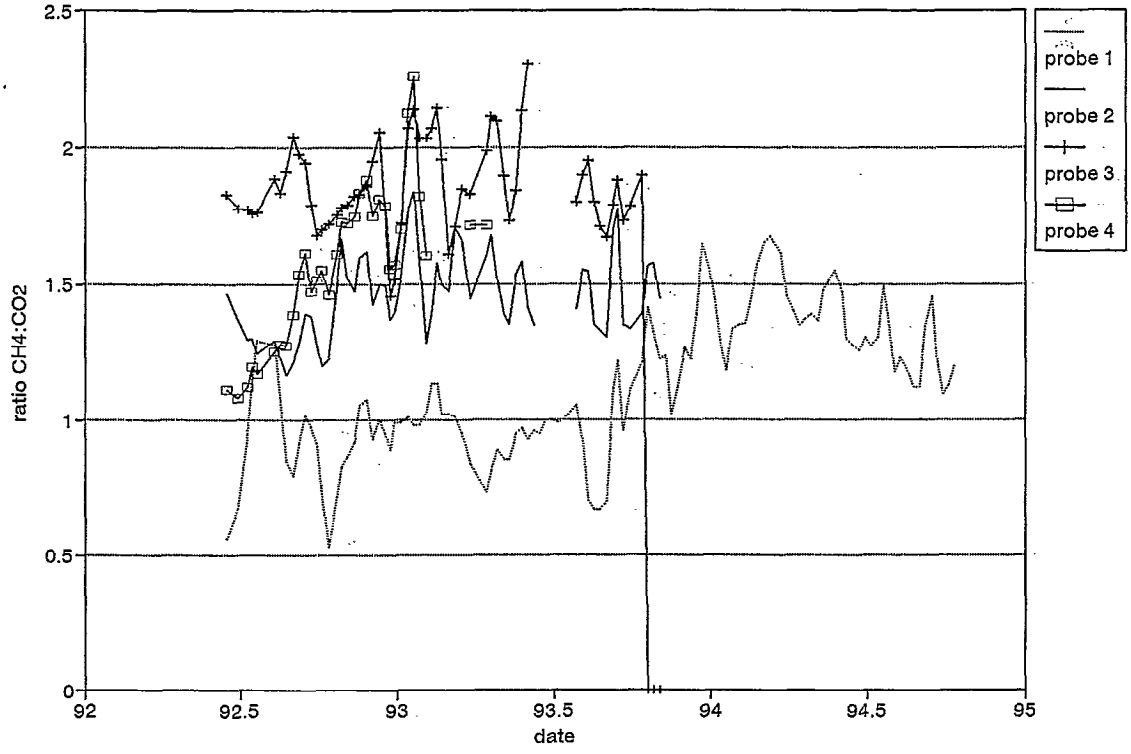


Figure 29. Cell 2 gas probe data
CH4:CO2 ratio; 2-point moving average.

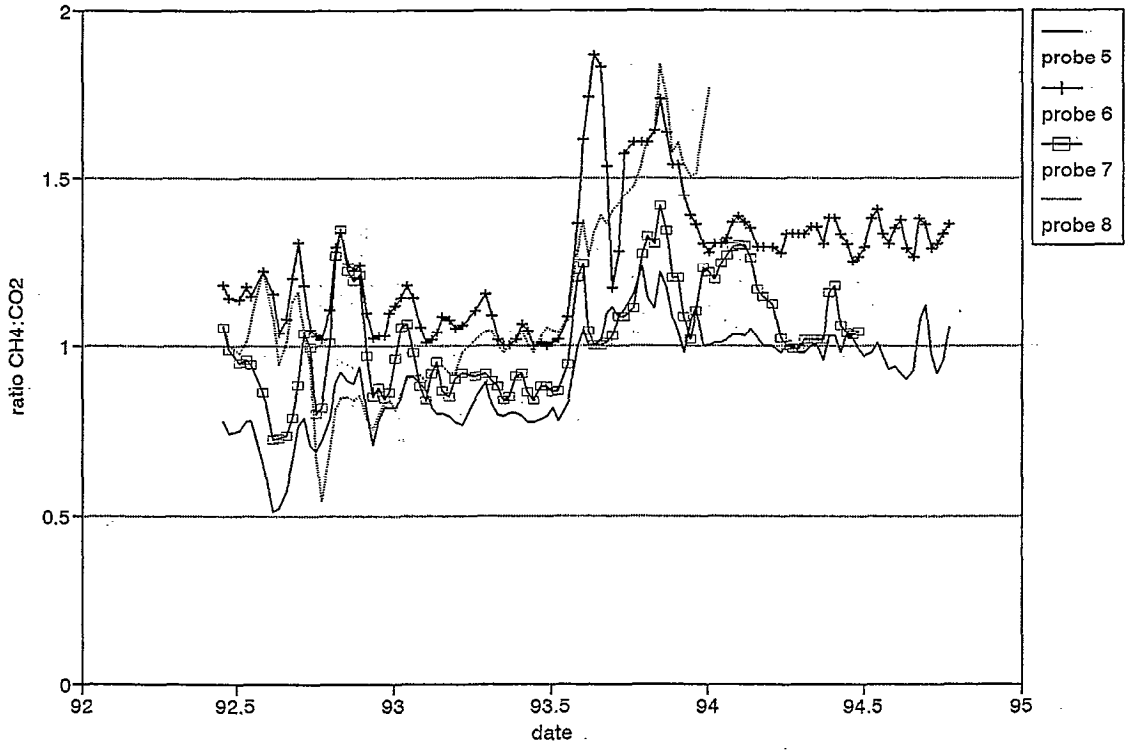
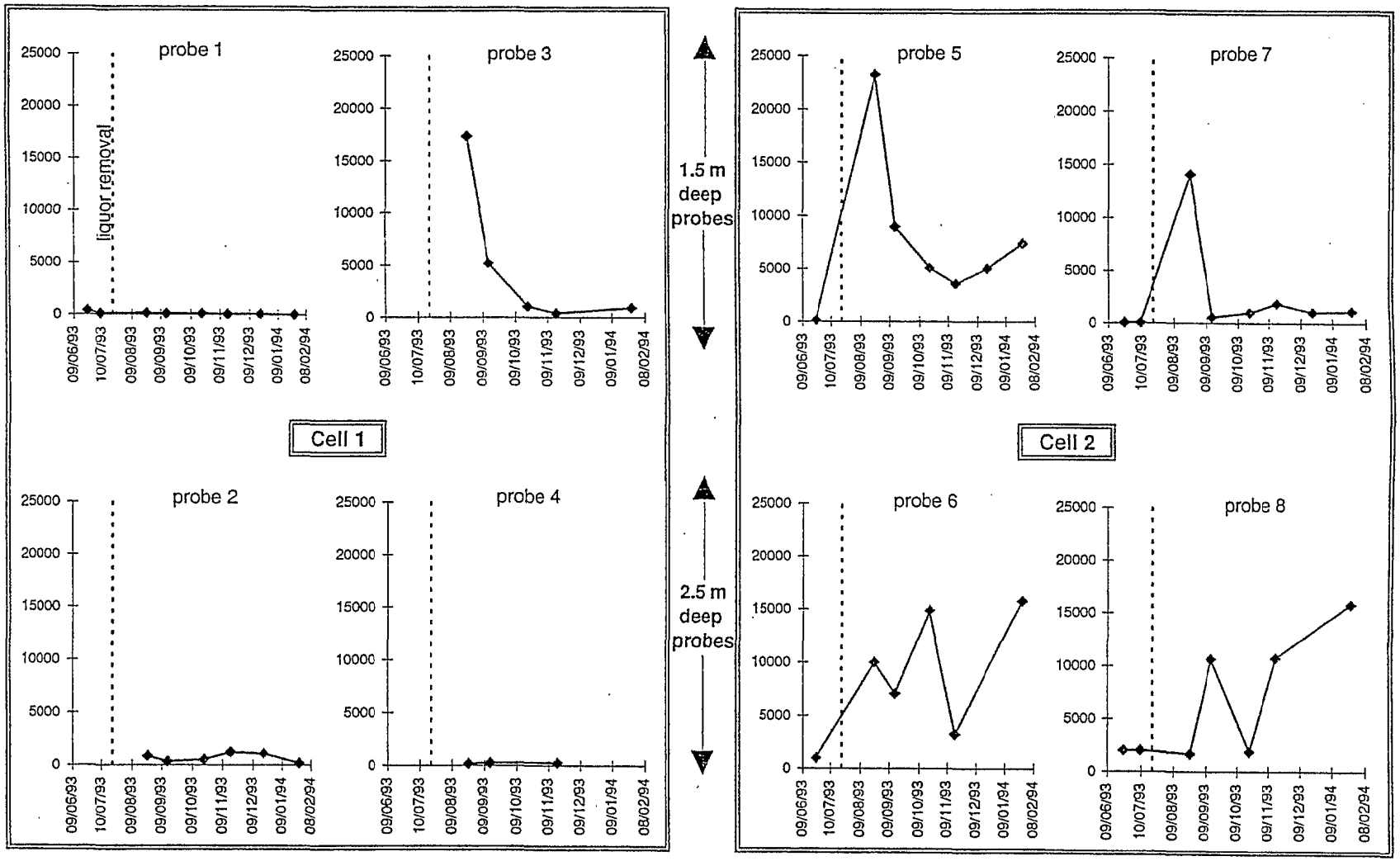


Figure 30. Hydrogen concentrations in gas probes in both Cells (after Blakey *et al.*, 1996)



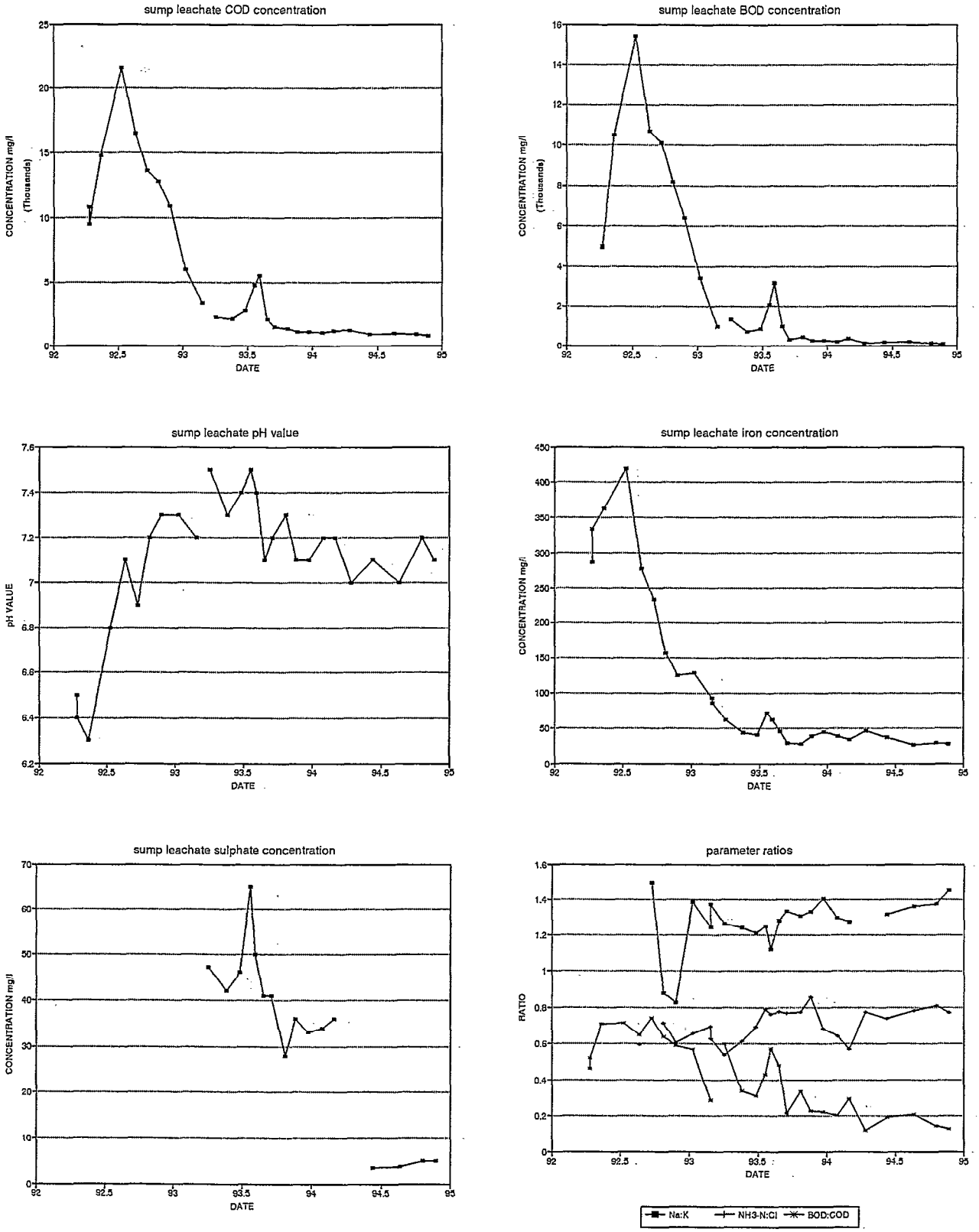


Figure 31. Sump leachate quality trends in Cell 1 at landfill 2000

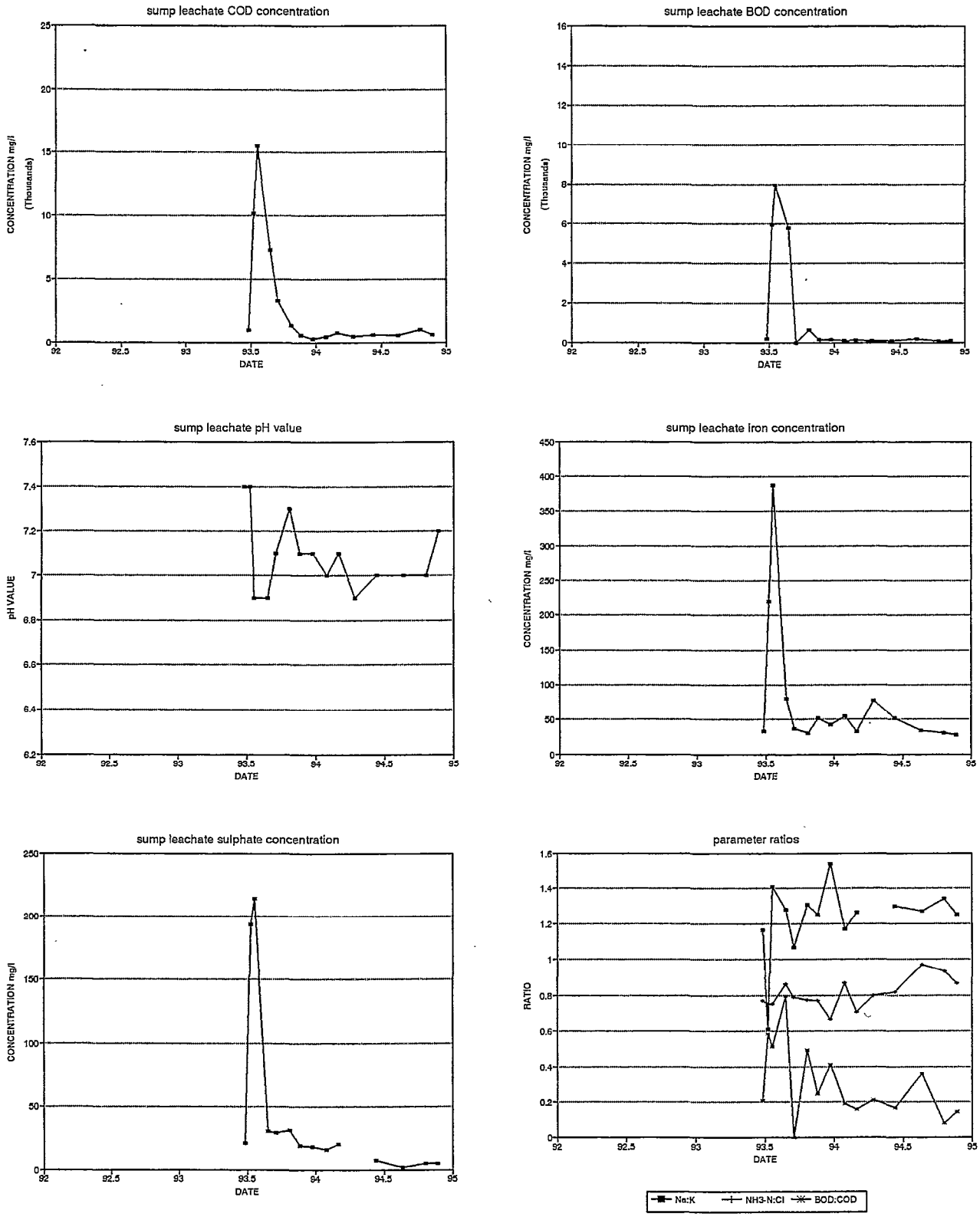
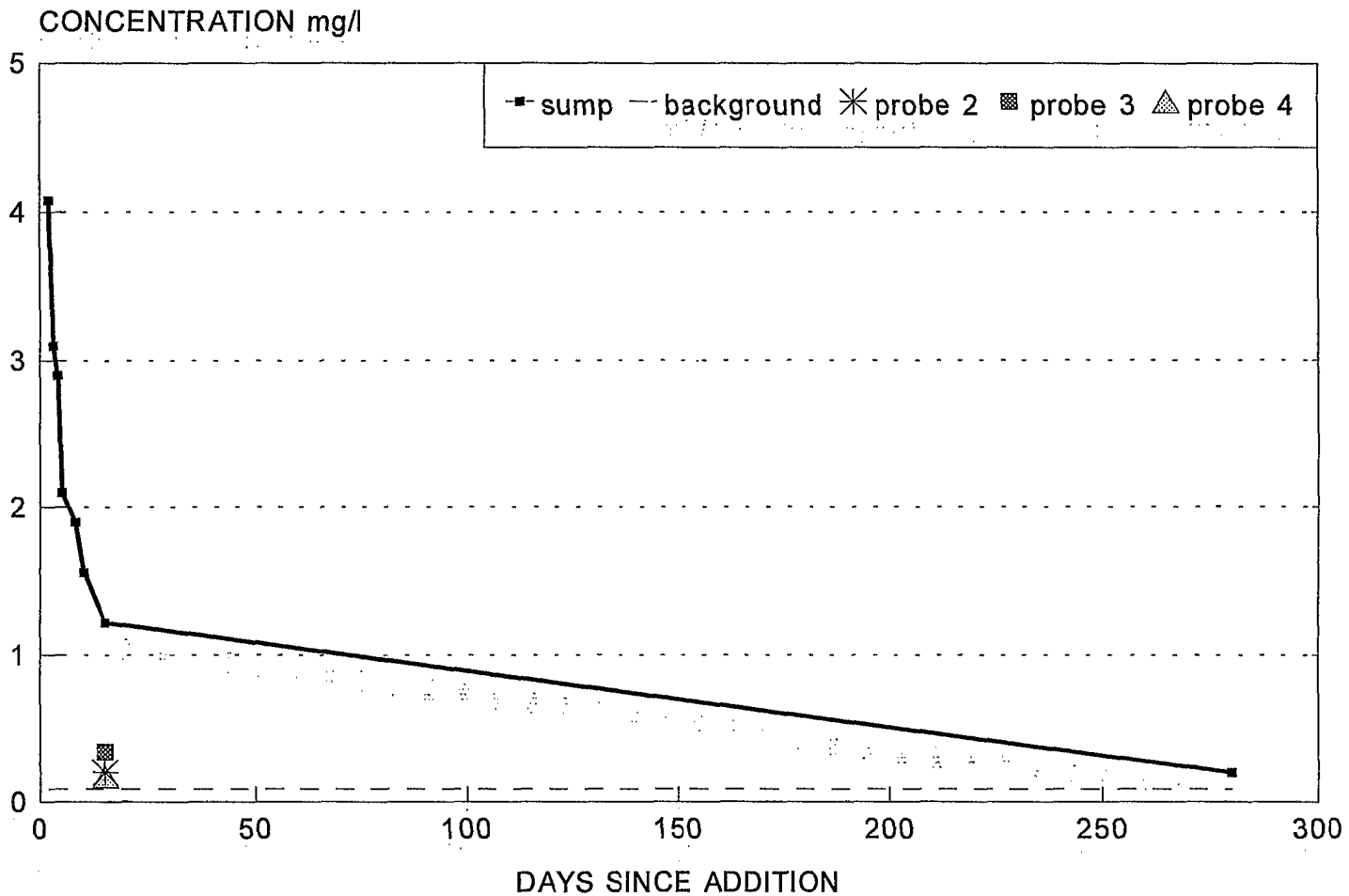


Figure 32. Sump leachate quality trends in Cell 2 at landfill 2000

Figure 33. Lithium concentrations following tracer addition at Landfill 2000.



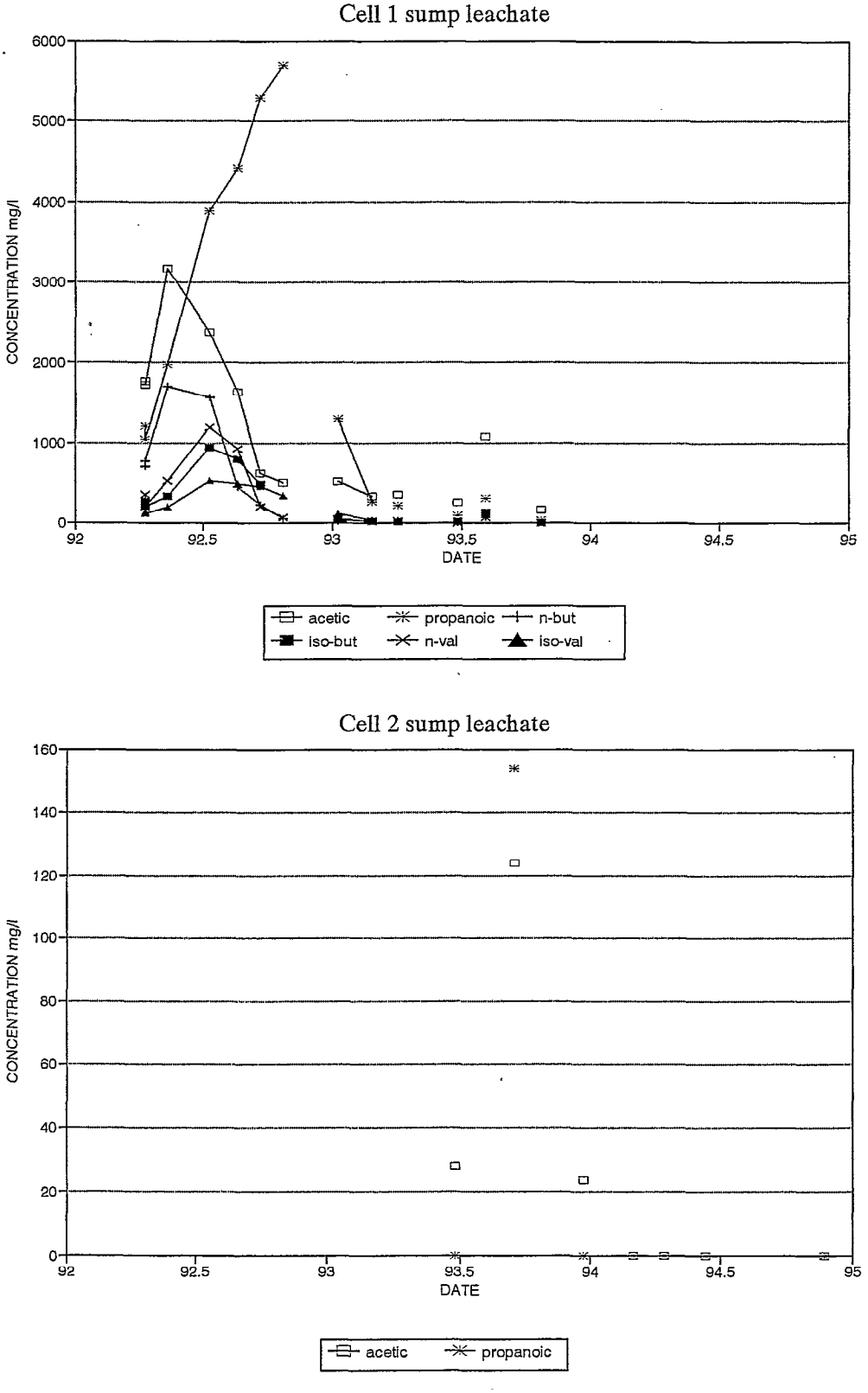


Figure 34. Volatile fatty acid concentrations in sump leachates at Landfill 2000.

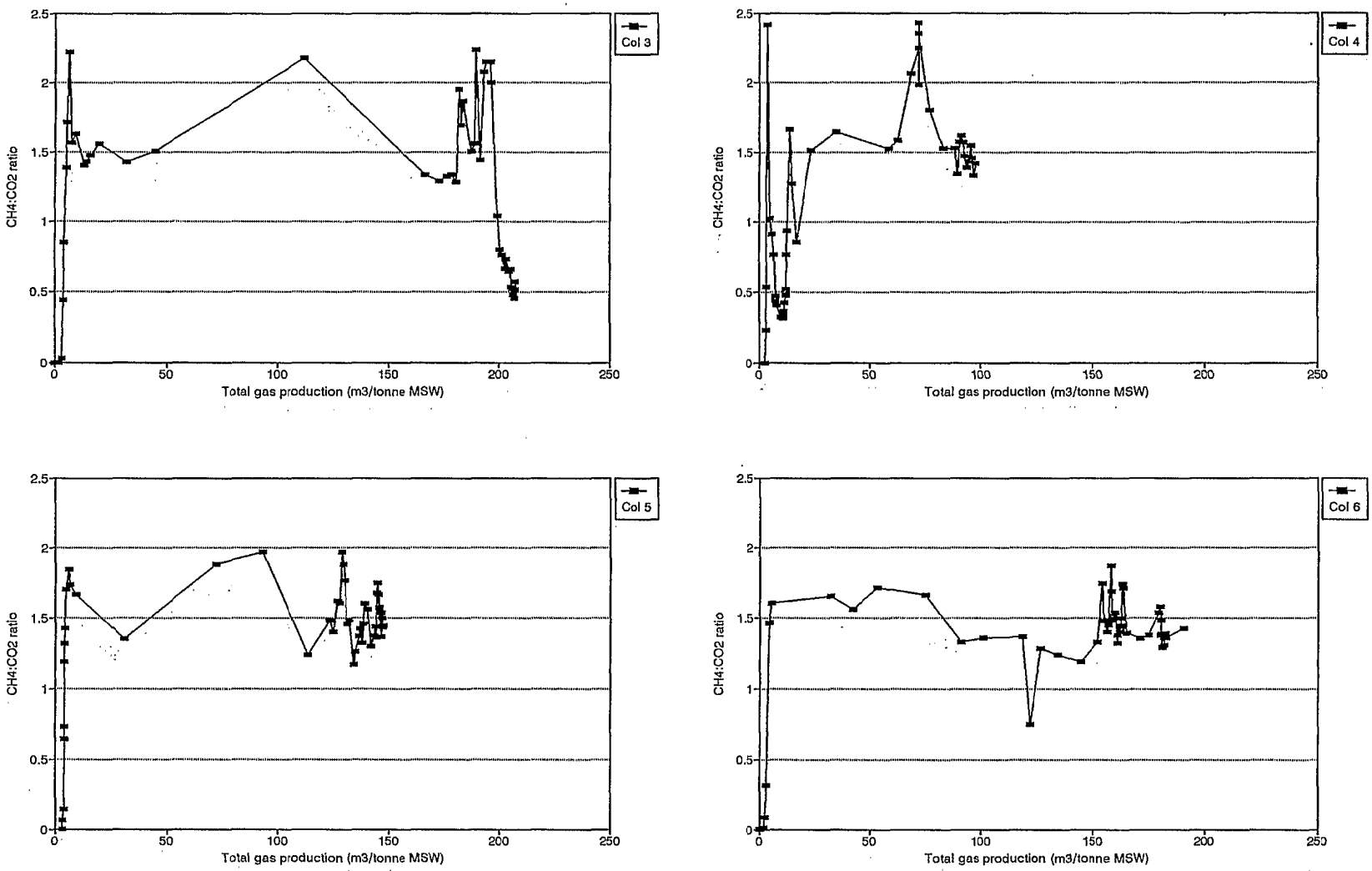
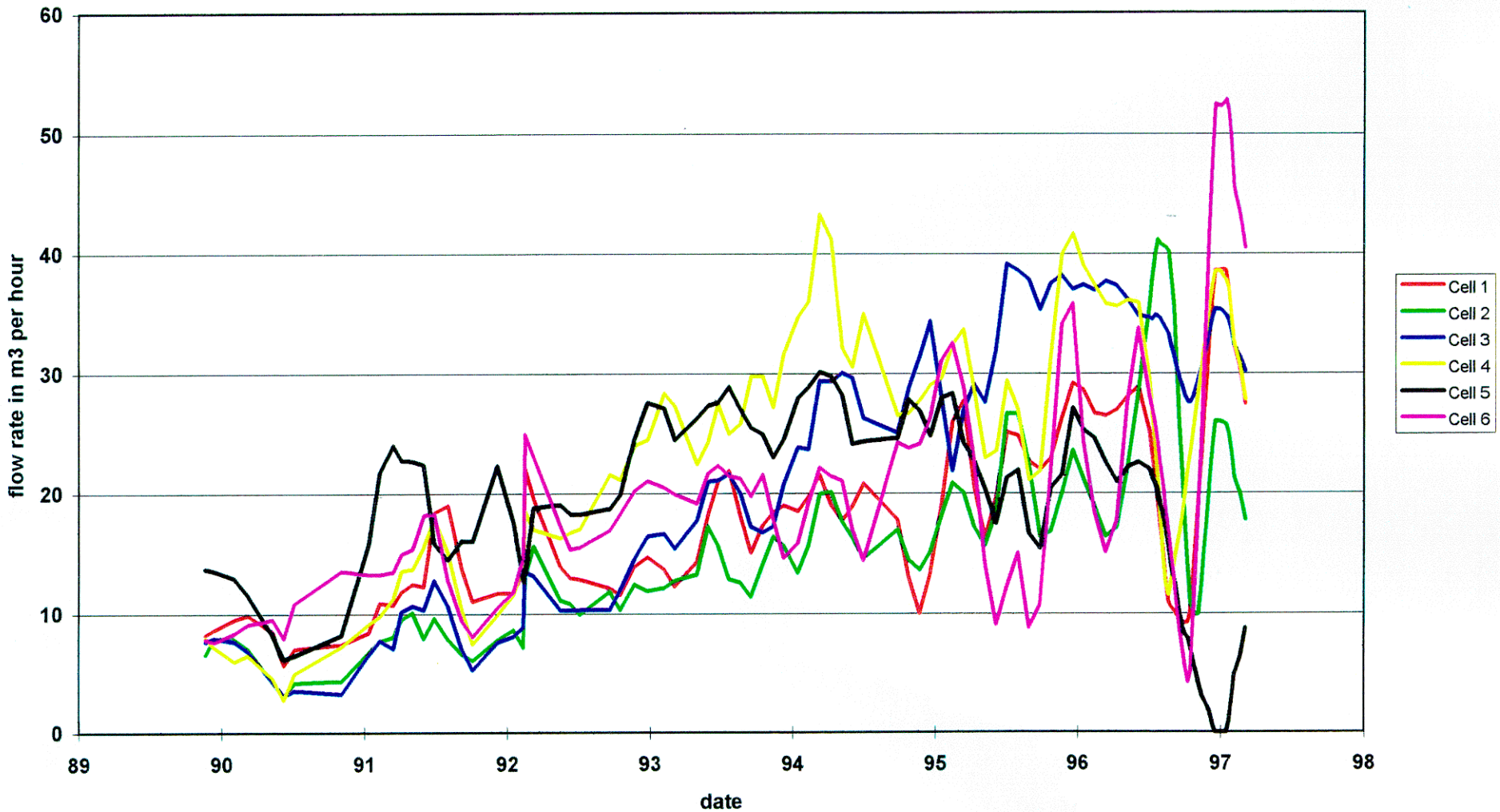


Figure 35. Methane:CO2 ratios in gas from Eastwood columns (Beaven, 1996)

Figure 36. Gas flow rates at Brogborough test cells



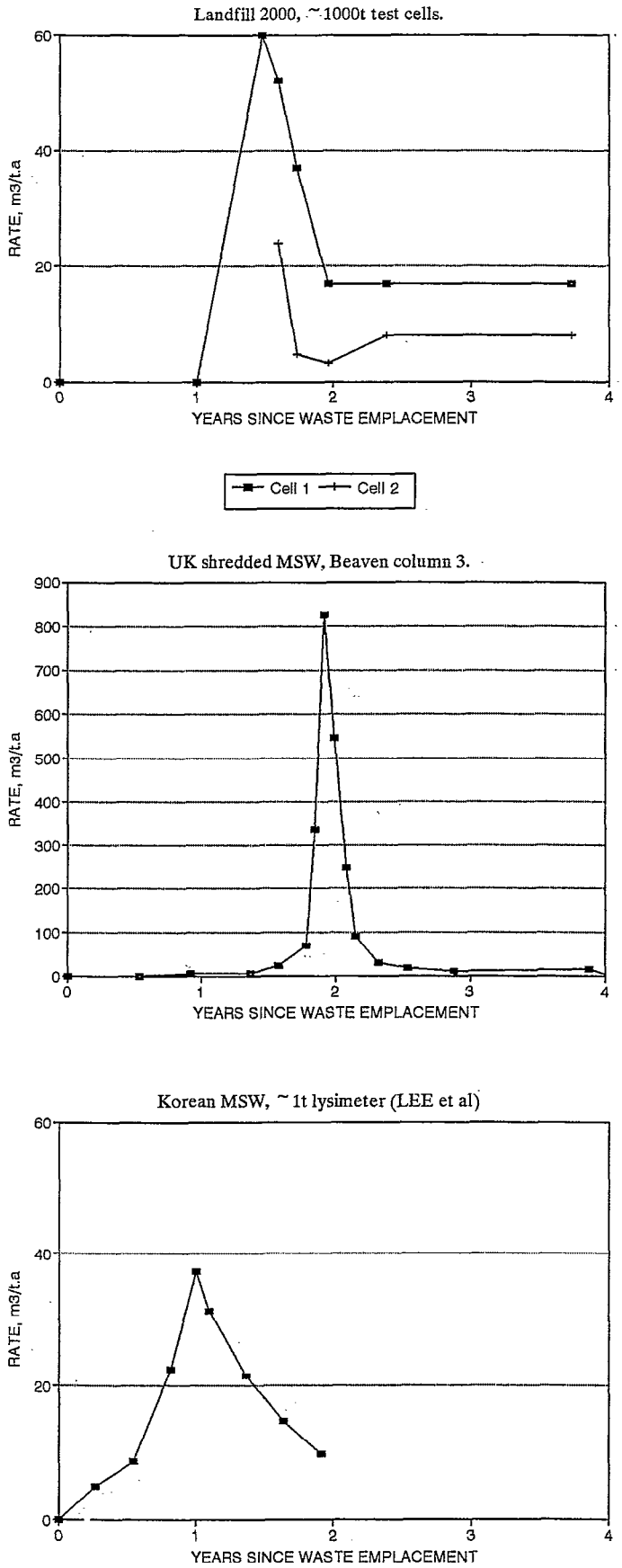


Figure 37. Gas flow profiles in Landfill 2000 and small-scale lysimeters

Figure 38. Cumulative gas flow from Helsingborg test cells, Sweden (after Meijer *et al.*, 1994)

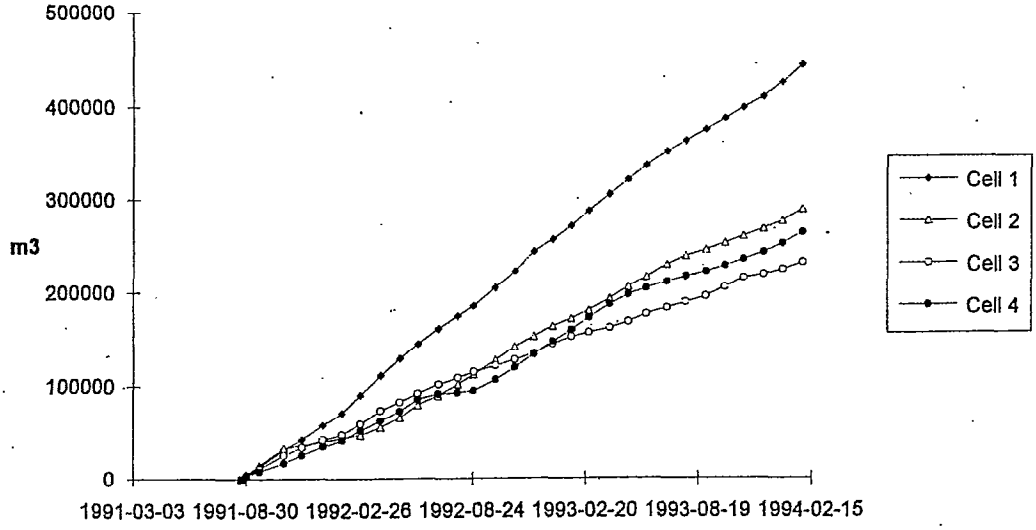


Figure 39. Methane flow rates from Malmö test cells, Sweden (after Nilsson *et al.*, 1994)