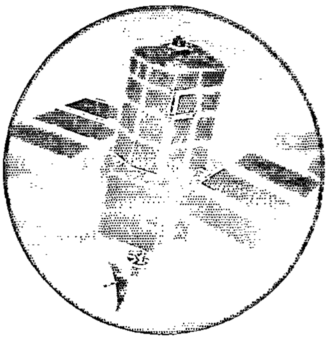
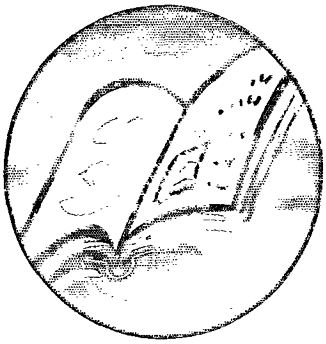
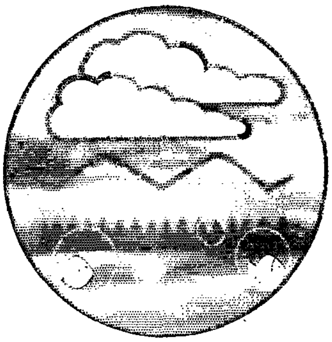
Long-Term Monitoring of Non-Contained Landfills: Burntstump and Gorsethorpe on the Sherwood Sandstone







Research and Development

Technical Report
P226

ENVIRONMENT AGENCY

Long-Term Monitoring on Non-Contained Landfills: Burntstump and Gorsethorpe on the Sherwood Sandstone

R&D Technical Report P226

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Statement of use
The Sherwood Sandstone is the second most important aquifer in the UK and is the main source of groundwater supplies and of base flow to rivers in the Midlands and much of northern England. Two landfill sites, Burntstump and Gorsethorpe, were selected for prolonged monitoring and investigation over an 18 year period to study the landfill leachate attenuation processes and capacity of this aquifer. Information gained will be invaluable to site operators and Agency officers in determining best management practice and risks to the Sherwood Sandstone Aquifer from landfill leachate.

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ACKNOWLEDGEMENTS

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The authors wish to thank the operators and/or owners of the two sites investigated in this report for continued access to the sites: namely Greenways Waste Management (Burntstump) and Nottinghamshire County Council (Gorsethorpe).

The field monitoring programme has been conducted with the assistance of many WRc staff both within the Soil, Waste and Groundwater Group, notably Robert Oliver, and the Analysis Section. In addition, the authors acknowledge the contribution of the late Mr Peter Maris (Monitor Environmental Services) who assisted with the installation of borehole B15 at Burntstump, in summer 1994.

DISCLAIMER

The opinions expressed in this report are those of the authors and do necessarily reflect the opinions of the Department of the Environment or National Rivers Authority. The results of this work may be used in the formulation of government policy but they do not necessarily represent government policy.

EXECUTIVE SUMMARY

Main objectives of the study

The contract under which this work has been carried out contained common objectives for complimentary studies to be completed with respect to non-contained landfills sited on the principal UK aquifers (Sherwood Sandstone and Chalk). The initial objectives (9 November 1993) were subsequently modified to include laboratory studies of Sherwood Sandstone/leachate interactions (7 May 1994, 14 January 1995) and to take advantage of synergism offered by contribution to an EC LIFE programme concerned with the improvement of landfill monitoring methodologies. This report addresses specifically the work undertaken on the Sherwood Sandstone aquifer. The main objectives may be summarised:

- to produce long-term monitoring data for landfill gas and leachate for non-contained landfill sites on the Sherwood Sandstone, so that the effects of modern and historic landfill practices may be compared and further information gathered on the long-term impact of waste disposal activities, in order to provide the Department with the technical background needed to establish and improve waste management policy and to conduct EC negotiations;

- to provide practical experience of recommended landfill monitoring protocols, and to identify improvements;

- to identify and assess leachate attenuating mechanisms, based on both field and laboratory studies.

Background

The Sherwood Sandstone is the second most important aquifer in the United Kingdom and is the main source of groundwater supplies and of base-flow to rivers in the Midlands and much of the North of England. The quality of the water is vulnerable to pollution by, *inter alia*, leachate derived from non-contained landfills and, potentially, by leakage from contained landfills. Investigations in Nottinghamshire during the late 1970s, by the former Severn Trent Water Authority, suggested that the ability of the Sherwood Sandstone aquifer to attenuate leachate derived contaminants is limited, when compared with aquifers such as the Chalk.

The rate of movement of groundwaters and the rate of many attenuating processes are slow. In order to gain sufficient knowledge of the processes in the Sherwood Sandstone which may attenuate leachate, two sites were selected for prolonged monitoring and investigation , one with a deep (>50 m) unsaturated zone (Burntstump) and the other with a shallow (<20 m) unsaturated zone (Gorsethorpe). The monitoring period reported has extended over 18 years (1978 - 1996) with active WRc involvement since 1983.

Main findings

Leachates generated from the wastes at both sites have migrated into the underlying Sherwood Sandstone. The annual volume of leachate production has been shown to be related directly to the efficiency of the capping materials in preventing ingress of rain, so that greater volumes of leachate are formed from the older waste deposits at both sites than from the more recent deposits which are capped with low permeability soils.

The initial compositions and strengths of leachates from the older and more recent waste deposits have been comparable. The strength of leachate and rate of landfill gas generation began to decrease some 15 to 20 years after deposit of the older wastes. It is probable that the onset of decline in leachate strength will be delayed in the case of the more recent waste deposits, because of the more efficient capping and less efficient flushing from the wastes.

The physical and chemical properties (buffering capacity and cation exchange capacity) which encourage efficient attenuation of leachates are relatively low in the Sherwood Sandstone, with the result that leachate has entered the groundwater beneath the shallow (c. 8 m) unsaturated zone at Gorsethorpe landfill. However, the deep (>50 m) unsaturated zone at Burntstump has encouraged effective attenuation of the organic components of leachate, by methanogenesis, and of ammonia by cation exchange. The rate of progress of the pollution front towards the water table is slow (c. 2 m y^{-1}) and the final impact on groundwater quality is expected to be further reduced by continued attenuation in the unsaturated zone before the front reaches the water table (c. Year 2005).

Laboratory studies, in the form of flow-through column tests carried out to supplement the understanding of the attenuating processes derived from the field investigations and monitoring surveys, have suggested that such tests may be developed to provide a reliable method for assessing the attenuating characteristics of the formation in advance of establishment of a landfill.

Main conclusions

- The Sherwood Sandstone formation has generally low buffering and cation exchange capacities and is potentially vulnerable to pollution from surface sources, including landfill leachate.
- Groundwater is at particular risk in situations where the unsaturated zone is shallow, particularly in those areas with a high fissure flow component.
- In those situations where a deep unsaturated zone is present, groundwater flow is dominantly intergranular and the rate of leachate release is controlled, natural attenuating processes form a valuable protection to groundwater quality, and these factors should be taken into account when carrying out risk assessment for proposed landfill developments.

1. INTRODUCTION

Contract details

This research contract was commissioned by the Wastes Technical Division of the Department of the Environment under Contract No. EPG/1/7/003 with part-funding by the National Rivers Authority. The work was undertaken by WRc plc over the period November 1993 to March 1996.

Statement of objectives

The objectives of the programme of work reported here were as follows:

- to produce long-term monitoring data for landfill gas and leachate for uncontained landfill sites on the Sherwood Sandstone, in order to provide the Department with the technical background needed to develop waste management policy and conduct EC negotiations;
- to provide further information on the long-term impact of waste disposal activities on groundwater quality;
- to compare the effects of modern and historic landfill practice to establish and improve technical guidance and codes;
- to identify and assess leachate attenuation mechanisms;
- to investigate the interaction of Sherwood Sandstone aquifer materials with landfill leachate (University of Birmingham sub-contract);
- to support the EC Landfill Monitoring for Life project;
- to provide practical experience of the NRA and DoE landfill monitoring protocols and identify improvements.

Methodology

The following activities have been conducted:

- drilling through a recently completed phase of Burntstump landfill and through sandstone outside the site perimeter to:
  - obtain a porewater chemistry profile through the waste and into the underlying Sherwood Sandstone;

  - determine the background chemistry and microbiology of the Sherwood Sandstone;
  - obtain composite waste samples for characterisation; and
  - install landfill gas monitoring ports.
- revision of the WRc water balance model to take account of compaction caused by settlement, and application of the model to both sites;
- groundwater monitoring in, around and beneath both sites;
- landfill gas monitoring in the waste and unsaturated zone at both sites;
- sub-contract a laboratory-scale study into the interaction between landfill leachate and Sherwood Sandstone to University of Birmingham.
- production of a separate report on the investigations conducted on the Chalk (CWM 139/96).

Structure of report

The methods employed at both sites are summarised in Section 2, followed by a brief presentation of results for Burntstump (Section 3) and Gorsethorpe (Section 4). Protocols and monitoring data (waste, porewaters, groundwater and landfill gas) are provided in nine appendices. The data are discussed in the light of previous findings in Section 5, drawing on work conducted by the University of Birmingham under sub-contract and also the findings of an MSc study which has used sandstone core generated by this contract. Finally conclusions concerning the impact of disposal operations in non-contained landfills on the Sherwood Sandstone are presented in Section 6.

Background information

In the 1970s the former Severn Trent Water Authority (STWA) investigated a number of landfill sites to determine the effect of different unsaturated zone depths on groundwater quality. It was concluded by STWA that a ten metre thick unsaturated layer below a landfill site was insufficient for the attenuation of the principal contaminants in the leachate and therefore for the protection of underlying groundwater resources.

Two of the sites (Burntstump and Gorsethorpe) were subsequently chosen by the DoE for further investigation with the objective of studying the attenuation capacity of the Sherwood Sandstone. The locations of these sites are shown in Figure 1.1. WRc became involved in this study from 1983 with DoE funding, and since 1991 with DoE and NRA funding.

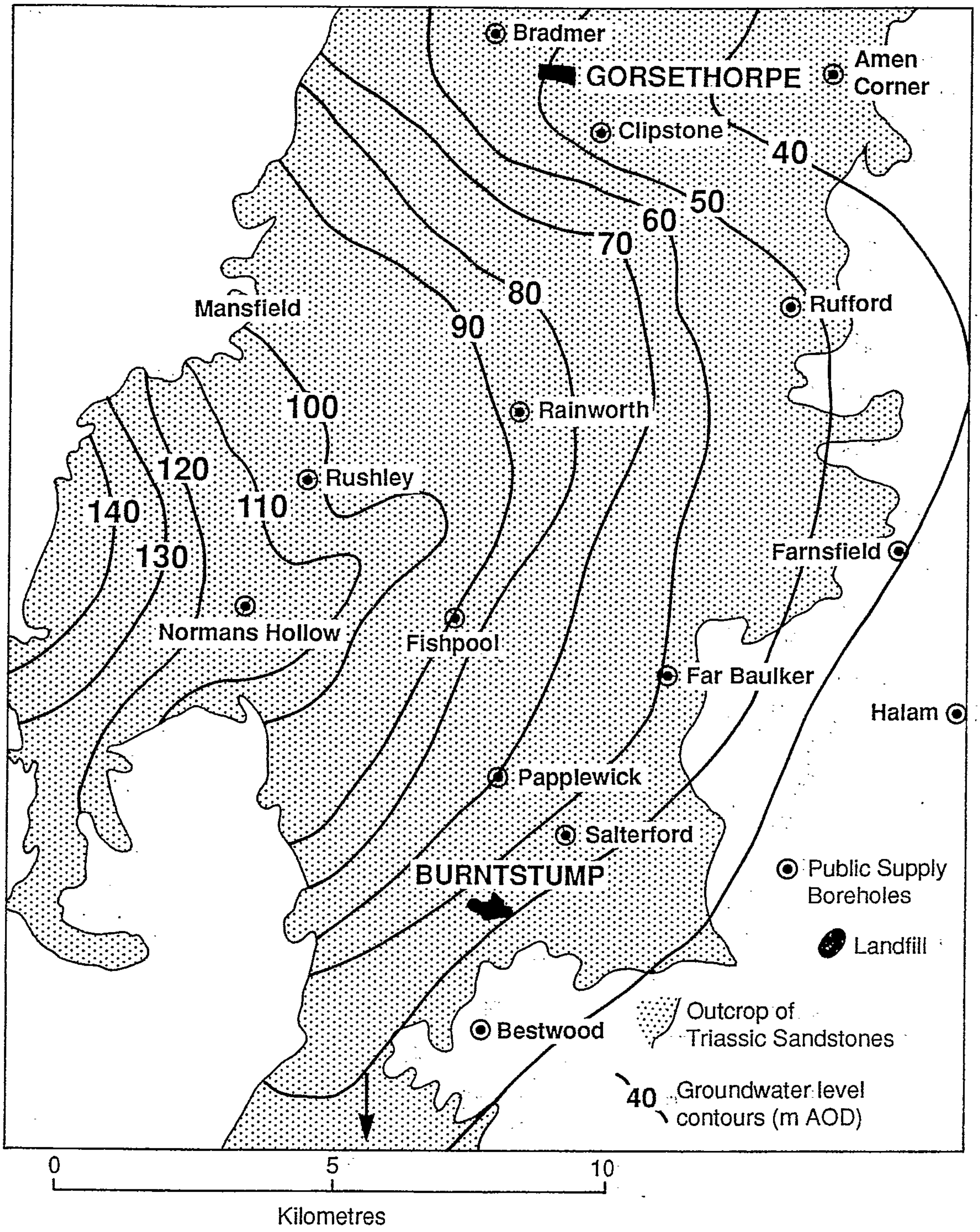

Figure 1.1 **Outcrop of Triassic Sandstones in the vicinity of Gorsethorpe landfill with groundwater contours**

Burntstump landfill

Burnstump landfill has accepted municipal solid waste and up to 30% non-notifiable commercial and hazardous wastes since 1974: initially in two shallow scrub-covered valleys to a depth of less than 10 m, extending into an adjacent 15 m deep quarry in 1978. Quarrying of the sandstone continued and in the 1980s filling to a depth of 30 m was carried out.

The site history and long-term investigations conducted beneath the old shallow parts of Burntstump landfill were reported in full in Lewin *et al.* (1994). Repeated porewater profiling in the thick (50 m) unsaturated zone allowed the migration of the leachate front to be observed. The long-term study demonstrated that while limited attenuation of the organic contaminants takes place at the leachate front, significant attenuation of organic compounds is observed in the section of the unsaturated zone three or four metres behind the advancing leachate front. Based upon the observed rates of leachate advancement, it was concluded that there was unlikely to be any significant impact from this leachate on groundwater quality until the year 2005 at the earliest. This report summarises the results of the groundwater and landfill gas monitoring which has continued in this part of the fill.

The unsaturated zone beneath the old, shallow part of Burntstump is well characterised. Attention has now moved to the deeper, more recently completed phase of the landfill to observe the attenuation of leachate generated by waste deposited under conditions more representative of current waste disposal practices. Cell 7 was completed in 1989 to a depth of 27 - 30 m over a 30 m thick unsaturated zone. This report presents the results of the investigations in this part of the site. An exercise has been conducted to characterise the waste and to profile the porewater through the waste and into the sandstone. In addition the generation of leachate from the site has been modelled in order to predict its migration through the unsaturated zone.

Gorsethorpe landfill

The unsaturated zone at Gorsethorpe is significantly more shallow (5-20 m deep) than at Burntstump and therefore attention at this site has been focused on attenuation mechanisms in the saturated zone. Landfilling of domestic and non-hazardous industrial waste and incinerator ash commenced in a 100 000 m^2 quarry in 1969. The first phase (23 800 m^2) was completed in 1979 and capped with colliery shale. The second (11 000 m^2) and third (66 000 m^2) phases were completed by 1983 and covered quickly with 1 m of colliery shale. The site history and details of the long-term investigations are reported in full in Young *et al.* (1994).

2. METHODS

2.1 Waste and sandstone core sampling at Burntstump landfill

2.1.1 Drilling exercise (Boreholes B15 and B16), August 1994

Two boreholes were drilled during August 1994. Their locations are shown in Figure 2.1.

Borehole B15 was drilled through a recently restored part of Burntstump Landfill and into the underlying unsaturated zone. Borehole B16 was drilled off-site, to the north east of Burntstump, through the sandstone to the water table. Waste samples were recovered by shell and auger from B15 to a depth of 27 m. A rotary air flush rig recovered the sandstone samples from B15 and B16 in rigid plastic Mylar™ core sleeve to prevent cross-contamination of interstitial fluids during drilling. Continuous coring was attempted, however, even the triple mazier barrel arrangement could not retain cores samples in sections where running sand was encountered (e.g. B15 28-36 m bgl).

Borehole B16 was backfilled to the surface with bentonite grout and soil. On completion of the coring of B15, a piezometer and gas monitoring stem was installed (Appendix A).

2.1.2 Sample preparation for microbial activity and porewater chemistry determinations

Samples of sandstone were removed for microbiological analysis using the protocols used in previous drilling exercises at Burnstump (Lewin *et al.* 1994). Samples were also collected for the determination of cation exchange capacity (MAFF 1986, ADAS Method 16).

The 1.5 m cores were wrapped in lay-flat polythene tubing and stored in a deep freeze on site. Waste samples from 2 m depth intervals were double wrapped in plastic bags and stored in a freezer. Both sets of samples were kept frozen immediately after sampling until 12 hours before porewater processing to minimise microbial activity during storage. Porewaters were extracted from the wastes and cores by centrifugation at 3000 and 6000 rpm respectively at WRc Medmenham and analysed within 24 hours of recovery for major ions, TOC, iron, manganese and carboxylic acids by the methods summarised in Appendix B1.

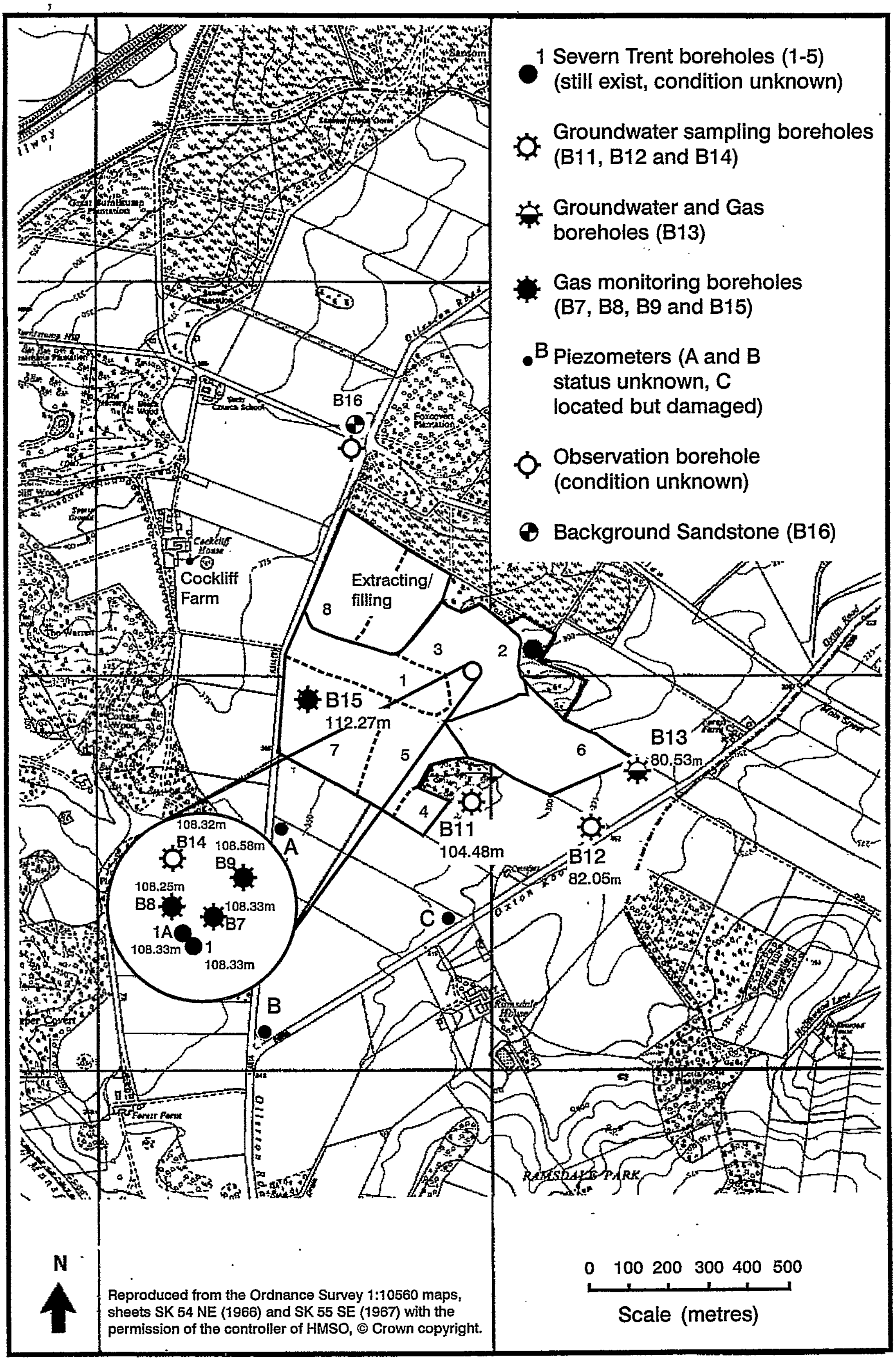

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Figure 2.1 Plan of Burntstump landfill site showing borehole positions and levels (m AOD from top of casing)

2.1.3 Waste characterisation

Fifteen samples of the waste were despatched in a frozen state to NETCEN (AEA) for characterisation. Once thawed, seven samples from the upper part (1-14 m below ground level) and eight samples from the lower part of the landfill (16-27 m bgl) were bulked to produce composite samples of 120 and 170 kg respectively. A sub-sample of the composite waste was retained for drying and grinding for chemical analysis and the remainder was passed over a series of screens (160 to 10 mm) and each screened fraction classified according to the eleven main waste categories (e.g. paper/card, plastic film etc.).

2.1.4 Analysis of the wastes

A sub-sample of the dried ground composite wastes were retained by NETCEN for determination of total nitrogen, moisture content and acid digestible fibre content (cellulose, lignin and residual ash). Proteins, oils, fats and other insoluble material that would interfere with the lignin and cellulose determination were first removed by condensing the material with a detergent (hexadecyltrimethylammoniumbromide) - expressed as 'first reflux loss'. The remaining material was then subjected to a sulphuric acid digestion to determine cellulose (including hemicellulose) content. The resultant residue was dried and weighed and then ignited at 550 °C to determine the ash content. Lignin was determined by weight difference.

A further subsample was returned to WRç for chemical analysis using the sample preparation techniques and analytical methods tabulated in Appendix B1.

The two composite waste samples were also subjected to two deionised water leach tests:

- DIN test, a single step 24 hour shake test with unbuffered deionised water at a 10:1 liquid to solid ratio (DIN 38414-S4, October 1994);

- CEN granular leach test as proposed by the CEN Technical Committee 292 on the characterisation of waste (CEN 1994) - a two step 24 hour shake test with unbuffered deionised water at a cumulative liquid to solid ratio of 10:1 (six hours at 2:1, 18 hours at 8:1).

The experimental conditions for the tests are summarised in Appendix B2. The waste were leached in duplicate with test and leachant blanks. Leachates were analysed for a range of major ions, TOC and heavy metals, pH and electrical conductivity (Appendix B1). The CEN test was repeated to generate leachate that could be determined for selected heavy metals using a more sensitive analytical technique.

2.1.5 Biochemical methane potential

Gas production from a mixture of a seed material and the dried ground wastes was measured over 56 days according to the protocol presented in Appendix B3.

2.2 Groundwater sampling - Burntstump and Gorsethorpe landfill

2.2.1 Preamble

Monitoring boreholes at both sites have been installed after removing core for porewater profiling purposes. These are of classic design, finished to 6 inch diameter with slotted stainless steel screen below the water table and solid screen above with a bentonite plug at the base of the landfill to prevent the entry of leachate into the borehole. (Well constructions are presented in Lewin *et al.* 1994 and Young *et al.* 1994). The wide diameter and deep unsaturated zone necessitates the use of a pump with a relatively high flow rate (40 l min^{-1}) to remove 3-4 well volumes of water in a reasonable length of time. Hence a 4 inch diameter submersible pump has traditionally used at Burnstump and Gorsethorpe.

2.2.2 Burntstump

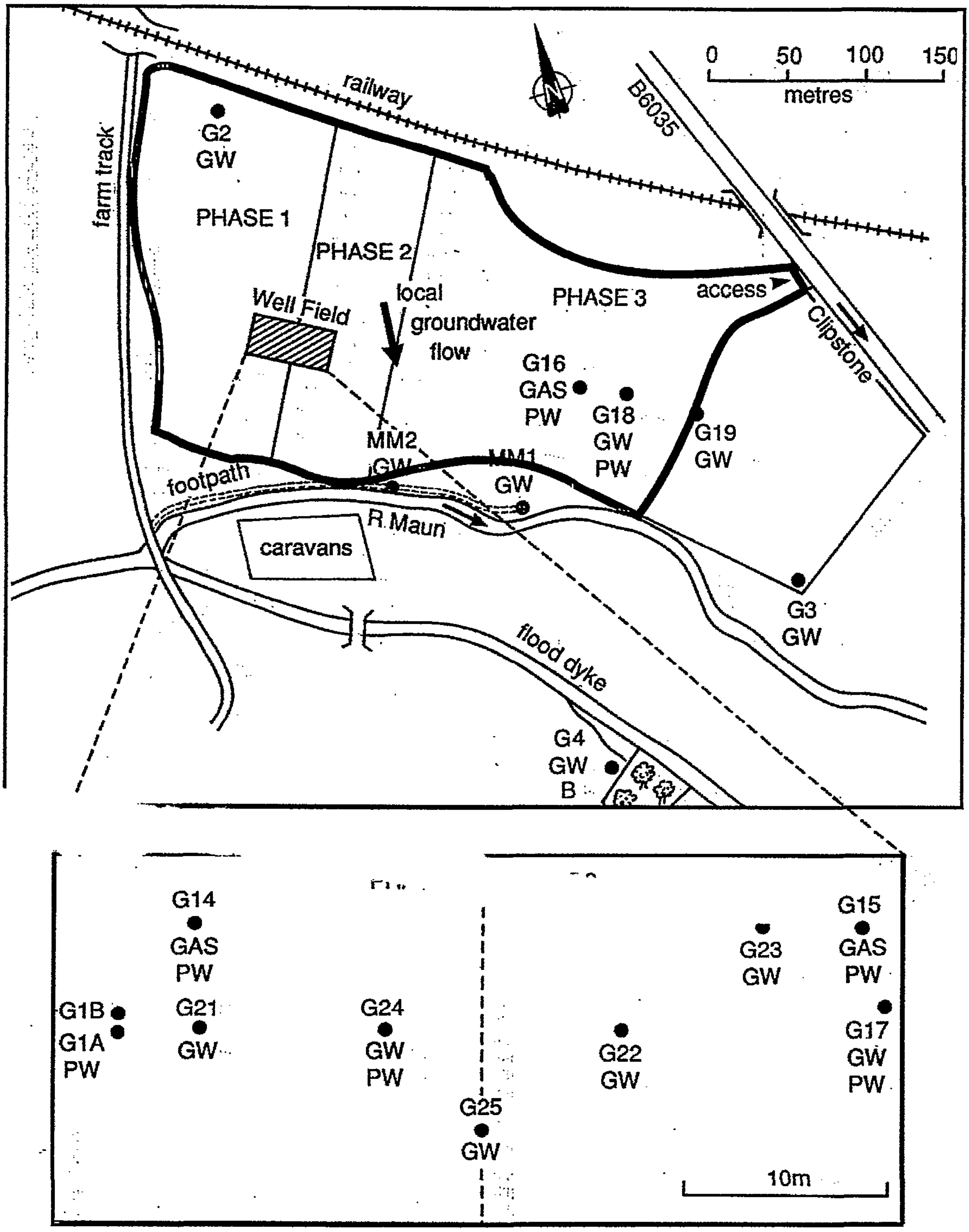
At Burntstump, groundwater monitoring boreholes have been installed below the old part of the site (B14) and around the southern perimeter of site (B11, B12 and B13) since 1991. The supply borehole at Cockliffe Farm, west of the landfill has also recently been included in the sampling programme to provide quality data of groundwater that could not have been affected by the landfill. Borehole locations and levels are presented in Figure 2.1.

Following completion of coring in Borehole B15 in 1994 (Section 2.1) a piezometer with a short screen intersecting the water table at approximately 56 m below ground level (bgl) was installed. Unfortunately it became damaged during the installation of the gas monitoring stem and withdrawal of the temporary casing and was subsequently backfilled with bentonite grout to prevent leachate from the wastes passing into the unsaturated zone via the piezometer.

2.2.3 Gorsethorpe

Routine monitoring

Long-term monitoring of boreholes at Gorsethorpe has included both bulk and depth samples since 1983. Boreholes G21-G25 (Figure 2.2) were designed with a series of slotted screens which can be isolated using a double inflatable 'packer', allowing discrete horizons to be purged and depth samples to be collected. This has allowed depth profiling of the aquifer below the three phases of the site to be conducted. The boreholes can also be sampled without the use of packers, purging and pumping the water in the traditional manner after lowering the pump a few metres into the water column. This generates a bulk groundwater sample which has been assumed to be representative of the average groundwater quality of the screened section of the borehole. Comparison of the bulk and depth samples from the same borehole allows the vertical variability of the hydraulic properties of the aquifer at that point to be assessed.



GW = Groundwater sampling borehole
GAS = Gas monitoring borehole
PW = Porewater results from cores

Figure 2.2 Site plan of Gorsethorpe landfill

Monitoring boreholes in the three phases of Gorsethorpe landfill were supplemented by the installation of Borehole G19 in October 1995. This was of nested piezometer design (Appendix A2) with a 6 m slotted screen straddling the water table (~19 m bgl) and a 3 m slotted screen between 37 and 40 m bgl. The slotted screens were separated by bentonite seals. Both piezometers were terminated with a 1 m sump to collect fines. The small diameter (50 mm) and short screen lengths result in a smaller volume of standing water to be purged prior to sampling than the traditional boreholes. Purging times are therefore significantly reduced even with the use of small diameter (50 mm) electrical submersible pumps. In addition it has been possible to use the pumps with flexible polyethythene tubing permanently rolled around a steel drum.

EC Landfill monitoring for *Life*

Gorsethorpe is one of the four English and Italian landfills which are being used as test-beds for research funded by the EC Landfill Monitoring for Life programme (UK work is co-funded by DoE/NRA). The project aims to use dedicated on-site monitoring equipment for the long-term monitoring of groundwater quality and compare different sampling methodologies to determine their impact on chemical determinations. Narrow diameter nested piezometers have been installed as an alternative to boreholes of a traditional design in order to compare the quality of data generated (see above).

The EC *Life* monitoring programme is not due to be completed until Summer 1996 and therefore many of the results are not yet available for comment. However, results of exercises conducted at Gorsethorpe to compare the effect of borehole pre-sampling purge volumes on groundwater chemistry are available. During the most detailed exercise a sonde containing the pH, Eh, conductivity and temperature probes was lowered into each borehole to determine the depth profile of these parameters. The depth profiling was repeated over a range of purging volumes. Some of the results and interim conclusions on the need for pre-sampling purging to be conducted are presented (Section 4.1.4).

2.2.4 Quality assurance measures

Groundwater samples have been collected at both sites following the in-house protocols presented in Appendix B4. After purging a volume of water equivalent to three or four times the water column within the borehole, sample bottles and lids were rinsed three times with the water and filled to the brim to exclude air. Pre-prepared sample bottles containing the appropriate preservative were filled to the required volume without rinsing. Samples collected for metal determinations were first passed through a 0.45 µm membrane filter before adding to a bottle containing the appropriate volume of acid preservative.

The flow rate was reduced to less than 2 litres per minute during the collection of samples for the determination of volatile compounds. The samples were collected in glass screw top vials with PTFE lined septa, with minimal agitation and with zero headspace as far as possible. Vials were transported and stored upside-down to minimise loss of volatiles.

Dissolved oxygen, pH, Eh and conductivity were monitored at the time of sampling using flow-through cells attached to the discharge line, except on the occasions when a submersible sonde was used (see above). On-site alkalinity determinations were carried out in 1995/96 using a portable titration kit.

All samples, including equipment and travel blanks and replicate samples as appropriate, were transferred to a cooler box for storage and transport and them to a refrigerator on return to the laboratory. The analytical suite was sufficient for an ion balance to be calculated for all samples using methods summarised in Appendix B1.

2.3 Landfill gas sampling - Burntstump and Gorsethorpe landfill

A series of gas ports has been installed at both sites allowing discrete samples to be taken within the waste and unsaturated sandstone to allow depth profiling of gas concentrations to be monitored. Monitoring well constructions are presented in Lewin *et al.* 1994 and Young *et al.* 1994. A further eight ports were installed in Borehole B15 in Summer 1994. The sampling lines are purged and samples are collected under suction into pressurised gas tubes (Young *et al.* 1994). The samples are returned to WRc for laboratory analysis by gas chromatography for bulk gases: methane, carbon dioxide, nitrogen, oxygen and hydrogen.

2.4 Modelling leachate generation - Burntstump and Gorsethorpe

The WRc water balance model (Blakey and Craft 1986) was modified to model landfill leachate production in 1989. In 1995 the concepts in the model were re-assessed and a significantly upgraded version developed.

The model now includes the following concepts which are all considered to represent key physical processes in the generation of leachate:

- the filling of cells at a monthly resolution;
- user-specified water content of the input waste;
- simulation of the landfill as a sequence of layers, each comprising one month's input;
- addition of each month's rainfall recharge to the top layer of the waste;
- capping of the landfill with consequent modification of rainfall recharge;
- settlement of the waste, dependent on age since placement;
- drainage of water from one layer into the next, dependent on water content of waste and the field capacity and saturation capacities of the waste; and
- calculation of leachate production on a monthly basis.

The background to the significance of each of these concepts is presented in Appendix C.

The model has been applied to the deeper, more recently completed phase of Burnstump landfill in which Borehole B15 was drilled (cell 7) and to Gorsethorpe. The raw data used in the modelling and the results of the Burntstump and Gorsethorpe models are also presented in Appendix C.

3. RESULTS AND OBSERVATIONS: BURNTSTUMP LANDFILL

3.1 Preamble

The results of the drilling investigation conducted in 1994 and the long-term monitoring at the site are presented in the following sections: waste characterisation (Section 3.1), waste leachability (3.2), porewater profiling (3.3), sandstone microbiology (3.4), cation exchange capacity of the sandstone (3.5), groundwater monitoring (3.6) and landfill gas monitoring (3.7). Monitoring data are presented in Appendices A-G.

In Section 5 the data are reviewed to demonstrate contaminant movement and attenuation below the site, and their implications for the future of existing non-contained landfills on the Sherwood Sandstone.

3.2 Waste characterisation

3.2.1 Gross waste composition - observations

The waste landfilled at Burntstump is a mixture of household, civic amenity and industrial waste. At the time of drilling it was noted that the waste was heterogeneous. The observations that were recorded both at the time of drilling and during sub-sampling of the waste samples for the waste assay and porewater extraction are presented in Table 3.1, to allow comparison with the waste compositional analysis.

3.2.2 Waste composition - analysis

The data are presented as follows:

- The full results of the waste assay, i.e. percentage of each size fraction by waste category and vice versa are presented in Appendix D1 and D2.
- The results of the acid digestible fibre (ADF) analyses conducted by NETCEN on the dried, ground waste materials are also presented in Figure 3.2. The data have been back-calculated to give concentrations on an 'as received' basis.

Table 3.1 Description of Burntstump waste samples

Depth bgl	Moisture content		Description
m	% wet weight	% dry weight [(1)]	
Material bulked into upper waste sample (1-14 m bgl)			
1.0	nd	nd	Sand and carpet, no household waste.
3.0	24.3%	32.1%	Mostly plastic bags, cobbles, rags, wood and cans.
5.0	45.7%	84.2%	Mostly plastic, soils and fines, wood, metal. Very wet.
7.0	nd	nd	Well degraded waste with little paper or plastic present.
9.0	46.4%	86.6%	Dry in appearance, little putrescible materials present - mostly cardboard, wood, some plastic and few fines.
11.0	nd	nd	Perched leachate at this level. Waste much wetter and warmer than overlying materials with a large proportion of plastics, textiles and tyres.
14.0	22%	28.2%	Well degraded - mostly soil, fines and wood with some plastic and paper (also tyres and chain link fencing)
Material bulked into lower waste sample (16-28 m bgl)			
16.0	nd	nd	Perched leachate. Mainly gravel and sand plus some sheet asbestos.
17.5	nd	nd	Very wet. Leachate saturated waste was like sludge (also large block of concrete).
18.6	44.4%	79.9%	Mostly tights, plastic bags, newspaper (print still legible - Jan 1987), fabric, wood, cans and plastic bottles.
20.8	nd	nd	plastic and paper dominant.
22.0	63%	170.3%	Mostly plastic bags, metal including cans, wood, glass and fines. Very wet.
23.7	nd	nd	Mixed refuse and broken bricks.
25.1	45.4%	83.2%	Household refuse - mostly rags, plastic, gravel and fines.
27.7	47.9%	91.9%	Mixture of putrescibles and plastics - mostly cardboard, plastic bags and fine. Very wet. Sand at bottom of sample.
27.8	nd	nd	Base of landfill (rock-face reached).

(1) The moisture content of waste on emplacement is generally reported to be 35% (dry weight). Field capacity of 45-55% (dry weight) can be achieved in moderately compacted waste before substantial leachate generation occurs.

- Table 3.2 also presents the mean volatile matter determined on four sub-samples and the mean biological methane potential of three sub-samples of each waste. The total gas produced has been converted to cubic metres of methane generated per tonne dry refuse on the assumption that 60% of the gas generated was composed of methane.
- The compositional analysis of the individual size fractions, totalled to indicate the gross composition of the bulk samples, the percentage size fractions and the ADF analysis are presented as pie charts for the upper waste sample in Figure 3.1. The data for each size fraction and waste category are also plotted. The same data are presented for the lower waste sample in Figure 3.2.
- The results of the chemical analyses of the upper and lower waste samples are presented in Appendix D3 and as a histogram in Figure 3.3.

Table 3.2 **Acid digestible fibres, biochemical methane potential and volatile matter**

Determinand	Upper waste sample (1-14 m depth)	Lower waste sample (16-18 m depth)
Moisture content (%)	33.6 (50.6 dry wt)	45.0 (81.8 dry wt)
Total nitrogen (% wet w)	0.70	0.47
First reflux loss (% wet wt)	18.1	25.5
Cellulose (% wet wt)	32.5	13.7
Lignin (% wet wt)	15.4	15.1
Ash (% wet wt)	4.2	3.6
Cellulose/lignin ratio	2.1	0.91
BMP(1) m^3 CH_4 $tonne^{-1}$ (dry wt)	55.8 ± 5.3	27.2 ± 4.6
Volatile matter (% dry wt)	76.6 ± 9.0	48.9 ± 4.8

Note: (1) Biochemical methane potential assuming methane content in the generated gas of 60% v/v.

The histograms in Figure 3.1 and Figure 3.2 demonstrate the heterogeneity of the waste samples with respect to both waste type and size of the waste components. The non-ferrous metal content of the upper and lower samples fall almost exclusively into the 20-40 mm and 10-20 mm size fractions respectively, and glass fragments are also generally quite small (>50% in the 10-20 mm fraction). The lower waste was evenly divided between the different size fractions whereas the upper waste sample contained almost 40% fines (<10 mm) and only 12% by weight was >80 mm.

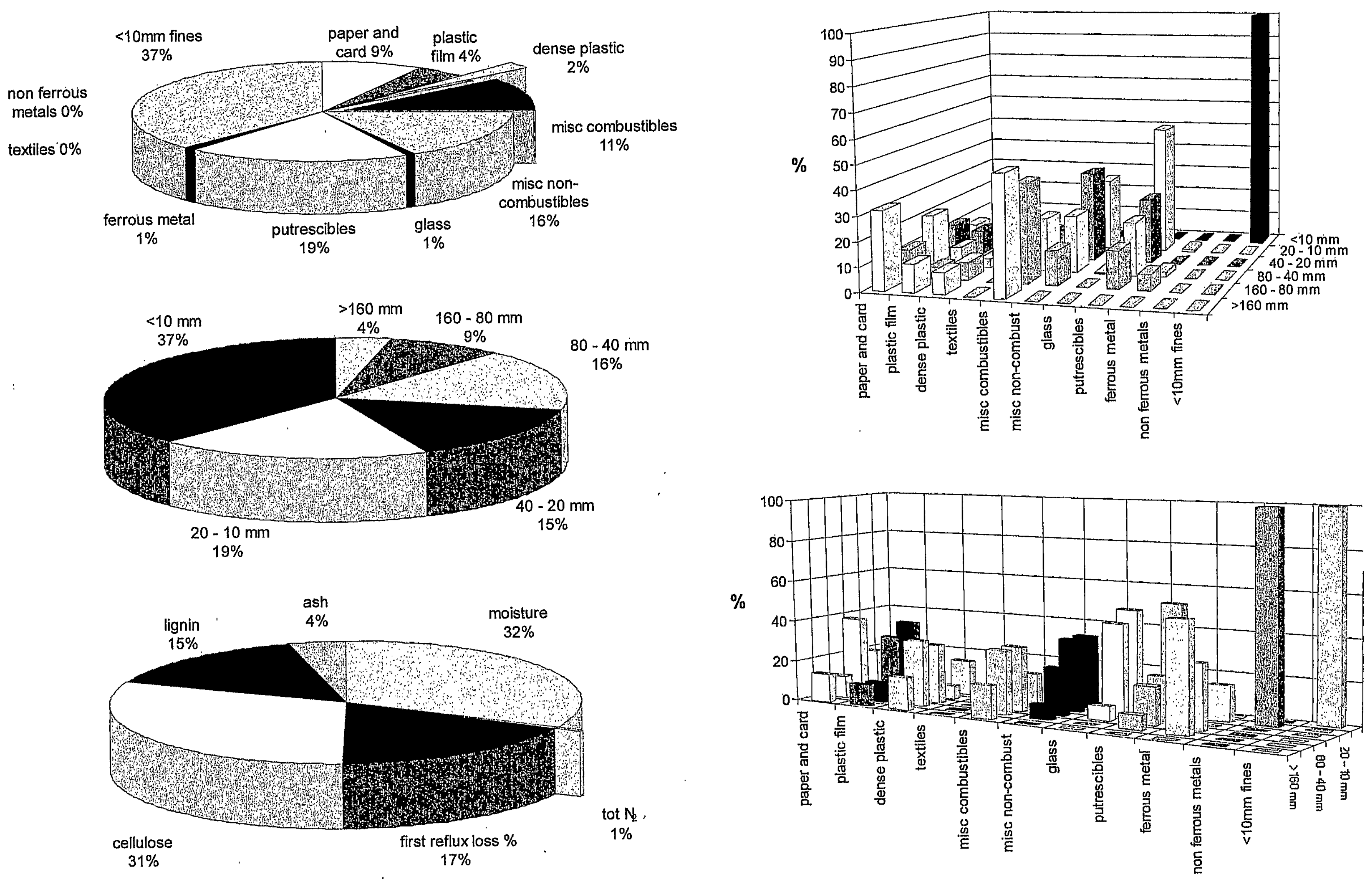


Figure 3.1 Characterisation of waste from upper half of Burntstump landfill

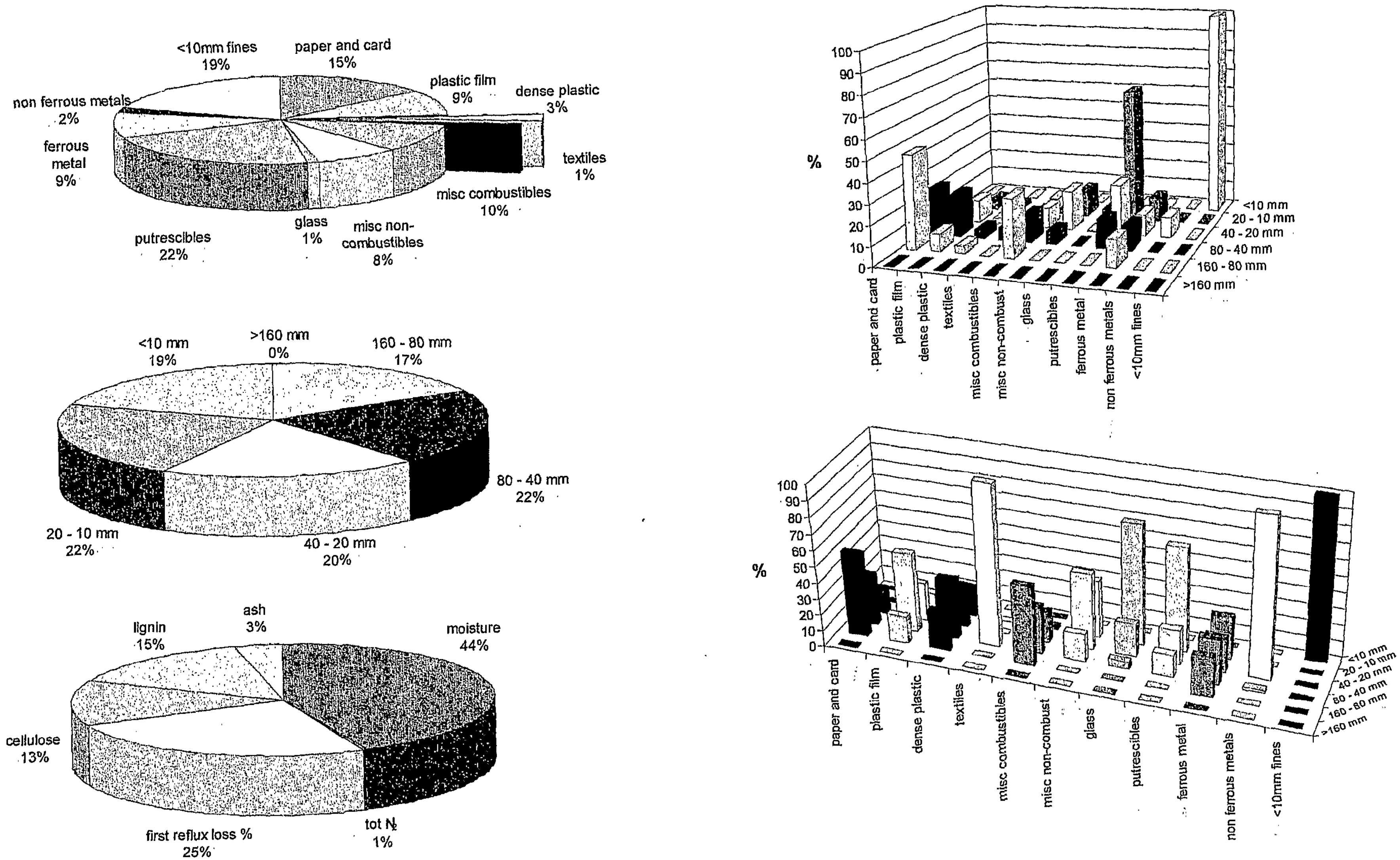


Figure 3.2 Characterisation of waste from lower half of Burntstump landfill

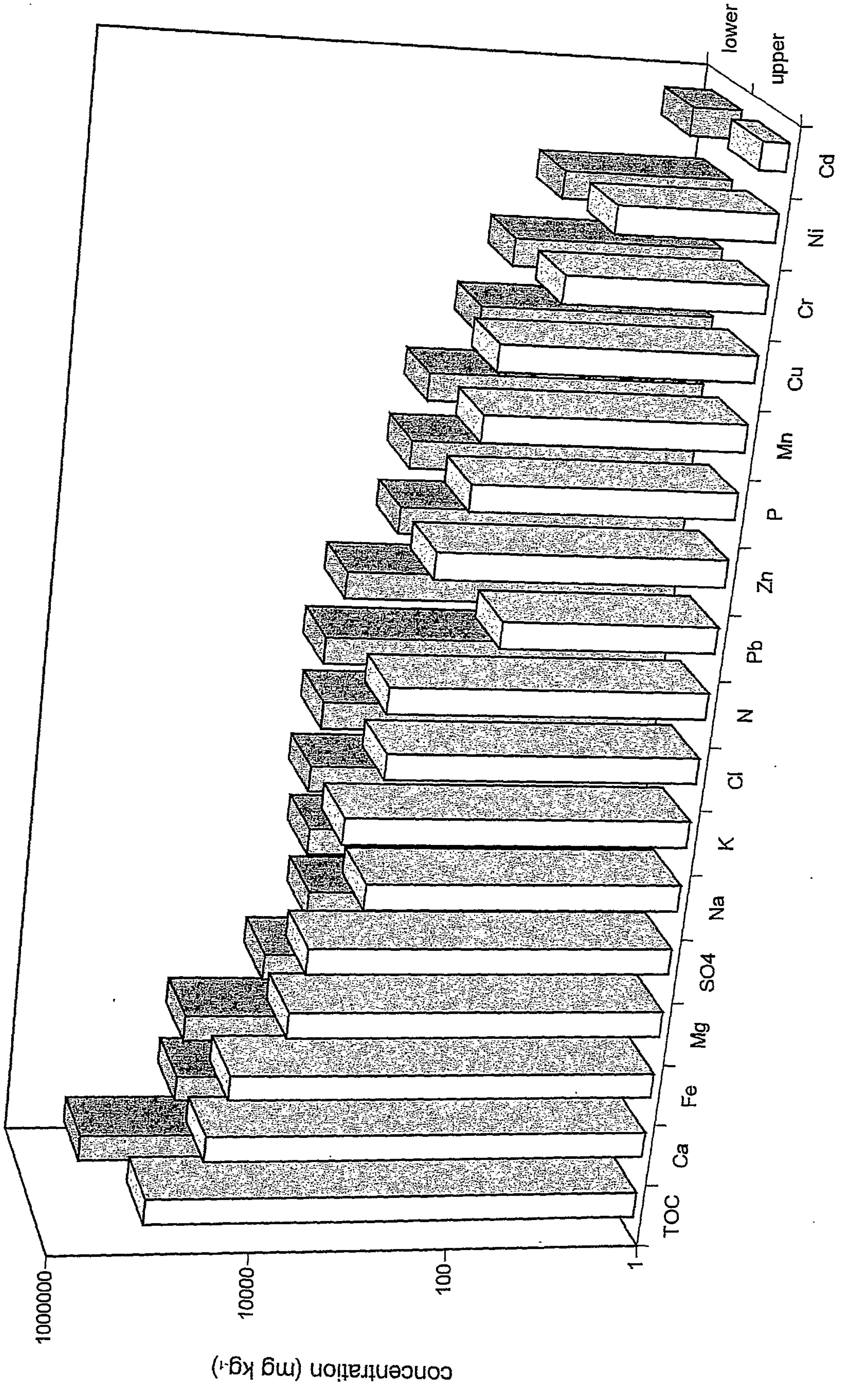


Fig 3.3 Elemental composition of landfilled wastes from Burntstump (B15, 1994)

This heterogeneity highlights the problems inherent in the collection of representative waste samples; a bulked sample can be biased both by inadequate mixing and by oversampling from one particular horizon which may be dominated by one particular waste type.

The chemical data from such a small number of samples must be viewed with care as the wastes were very heterogeneous with respect to certain heavy metals, Cu in particular. However, the replicate determinations of **major** elements were reasonably consistent and the original samples quite large (300 kg in total), allowing gross differences between the two bulked samples from the upper (1-14 m) and lower (16-27 m) part of the landfill to be identified. The major elements in both waste samples were TOC (10-30% w/w, Ca and Fe at 2-3 % w/w, followed by Mg, SO_4, Na, K, Cl and N (0.2-0.6% w/w); Si which would be expected to be another major component was not determined.

The following observations can be made about the **lower** waste sample (16-27 m bgl):

- the moisture content of the lower sample was in excess of field capacity and is considered to be saturated (82% dry weight);
- the lower waste contained 28% w/w TOC, some 2 to 3 times higher than the upper sample. Its pH was 8.0;
- it contained a slightly higher proportion of paper and card, plastic film and dense plastic than the upper waste;
- the ferrous and non-ferrous metal content was also higher at 9% and 2%, than in the upper waste sample (1% and zero respectively);
- this higher metal content was confirmed by significantly higher levels of Pb (by a factor of 20), Fe and Cd (by factors of 2-3);
- other elements present at higher levels in the lower waste sample were: N, Na, P (by a factor of 1.5 - 2), Mn and Ni (by factors of 1.3-1.5). Cl, Ca, K, Mn, Zn and Cr were only approximately 10% higher than in the upper waste sample;
- the distribution of the size of the waste particles was fairly uniform (17-22% for each category).

The data indicate the following about the **upper** waste sample (1-14 m bgl):

- the moisture content of the bulk upper waste sample was within the range considered to represent field capacity (50.6% dry weight);
- the mean pH of the upper waste samples was 7.6. It had a moisture content of 34% and a TOC of just 10.5% w/w;

- the volatile matter of the upper waste samples (48.9%) was nearly double that of the lower waste (27.2%);
- in comparison with the lower waste sample it contained a significantly higher proportion of fines (37% cf 19%) and miscellaneous non-combustibles (16% cf 9%);
- of all the elements determined, only SO_4 was present at a significantly higher levels in the upper waste (by a factor of 2) while Mg was just 10% higher.

In some respects the bulked wastes were very similar, for example both the upper and lower portions of the waste contained approximately 20% putrescibles, 10% miscellaneous combustibles and a very small proportion of glass (1%) and textiles (0-1%). Mercury was not detectable (<2.5 mg kg^{-1} in either sample).

The lignin (15%) and ash contents (4%) of the two samples were very similar. However, the cellulose to lignin ratios of the upper and lower wastes were 2.1 and 0.9 respectively. The cellulose content of the upper waste was greater than twice that of the lower waste, despite a lower proportion of paper and card, which would tend to indicate that the lower waste has undergone a greater degree of (cellulose) degradation than the upper waste. This is supported by the lower biochemical methane potential of the lower waste sample in comparison with the upper waste sample, 55.8 and 76.6 m^3 methane/tonne respectively.

Table 3.3 summarises the significant similarities and differences between the two waste samples investigated.

3.3 Waste leachability

The results of the leaching tests (both CEN (1994) and DIN (1984)) as leachate concentration in mg l^{-1} are presented in Appendix D4. Leaching test data can only be directly compared after conversion to mg kg^{-1} which makes an allowance for the different solid to liquid ratios employed during the tests. Leached concentrations (i.e. the mass of the element released per kg dry residue tested) are presented in Appendix D5.

Porewater concentrations (Section 3.4) have also been corrected for the moisture content of each waste horizon, and the values averaged to give a mean porewater concentration in mg kg^{-1} for the upper and lower waste samples. These data are plotted with the mean elemental composition of the wastes as determined by chemical analysis; major elements in Figure 3.4 and heavy metals in Figure 3.5.

Table 3.3 Summary of the main characteristics of the Burntstump wastes

Characteristic	Upper waste 1-14 m bgl	Lower waste 18.5-27.7 m bgl
Waste composition	• 33% moisture (50% dry weight) • 1% ferrous/non ferrous metals • 2x higher fines and misc. non-combustibles • only 30% >40 mm, 40% <10 mm	• 44% moisture (79% dry weight) • 11% ferrous/non metals • higher plastic, paper/card content • even distribution from <10 to 160 mm, 40% >40 mm
Elemental composition	• 2x higher SO_4 • slightly higher Mg • TOC = 10% w/w	• Pb 20x higher • Fe, Cd 2-3x higher • N, Na, P, Mn, Ni 1-2x higher • TOC 30% w/w
Acid digestible fibres, biochemical methane potential	• cellulose 33% • cellulose/lignin 2.1 • volatile matter 27.2% • cellulose/volatile matter ratio - 0.66 • 77.6 m^3 CH_4/dry tonne	• cellulose 14% • cellulose/lignin 0.9 • volatile matter 48.9% • cellulose/volatile matter ratio - 0.50 • 55.8 m^3 CH_4/dry tonne
General	Dryer, less cellulose has degraded, higher potential for generating methane.	Saturated, less cellulose remaining, lower potential for generating methane, higher levels of most ions

The data show that while the major ions were relatively easily released during leaching tests, metal release under deionised water conditions was up to 2-4 orders of magnitude lower than would be released during an acid digestion. Most heavy metals were not determined in the porewaters and were generally not detectable in the dilute DIN test leachates.

No consistent pattern was demonstrated with respect to leaching behaviour of the wastes in comparison with the quantities concentrations in the solid residues and this is probably due to the small number of samples and heterogeneity of the wastes.

As the DIN and CEN leaching tests are conducted without pH control the final pH of the leachates generated by these tests is always controlled by the buffering capacity of the waste material. Figure 3.6 presents leachate concentrations from the first step of the CEN test on a large number of residues from the incineration of municipal solid waste. The data have been collated by the International Ash Working Group and added to by results produced by WRc (Lewin *et al.* 1996).

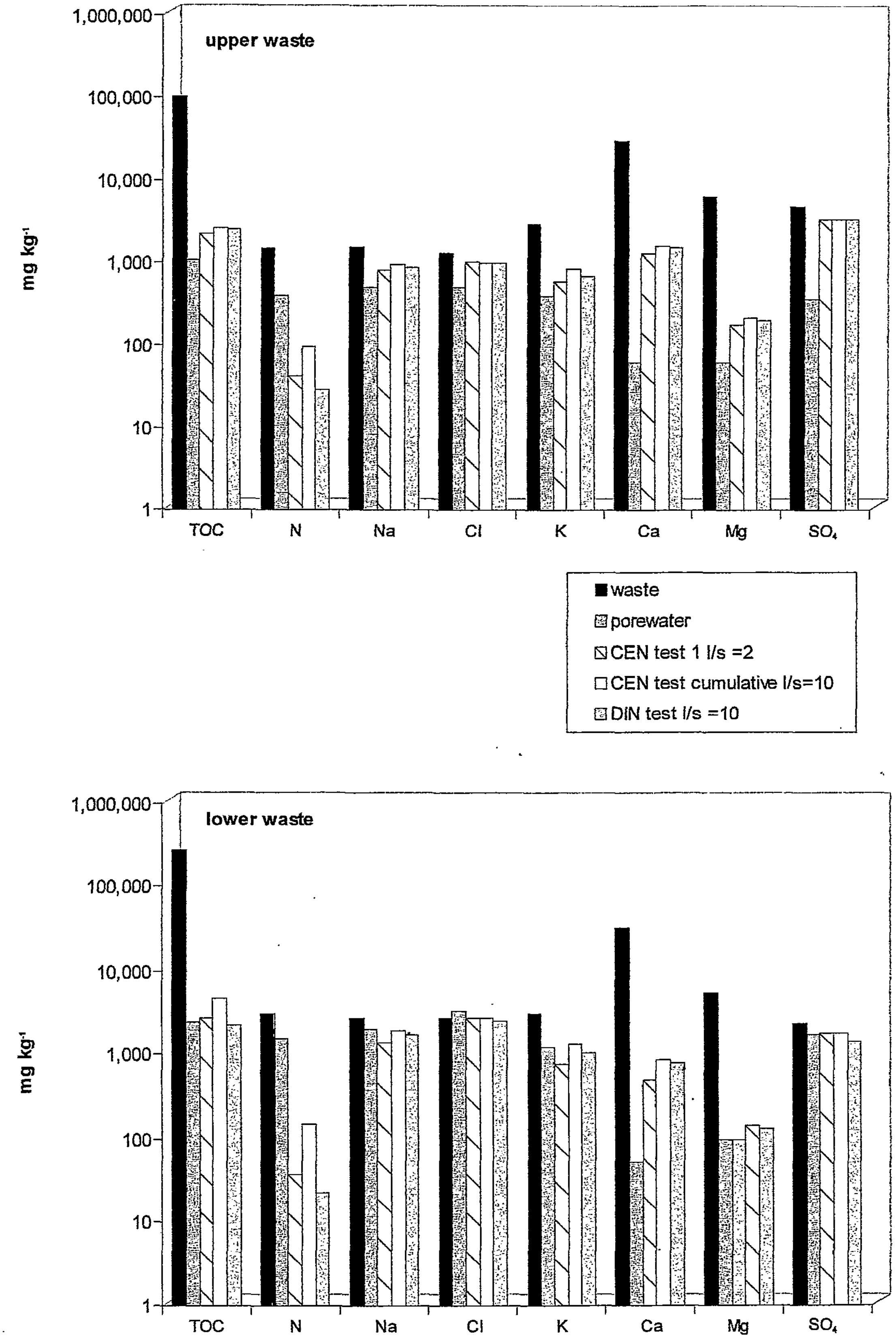


Figure 3.4 Comparison of elelmental composition of wastes with porewater and leachate concentrations: major elements (mg kg^{-1} dry weight).

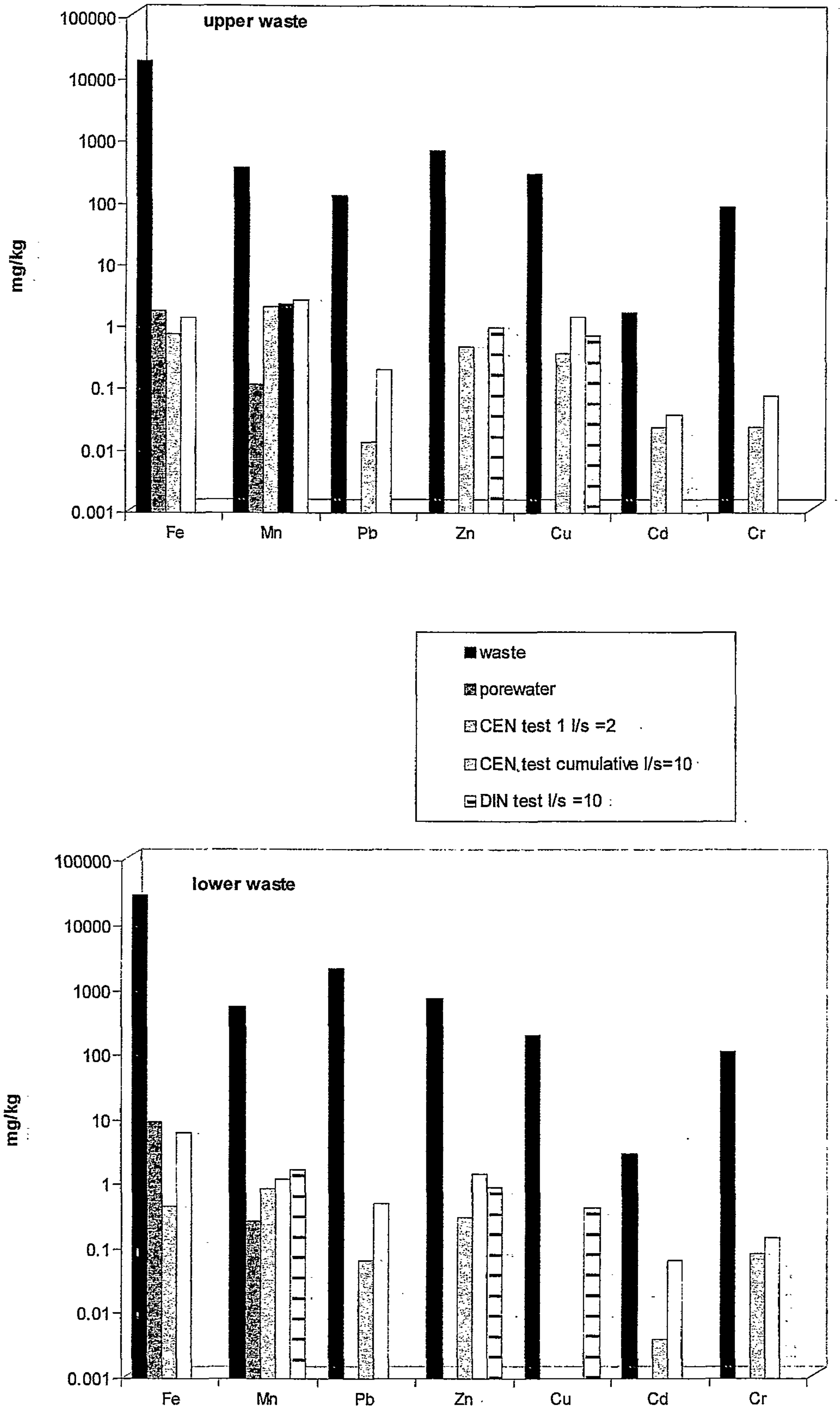


Figure 3.5 Comparison of elemental composition of wastes with porewater and leachate concentrations: heavy metals (mg kg^{-1} dry weight)

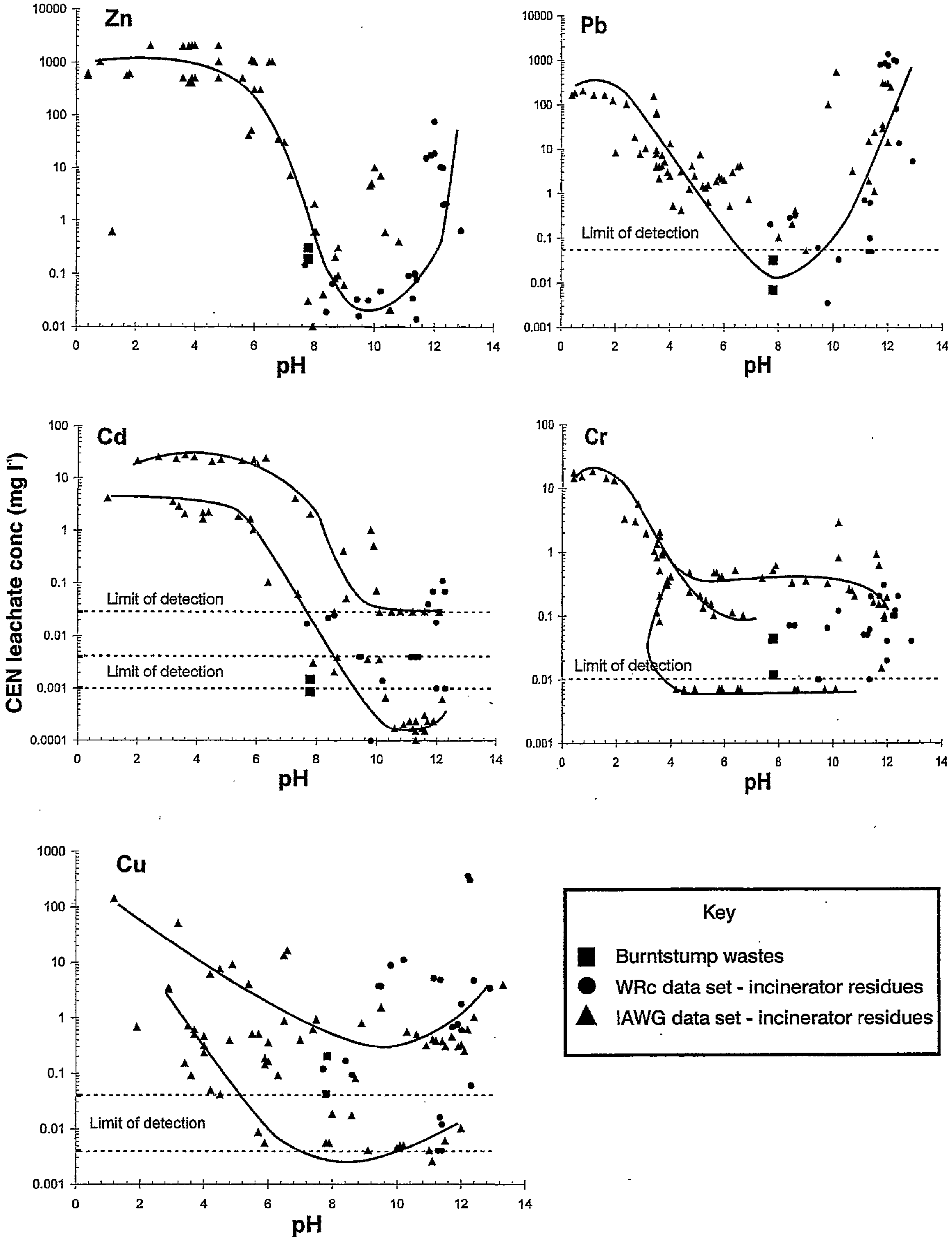


Figure 3.6 Leaching behaviour of the Burntstump wastes in comparison with incineration residues

Although detection limits obscure the trends for some parameters, the Burntstump wastes generally sit within the scatter of the datasets. The sample from the lower half of the landfill is consistently represented by the upper of the two Burntstump waste data points. The data indicate that, with the exception of copper release (which is controlled largely by complexation with organic matter), leachability of heavy metals is controlled by the final pH of the leachate. At the pH conditions which prevailed during the leaching tests, metal solubility is at a minimum.

As the Burnstump leachate pH values of 7-8 are relatively representative of landfill leachate, and consistent with porewater pH (Section 3.4), this would suggest that release of metals from the wastes in Burntstump landfill would be minimal unless *in situ* leachate pH was significantly raised or lowered.

3.4 Porewater profiling

Porewaters were extracted from wastes and sandstone from the landfill borehole B15 and an off-site borehole (sandstone only) in Summer 1994 as described in Section 3.1.2.

The results of the porewater analyses are presented as follows:

- full data from boreholes B15 and B16 are tabulated in Appendix E1 and E2;
- profiles of the waste and sandstone from the landfill borehole, B15 are plotted in Figures 3.7 and 3.8;
- the average porewater concentration for waste from the upper and lower halves of the landfill, the unsaturated sandstone below the waste and the unsaturated sandstone from the background borehole are presented in Table 3.4.

Samples considered to have been contaminated by drilling foam during drilling have been excluded from the plots and calculation of the average porewater concentration. (See Appendix D3 for explanation.)

The data demonstrate the following general trends:

- the leading edge of the advancing leachate front as defined by a 2-3 order of magnitude decrease in leachate concentration, lay within the region of sandstone where core recovery was not possible (28-36 m bgl);
- major ions were present at similar levels to those observed in porewaters from wastes elsewhere on site;
- major ions concentrations were generally higher in porewaters from the lower half of the landfill than the upper half reflecting the elevated concentrations in the solid waste samples (see also Figure 3.5);

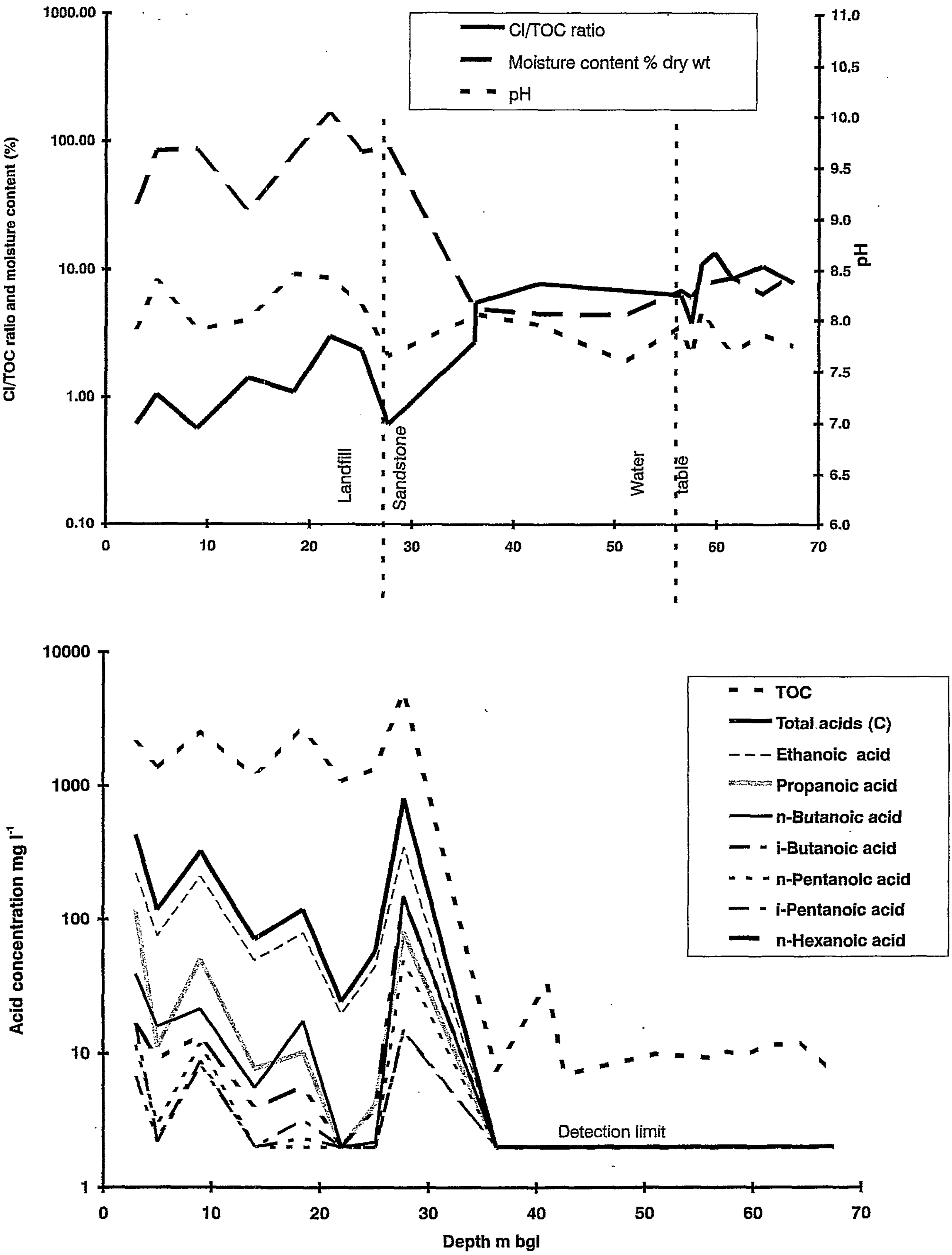
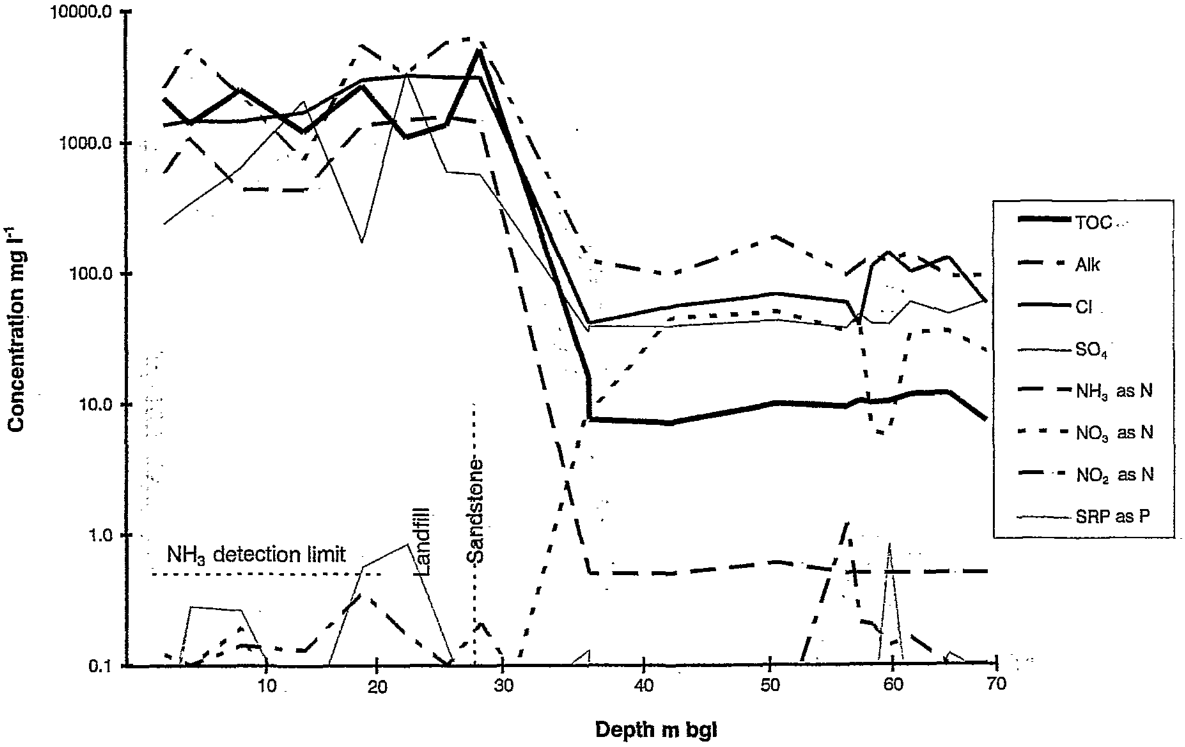


Figure 3.7 Porewater chemistry of Borehole B15 (1994) - general parameters and carboxylic acid concentrations



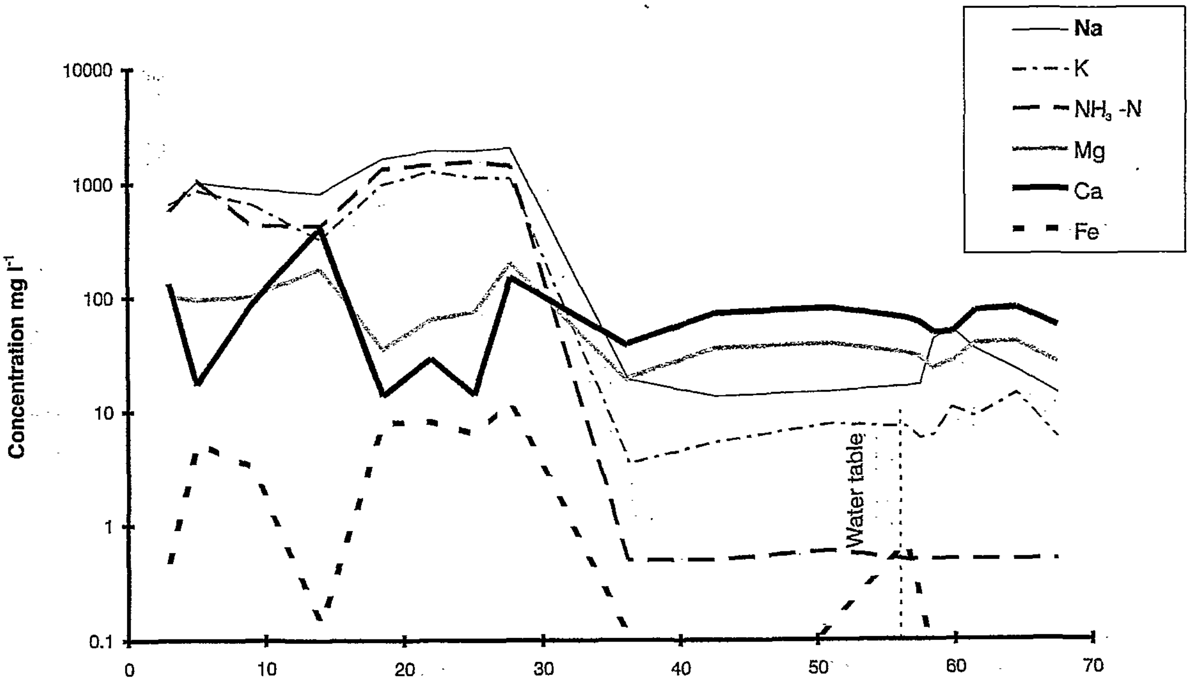


Figure 3.8 Porewater chemistry of Borehole B15(1994) - major ions

- the chemistry of the unsaturated sandstone below the waste was very similar to that in the off-site borehole and would appear to have been unaffected by the landfill leachate;

- the porewater from the saturated zone contained levels of Cl, Na, SO_4 and NO_2-N which were elevated above background.

Table 3.4 Average concentration of porewaters from the landfill borehole B15 and 'background' borehole B16

Determinand	Concentration in mg l^{-1} except conductivity ($\mu S\ cm^{-1}$) and pH.			
	B15 Upper waste (1-14 m)	B15 Lower waste (17-27 m)	B15 Sherwood Sandstone (36-68 m)	B16 Sherwood Sandstone (25-43 m)
pH	8.1	8.2	7.9	7.7
Conductivity	8510	16 162	651	686
TOC	1813	2 575	10	14
Total VFAs (C)	237	254	<2.2	<2.2
Cl	1482	3 123	77	160
SO_4	213	126	45	25
NH_3-N	632	1 454	0.09	0.49
NO_3-N	0.08	0.06	28	9.8
Alkalinity ($CaCO_3$)	3342	5 224	120	86
Na	844	1 898	25	16
K	644	1 132	7	9
Mg	121	95	30	25
Ca	164	52	61	81
Fe	2.3	8.7	0.12	0.09
Mn	0.25	0.30	0.09	0.07

With respect to individual parameters:

- porewater pH varied between 7.5 - 8.5;

- the porewater profiles of Cl, Na, K and NH_3-N and Ca, Mg and SO_4 followed similar trends whereas Ca and total Fe behaved in an opposite manner;

- chloride levels were relatively constant in the lower part of the waste, TOC was more variable;

- ammoniacal nitrogen levels were three orders of magnitude lower in the sandstone than the wastes (most ions show only 2 orders of magnitude decrease). Conversely porewater nitrate levels were approximately 3 orders of magnitude higher in the sandstone than the wastes and probably a result of agricultural activity prior to filling. The change-over between ammoniacal and oxidised nitrogen dominance of the porewaters was very marked (Figure 4.1);

- high chloride levels were observed in porewaters from the background borehole and may be due to road salt ingress;

- carboxylic acid concentrations in the wastes were dominated by ethanoic acid (up to 83% of the total carboxylic acid concentration in the lower wastes). The acids were not detectable in the sandstone core;

- average porewater concentrations from the wastes were similar to leachates generated by 'aged wastes', and/or those with high moisture contents (Appendix E1, Waste Management Paper 26a).

3.5 Analysis of sandstone core

3.5.1 Microbial activity

The presence or absence of sulphate reducing bacteria and the total viable bacteria counts are tabulated in Appendix E4.

Scatter plots presenting the distribution of the total viable bacteria in the sandstone from B16 (6-50 m bgl) and B15 (36-71 m bgl) are presented in Figure 3.9. Cores in which the presence of sulphate reducing bacteria was determined by a qualitative test are indicated by a symbol close to the x axis.

No consistent pattern was observed in the distribution of viable aerobes in the unsaturated sandstone - the bacteria counts fluctuated over 6-7 orders of magnitude throughout the profile. However, a general reduction in the counts in B16 core was apparent as the water table was approached, down from 10^3 - 10^4 at 6-36 m bgl to <10 between 40-46 m bgl.

In comparison bacteria counts in the B15 core (36-71 m bgl) were generally in the 10^3-10^6 range. On average the range of bacterial counts was 2-3 orders of magnitude higher in the sandstone from B15 (below the landfill) than in the 'background' hole (B16).

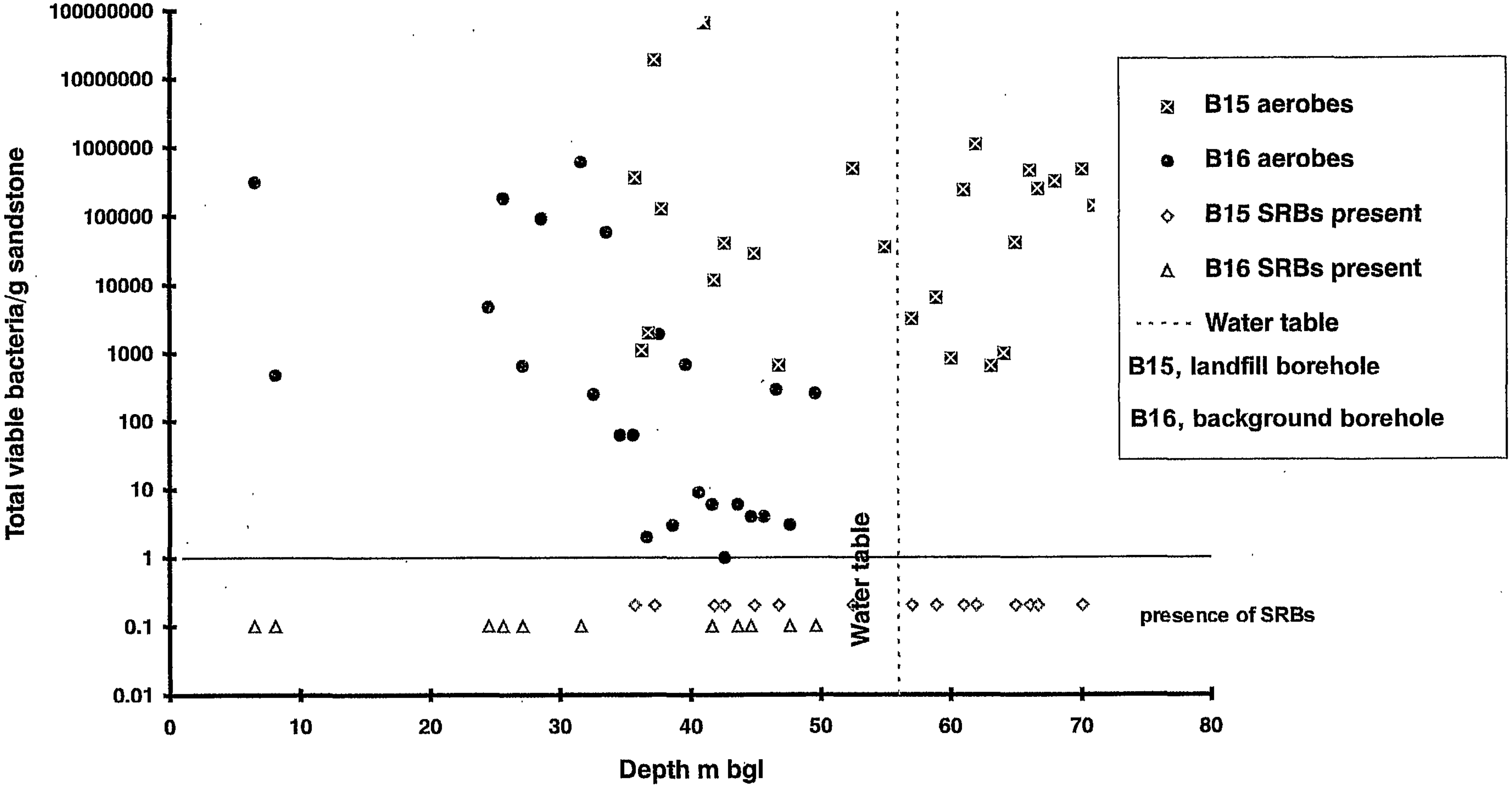


Figure 3.9 Sandstone microbiology - total viable count and presence of sulphate reducing bacteria

Previous studies have demonstrated a rapid reduction in viable bacteria in a low porewater pH zone at the leachate front, the population re-establishing itself once neutral pH conditions have returned behind the leachate front. Core could not be collected between 28 and 36 m bgl and therefore the precise location of the leachate front cannot be determined and its local impact on the bacterial population assessed. However, the pattern observed in B15 and B16 is consistent with the observations from the porewater chemistry profile that the leachate front has yet to penetrate a significant distance (i.e. >8 m) into the unsaturated zone.

Sulphate reducing bacteria were present within most of the core samples from B15, however they are absent between 33 and 39 m bgl in B16.

3.5.2 Cation exchange capacity

The results of the determination of cation exchange capacity and exchangeable ions in the sandstone from B15 and B16 are presented in Table 3.5.

Table 3.5 Cation exchange capacity and exchangeable cations of sandstone samples from B16 and B15 (dry matter)

Determinand	Exchange capacity (meq/100 g sandstone)			
	B16: 24.5-25.5 m	B16: 40.6-41.6	B15: 67-68 m	Mean
Cation exchange capacity (CEC)[1]	2.10	1.96	1.72	1.93
Exchangeable Ca	1.52	1.73	1.37	1.54
Exchangeable Mg	0.36	0.28	0.21	0.28
Exchangeable Na	0.16	0.06	0.14	0.36
Exchangeable K	<0.1	<0.1	<0.1	<0.1
Exchangeable Mn	0.021	0.020	0.012	0.018
Ammonia (N) (mg kg^{-1})	0.6	0.9	0.6	0.7

[1] Ammonium acetate extraction method (ADAS Method 16)

In previous investigations a low CEC (<4 meq/100 g) had been estimated based on determinations in Sherwood Sandstone in the Bromsgrove area (Lewin *et al.* 1994, Young *et al.* 1994). The results demonstrate that the cation exchange capacity is lower than was previously assumed, but consistent with a retardation factor of 50% for ammoniacal nitrogen compared with a mobile, non-sorbed species such as chloride.

3.6 Groundwater monitoring

3.6.1 Groundwater quality

Groundwater monitoring data collected at Burnstump since 1991 are presented in Appendix F.

Immediately after drilling the boreholes elevated levels of TOC and metals were recorded in the groundwater. Since then iron, manganese and zinc have been recorded at 10-100 $\mu g\ l^{-1}$ levels in B12-B14. No other heavy metals were detectable in most boreholes. With the exception of Borehole B11 which in 1995 still showed evidence of grout contamination (it has been sampled only twice since drilling) the boreholes have settled down to produce more consistent groundwater quality characteristics.

Major ions are plotted as percentage milliequivalents as a piper diagram (Figure 3.10). As no temporal trends are evident in the more recent analyses, the data from each borehole have been plotted as single symbols for clarity.

The major ion characteristics of groundwater from each borehole appear to be fairly distinctive. There is a general trend apparent in major ion chemistry from Cockliffe Farm the upstream 'background' borehole (calcium sulphate dominated), B14 below the older part of the site to the north of the landfill and B13 close to the south east perimeter, to B12 the most southerly borehole (calcium carbonate dominated). However, the dissolved ion content of these sandstone groundwaters is relatively low, with electrical conductivities generally <0.5 $mS\ cm^{-1}$. Therefore quite small differences in major ion chemistry can cause these apparent trends. The value of these data is as a baseline against which groundwater quality in the future can be compared. Temporal groundwater quality trends, particularly in the downstream boreholes, may become apparent with continued monitoring.

In March 1995 samples were collected from Borehole B12 and the 'background' groundwater source at Cockliffe Farm for the determination of a range of brominated and chlorinated solvents (Appendix F2) Of the nine solvents only bromodichloromethane and dibromochloromethane were detected (0.5 $\mu g\ l^{-1}$) in the background borehole. None of the brominated solvents were detectable in the landfill borehole, B12, however, tetrachlorethene (PCE) was determined at 5 $\mu g\ l^{-1}$ and trichloroethene (TCE) and 1,1,1-trichloroethane (TCA) were just detectable (0.4 and 0.6 $\mu g\ l^{-1}$ respectively).

Carboxylic acids have not been detected in any of the boreholes around Burnstump on the three occasions that they have been determined (Appendix F3).

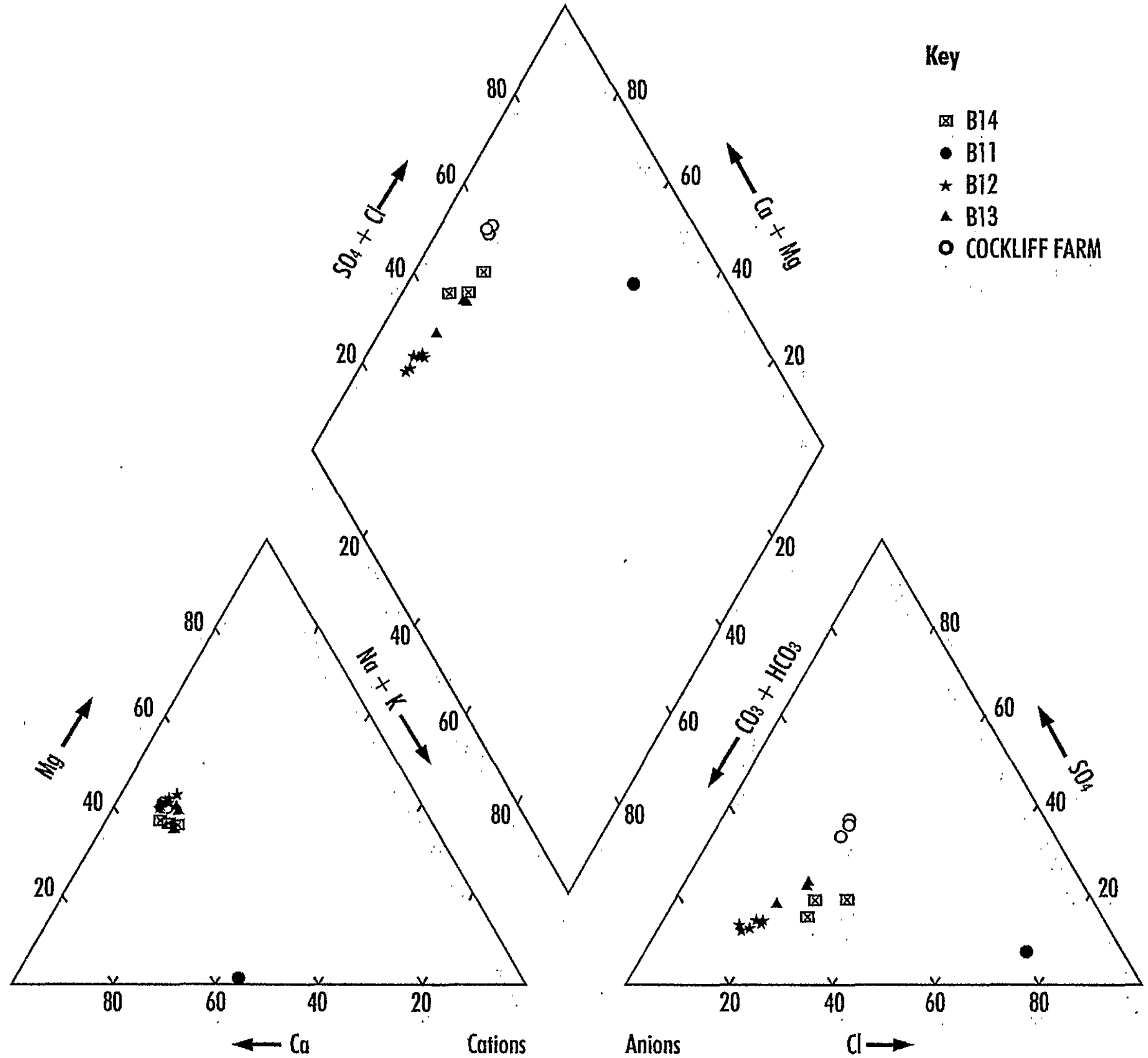


Figure 3.10 Piper diagram showing variations in the ratio of major ions in groundwater below Burntstump landfill (1991 - 1995)

3.6.2 Groundwater levels

Boreholes on and south of the site were levelled in Spring 1995. The top of the casing or the manhole cover, as appropriate, was taken as datum point. The levels are shown on the borehole location plan (Figure 2.1) and relative depth to groundwaters (m AOD) are presented with the groundwater quality data in Appendix F1. Although the number of points are limited, rest water levels in metres above ordnance datum in September/October 1995 of 54.86 (B14), 53.48 (B11), 52.41 (B13) and 51.27 (B12) tended to confirm that groundwater flow below the site is in a south-easterly direction.

3.7 Landfill gas

3.7.1 Within and below the shallow fill (B7-B9)

Landfill gas monitoring has been conducted in and immediately below the wastes in the older, shallower part of the fill to north of the site since 1986. The data are plotted and tabulated in Appendix G to illustrate gas quality trends with depth and time.

The data represent an almost continuous run of 11 years commencing nearly a decade after filling ceased and show the following:

- Landfill gas quality near the surface has been extremely variable. The area was restored with soils rather than an impermeable cap, and the gas quality fluctuations appear to have been in direct response to air ingress through the cover materials. Barometric pressure readings have been recorded before and after each monitoring exercise since 1990. Aerobic conditions coincided with high barometric pressure whereas the levels of methane and carbon dioxide tended to be greatest when low barometric pressure was recorded;

- Landfill gas concentrations were at a maximum within the wastes and a couple of meters below the site in 1986-97, indicating that gas production peaked approximately eight years after disposal operations in that part of the site ceased. Levels of 65% CH_4 and 32% CO_2 by volume were recorded at this time;

- Landfill gases had already reached 25m below the base of the site when monitoring began, albeit at relatively low levels (~5% CH_4 and CO_2);

- Landfill gas was still being generated within the waste in 1995 at levels of 50-55% CH_4 and 20% CO_2 by volume, however gas flux into the unsaturated zone was waning. Landfill gas components in the unsaturated zone below 21 m bgl have decreased markedly in the 1990s.

- The marked drop in landfill gas concentrations in 1992 was originally attributed to air-flush drilling in the vicinity (Lewin *et al.* 1994). However, continued monitoring has shown that anaerobic conditions in the unsaturated zone have not returned, with the exception of a single event of high levels in all ports in late 1995. The reduction of landfill gas levels in 1991 was in direct response to the installation of an additional 26 gas extraction wells in and around the old area of the site in November 1991. Gas quality within the wastes stayed at a relatively constant level however the gas extraction system has maintained negligible levels of methane within the upper 10 m of the sandstone between 1992 and 1995, although CO_2 levels of 1-15% have still been recorded.

- In late 1995 landfill gas concentrations were again elevated but had returned to background level in January 1996. This 'blip' was caused by a breakage in gas lines first noticed in October 1995. Lateral migration occurred while remediation work was carried out, however the system was fully functional again by December as indicated by the final monitoring exercise in January 1996.

3.7.2 Deeper phase (B15)

Monitoring within and below the deeper, more recently filled part of the site (Cell 7) commenced after the construction of Borehole B15 in 1994. Filling was carried out in the late 1980s and by 1994, methane levels were already at 50-60% within the wastes (Appendix G). In 1996 and methane and carbon dioxide were recorded at 4% and 15% respectively 47 m below the surface, some 20 m below the base of the landfill. Landfill gas has not been actively extracted in this area of the fill due to poor quality yield and air ingress through the gas lines.

3.7.3 Downgradient of site (B13)

Monitoring has also been conducted downstream of the site on the south-eastern perimeter since 1990 (Appendix G) The only evidence of lateral landfill gas migration is the presence of carbon dioxide at 1-2.5% by volume levels to 6 m bgl and occasionally to 1.5% by volume to 24 m bgl. However, methane has yet to be detected in any of the monitoring ports.

3.8 Modelling

The modified water balance model has been applied to Cell 7 of Burnstump landfill, i.e. the 27-30 m area of wastes which were filled in the late 1980s and in which borehole B15 was installed in 1994. The parameters which have been incorporated into the model are presented in full in Appendix C and include the filling rates for that part of the site (1987-1990), capping functions, a drainage rate constant of 0.75 litres per month and a total final settlement of 20%.

Cumulative leachate production for the cell to 1994 was estimated to be 34 000 m^3 equivalent to penetration of 2.8 m into the unsaturated sandstone (Figure 3.11). Although the extent of leachate penetration could not be determined from the drilling of Borehole B15 due to poor ground conditions, it is known that leachate has not migrated greater than 8 m below the base of the site. Some penetration would be expected as the lowest wastes were saturated. The results of the leachate model is clearly not in conflict with this observation.

However, when the model was rerun with a settlement factor of zero, the predicted leachate generation was $<1500\ m^3$. Such a figure would be insufficient to allow any leakage into the sandstone, inconsistent with the field observations. Clearly an allowance for settlement must be made for in cells where the wastes are of this order of thickness.

The refined model predicts that cumulative leachate production will be ~45 000 m^3 in 2000, assuming a porosity of 0.2 and the absence of fissures, this is equivalent to penetration of 3.7 m into the sandstone.

Table B3 Amounts of test and reference substance added to serum vials

Vial number	Test substance	Amount of test sample required (g or ml)
1-3	Control	Zero
4-6	Control	Zero
7-9	B1	0.5
10-12	B2	0.5
13-15	Sodium benzoate	5 ml

B3.6.2 Reference chemical addition

Sodium benzoate was used as the reference compound. A stock solution of 1 g C per litre was prepared (pH 7.0 ± 0.2). 100 ml of the stock solution was placed into a serum vial of 160 ml capacity. The solution was initially degassed for a period of 10 minutes with nitrogen prior to addition to test bottles. 5 ml of the reference compound was then be added by syringe to the stoppered test vessel prior to incubation.

B3.6.3 Experimental design

Addition of test or reference chemicals will be performed in the following fashion:

Table B4 Experimental Design

Bottle Number	Test Compound Addition	Analysis
1-3	Control	pH
4-6	Control	Pressure
7-9	B1	Pressure
10-12	B2	Pressure
13-15	Sodium benzoate	Pressure

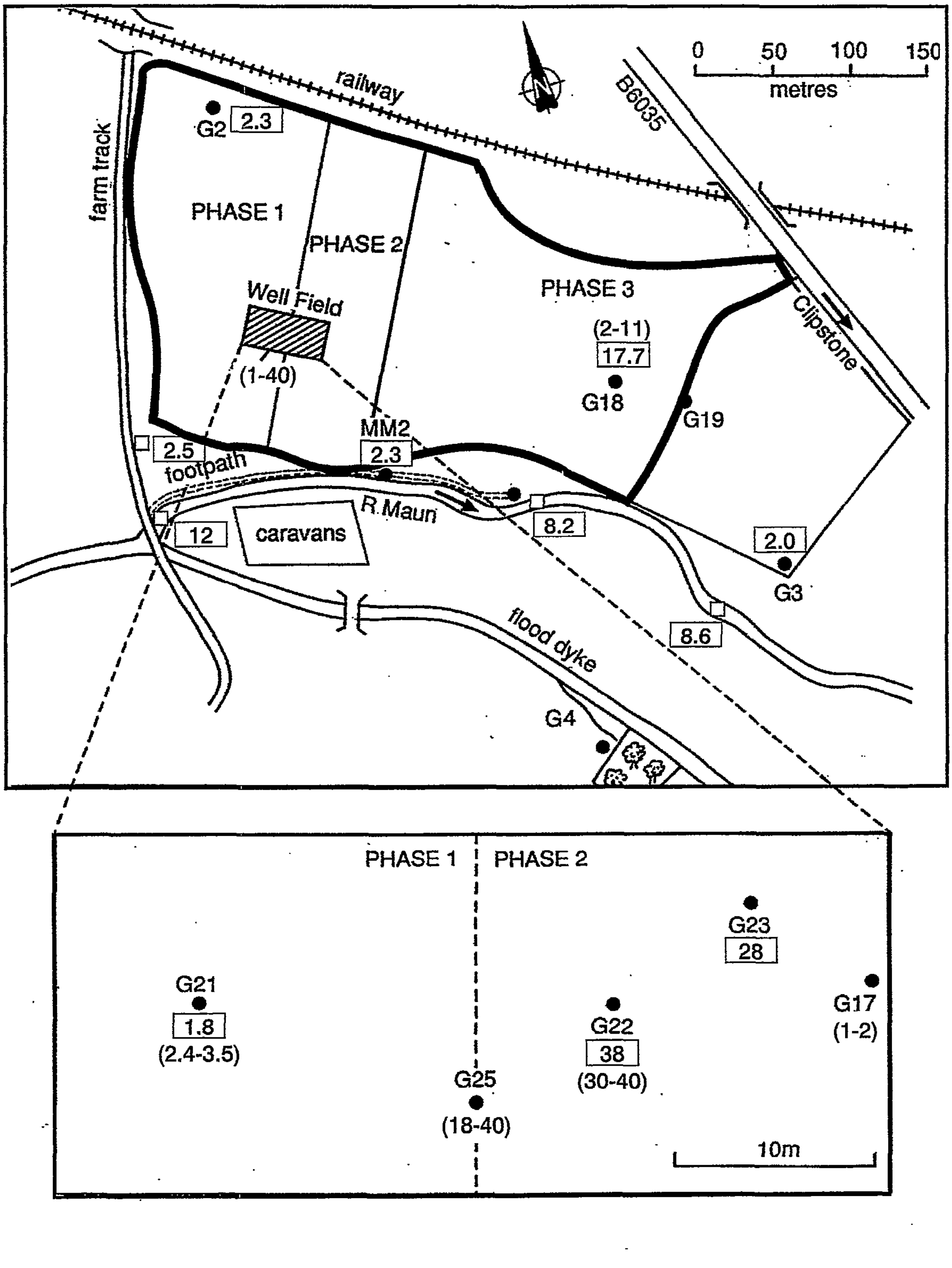


Figure 4.1 Surface and groundwater TOC concentrations in 1994
(Values for bulk groundwater samples are in boxes, concentration ranges for depth samples are in brackets)

The highest levels of most contaminants (Appendix H1) were obtained in phase 2 boreholes, particularly in samples from G22 and G25 which were observed to be frothy with a chemical odour. These samples contained elevated levels of TOC (20-30 mg l^{-1}), Cl, NH_3-N, alkalinity, Fe, Mn, Na, K, Mg, Ca and temperature. Carboxylic acids were not generally detectable, with the exception of samples from near the top of the water column in G25 (e.g. 7 mg l^{-1} n-hexanoic acid). Sulphate levels were lower than in other samples.

The decreasing chloride and TOC levels with depth in G25 indicate that leachate contamination was strongest at the top of the aquifer. However, G22 TOC and chloride profiles did not exhibit a consistent trend. While chloride levels decreased with depth, TOC concentrations rose to 40 mg l^{-1} at 27 m bgl.

Elevated levels of TOC were also recorded in the phase 3 borehole G18 (2-20 mg l^{-1}). However, TOC concentrations in groundwater from other boreholes in phases 1 and 3 were relatively low (1-2 mg l^{-1}).

In general the bulk samples, which were taken from close to the top of the aquifer, tended to be more highly contaminated than most of the depth samples.

Chlorinated and brominated solvents were not detected in the four bulk groundwater samples, with the exception of low levels of tetrachloroethene (0.1-0.4 µg l^{-1}) which were no longer detectable (<0.1 µg l^{-1}) by October 1994. Apart from G25, carboxylic acid concentrations were only elevated in the sample from borehole MM1 close to the River Maun (e.g. 10 mg l^{-1} n-hexanoic acid) and from G2 (e.g. 8 mg l^{-1} ethanoic acid). Neither samples exhibited evidence of strong leachate contamination, having low levels of the main leachate indicators (2.3 mg l^{-1} TOC, <0.5 mg l^{-1} NH_3-N and 48-88 mg l^{-1} chloride).

Samples were also collected from the middle of the River Maun which flows close to the southern perimeter of the site (Figure 4.1). A sample taken from above the weir just north of the bridge was clear and odourless with a TOC concentration of 2.6 mg l^{-1}. At the bridge however, the water was foamy and the TOC concentration had increased to 12 mg l^{-1} and the dissolved oxygen concentration had decreased from 100% to 77%. At the sampling point near borehole MM1 the river was still frothy with a TOC concentration of 8.2 mg l^{-1}. The river at the downstream monitoring point was clear with no foam or odour, however the TOC concentration and electrical conductivity were still high (8.6 and 1157 µS cm^{-1}) and the chloride levels had increased to 172 mg l^{-1}.

Clearly the river was contaminated close to the south west corner of the landfill in 1994. While some radial seepage of leachate from that corner of phase 1 could have occurred, the section of river that is contaminated is upstream of the landfill and it is therefore more likely that alternative activities were responsible for the contamination - for example from the caravan park or the farm.

1995

In July 1995 a less extensive sampling exercise was conducted with bulk and/or depth samples taken at boreholes G21, G22, G23 and G18. A general decrease in leachate contamination of the groundwater occurred between 1994 and 1995 (Appendix H2): TOC was no longer detectable in the phase 1 boreholes and phase 2 levels had decreased from 20-30 mg l^{-1} in February 1994 to 10-20 mg l^{-1}, with the exception of the uppermost sample from G22 (32 mg l^{-1}). The levels in the phase 3 borehole, G18, had also decreased (2-10 mg l^{-1} TOC).

4.1.3 Long term groundwater quality trends

Long-term trends: 'bulk' groundwater samples

The results of groundwater determinations of chloride and TOC are plotted in Figure 4.2 for boreholes with the greatest number of monitoring points. Each of the three phases of the landfill are represented by at least one borehole as well as an off-site borehole, south of the southern perimeter of the site (i.e. downstream of the site). The full monitoring data are presented in Appendix H3.

Phase 1 (G21)

- TOC levels have decreased from nearly 4 to <1 mg l^{-1} between 1986 and 1995 while chloride levels have fluctuated at around background levels, peaking at 96 mg l^{-1} in 1990. Nitrate levels have increased from ~10 to ~20 mg N l^{-1} over the same period, attaining 24 mg l^{-1} in 1994. Ammoniacal nitrogen levels were just detectable ~0.5 mg N l^{-1} in 1994/95.

- Levels of contaminants were initially higher in G24 (Appendix H3) which is located slightly further east in phase 1 than G21. However levels of TOC, chloride and NH_3-N declined between 1986 and 1990 (when it was last sampled) while nitrate levels rose.

Phase 2 (G22 and G23)

- Ammoniacal nitrogen was first detectable (~0.05 mg N l^{-1}) in boreholes G22 and G23 in 1989/90, rose to 27 and 23 mg N l^{-1} respectively by February 1994 and have since decreased sharply in G23 to <0.05 mg N l^{-1} (February 1996). Figure 4.3 clearly shows the arrival of the ammonia front at the water table between 1990 and 1994 and its dispersion in 1995/96. Nitrate levels (Appendix H3) increased earlier than ammoniacal nitrogen, between 1986 and 1989/90.

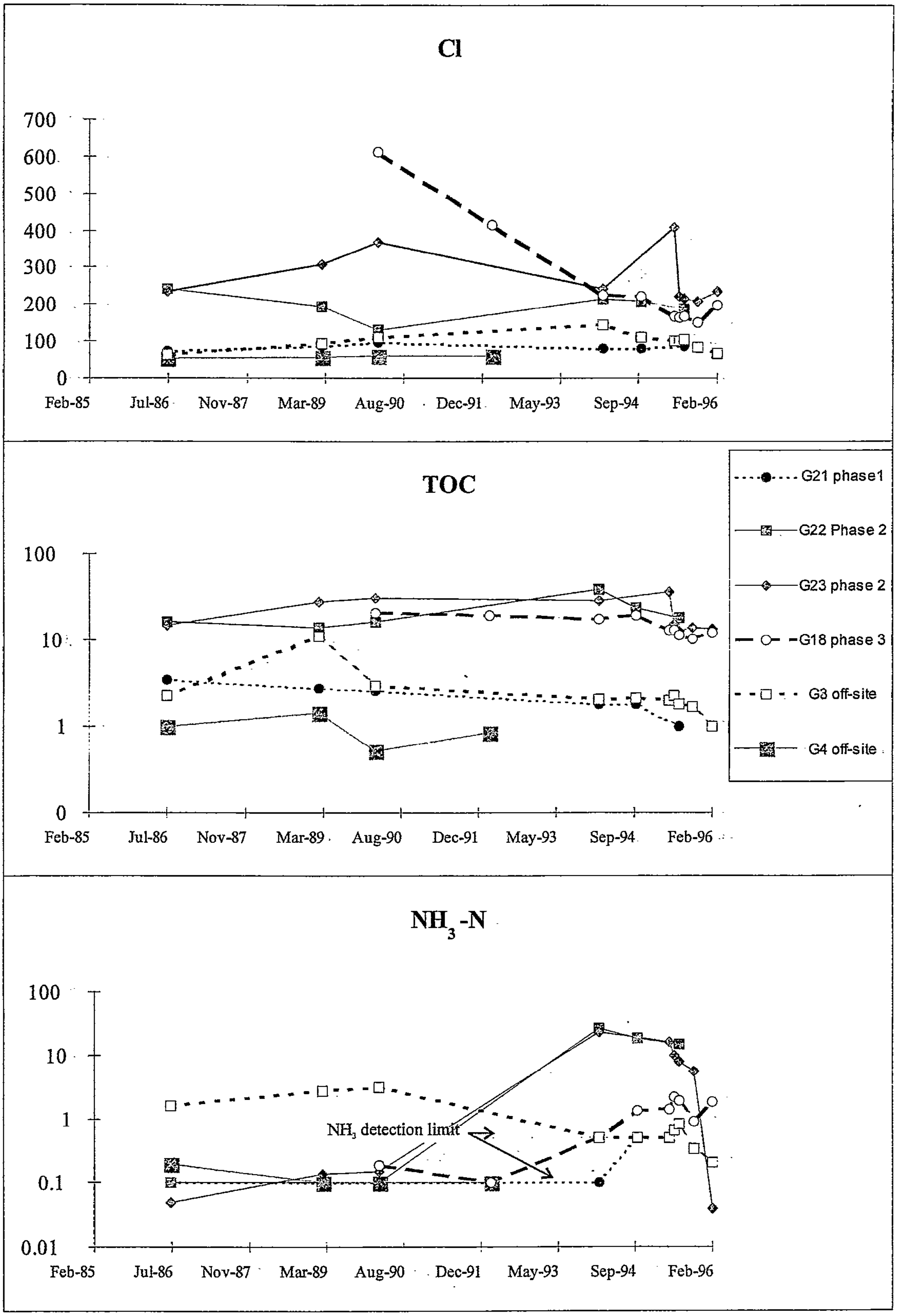


Figure 4.2 Quality of 'bulk' groundwater below Gorsethorpe landfill with time (concentrations measured in mg l^{-1})

- A doubling in TOC concentrations to 28 and 32 mg l^{-1} was recorded in G23 and G22 respectively. Levels rose first in G23 (1986-1989) whereas a similar increase in the more easterly borehole, G22, was not observed until after 1990.

- Chloride levels in G23 increased to 367 mg l^{-1} in March 1990 and peaked again at 409 mg l^{-1} in May 1995 before decreasing sharply later that year. In contrast G22 decreased almost to background levels (131 mg l^{-1}) in March 1990 and has been relatively stable since.

Phase 3 (G18 and G3)

- G18 is located towards the east of phase 3. Between 1990 and 1995, chloride levels which were significantly higher than in phase 2 boreholes, decreased from ~600 to 150 mg l^{-1}. TOC dropped by a factor of 2 over the same period.

- Ammoniacal nitrogen which was not detectable until October 1994, rose to 2.2 mg N l^{-1} in June 1995, an order of magnitude less than the levels recorded in phase 2 boreholes and has been fluctuating at 1-2 mg N l^{-1} since. Nitrate levels increased from 2 to 11 mg l^{-1} between 1990 and 1992 but have been fairly stable since.

Off-site (G3)

- G3 is located to the south-east of the site but shows evidence of leachate contamination. TOC increased between 1986 and 1989 to peak at 11 mg l^{-1} C then dropped back rapidly to 3 mg l^{-1} (1990) and has decreased steadily since, to just 1 mg l^{-1} in February 1996. Ammoniacal nitrogen has undergone a similar trend, attaining 3 mg N l^{-1} in 1990 and was present at higher levels than in the phase 3 borehole, G18, until 1994.

- Chloride has increased from 62 to 144 back to 85 mg l^{-1} over the monitoring period, however maximum Cl levels were attained in February 1994, i.e. 3 or 4 years after TOC and NH_3-N peaked. Nitrate levels have remained fairly high (15-19 mg N l^{-1}).

Off-site (G4)

- All three ions have remained at background levels throughout the monitoring period: 0.5-1.5 mg l^{-1} TOC, 50-80 mg l^{-1} Cl, <0.1-0.2 mg l^{-1} NH_3-N. The highest levels were generally observed in March 1989.

- Nitrate levels have ranged from 14-19 mg N l^{-1}.

The bulk groundwater samples suggest that the leachate flux from phase 1 was waning by 1986 and that leachate contamination of groundwater below phase 2 peaked in the early 1990s. The influx of leachate into the saturated zone from phase 3 was also occurring in the late 1980s and early 1990s. However although groundwater chloride levels below phase 3 were higher than below phase 2, TOC and NH_3-N contamination was less acute. Significantly elevated levels of NH_3-N in groundwater below both phases 2 and 3 were apparent 2-3 years after the contamination with respect to TOC was observed.

Major ions in groundwater from G3, G23 and G21 are plotted as percentage milliequivalents in a piper diagram (Figure 4.3). The plots demonstrate the trend in relative significance of the ions over the nine-year monitoring period. The phase 2 borehole G23 demonstrates the wide fluctuation in chemistry that was observed in the groundwater in 1994, before leachate ingress diminished. The downstream borehole G3 has also been affected by leachate contamination since 1988. However, levels of contaminants have been returning to 1986 background levels since 1994. The ratio of major ions in borehole G21 has been relatively stable, as leachate ceased to affect the groundwater after the mid-1980s.

Long-term trends: depth samples

Groundwater depth profiling below the three phases of the site have been carried out between 1983 (3 years before bulk sampling commenced) and 1995. The results of the 1994 and 1995 surveys are presented in Appendix H, previous monitoring results are reported in Young *et al.* (1994). Chloride and TOC have been taken as the key indicators of leachate contamination and plotted to demonstrate depth related trends with time below the site. The data demonstrate the following trends.

Phase 1

The depth profiles of TOC and chloride below phase 1 borehole G21 are plotted in Figure 4.4. In 1983 maximum concentrations of both TOC and chloride occurred at the highest point sampled, 3 m below the water table, and then gradually decreased over the remaining 10 m of water column at approximately 1-2 mg l^{-1} TOC and 60-80 mg l^{-1} chloride. The 1983 data show that leachate flux from phase 1 was already on the decrease when the first 'bulk' samples were collected in 1986 (see above).

The variations observed between 1986 and 1995 are at about background levels. In 1986, levels of both ions were at slightly lower levels than in 1983 over the same depth. Since then the profiles have fluctuated but remained close to background levels. For example the profile showed a general increase between 1989 and 1992, decreasing again in 1994 and 1995. However, the levels recorded in 1992 were only at 1-1.5 mg l^{-1} TOC and 58-82 mg l^{-1} chloride. After 1983, ingress of leachate from phase 1 into the saturated zone was not great enough to raise the levels of contaminants below 3 m into the water column above background levels.

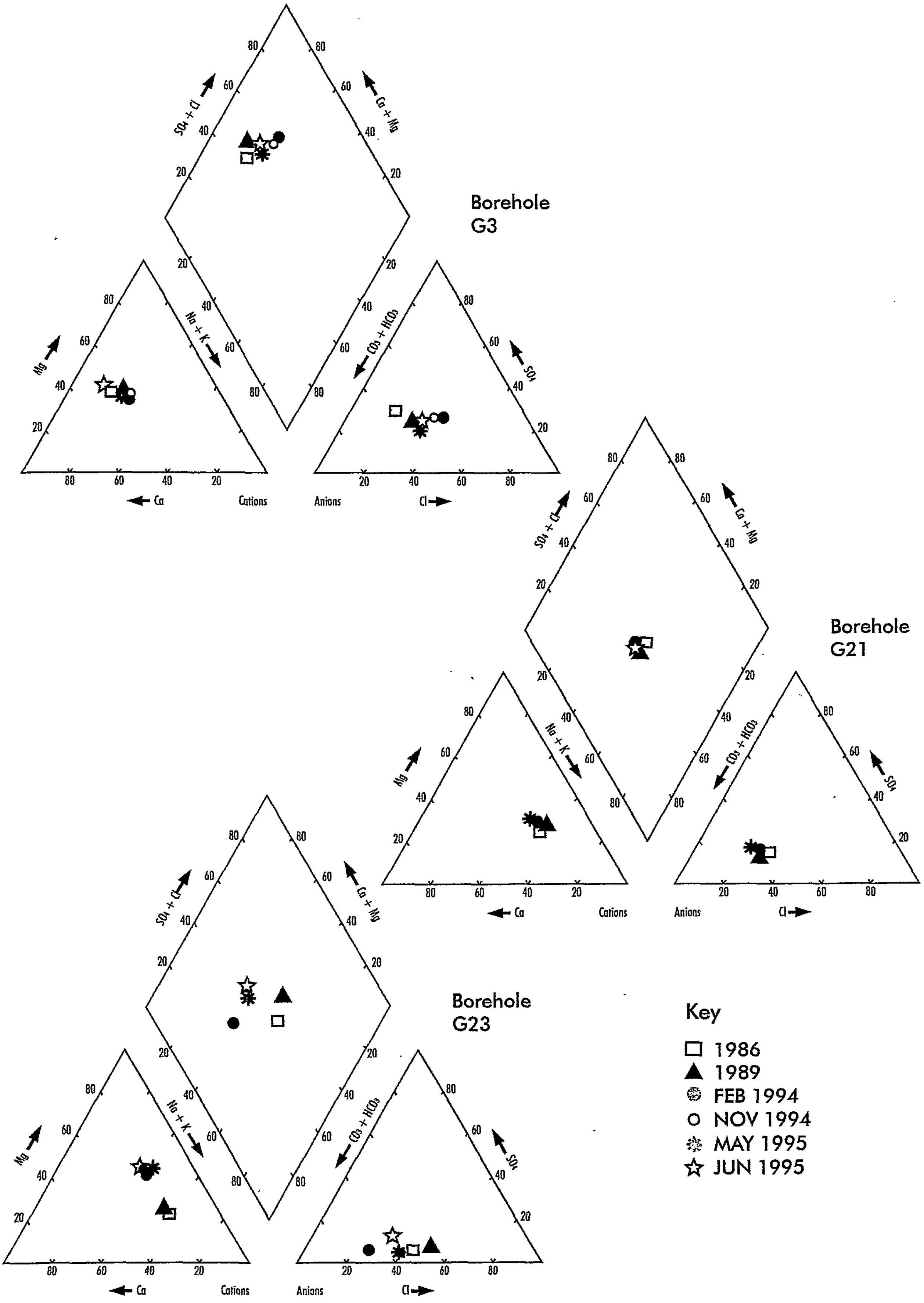


Figure 4.3 Piper diagram showing variations in the ratio of major ions in groundwater below Gorsethorpe Landfill Site

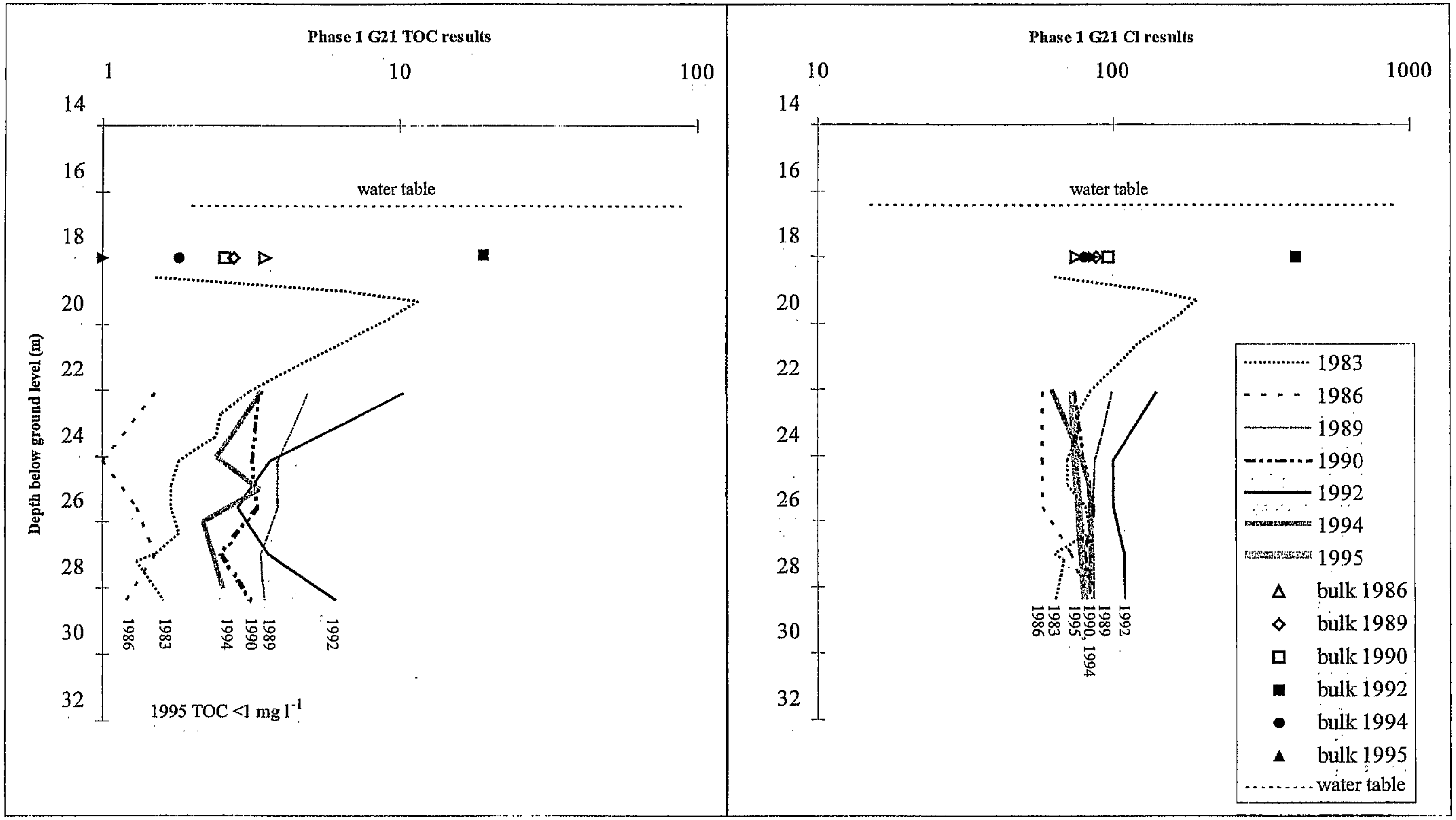


Figure 4.4 Depth profiles of TOC and Cl concentration in groundwater below phase 1 (mg l^{-1})

In 1995, TOC levels were not detectable (1 or 0.1 mg l^{-1}) for the first time at all 5 depths. (Ammoniacal nitrogen was also not detectable (<0.05 mg N l^{-1}), suggesting that by then the contribution of leachate to the water column was negligible).

It was assumed that the 'bulk' samples obtained by lowering a pump only 3-4 m into the water column would collect a sample representing the average quality of the screened sections of the borehole. In borehole G21, the bulk samples were generally more highly contaminated than most of the depth samples indicating that the 'bulk' sample preferentially sampled the upper, most highly contaminated water without the diluting influence of cleaner water from greater depth. The trends identified by the phase 1 bulk samples above therefore represent variations in the groundwater from the top of the aquifer, i.e. closest to the source of the leachate contamination.

Phase 2

The spread of results for the groundwater below phase 2 (Figure 4.5) has been greater than observed below phase 1. Background levels were observed in 1983 and in samples collected below 24 m bgl (8 m below the water table) in 1986, although contamination just 1.5 m above this depth was apparent in that year (both from the uppermost depth sample and from the bulk sample).

Figure 4.5 shows a steady increase from the 1983 background levels throughout 1989 and 1990, peaking in 1992 at 50-150 mg l^{-1} TOC and ~500 mg l^{-1} Cl. Monitoring exercises in 1994 and 1995 indicated a progressive decrease in contaminant levels. However, above-background concentrations were still observed.

With the exception of the 1986 profile when a pulse of leachate into the groundwater was commencing, the bulk samples were consistently LOWER in concentration than most of the depth samples, unlike the samples from G21.

Phase 3

An increase in contaminant levels below phase 3 has not been observed as TOC levels in G18 were already eight times greater than background by the time monitoring of G18 commenced in 1990 (Figure 4.6). Concentrations of TOC and Cl have both dropped sharply since, to background chloride levels and ~ 4 mg l^{-1} TOC in 1995.

In 1992 and 1994 the highest concentrations of TOC and Cl were at the deeper of the two monitoring points indicating that a greater quantity of fresh water was being introduced into the water column (e.g. via a fissure) close to the upper screen, preferentially diluting the leachate-contaminated water near the top of the aquifer. This is the reverse of the trend witnessed in G21 (phase 1). Bulk samples have not exhibited a consistent trend in comparison to the depth samples.

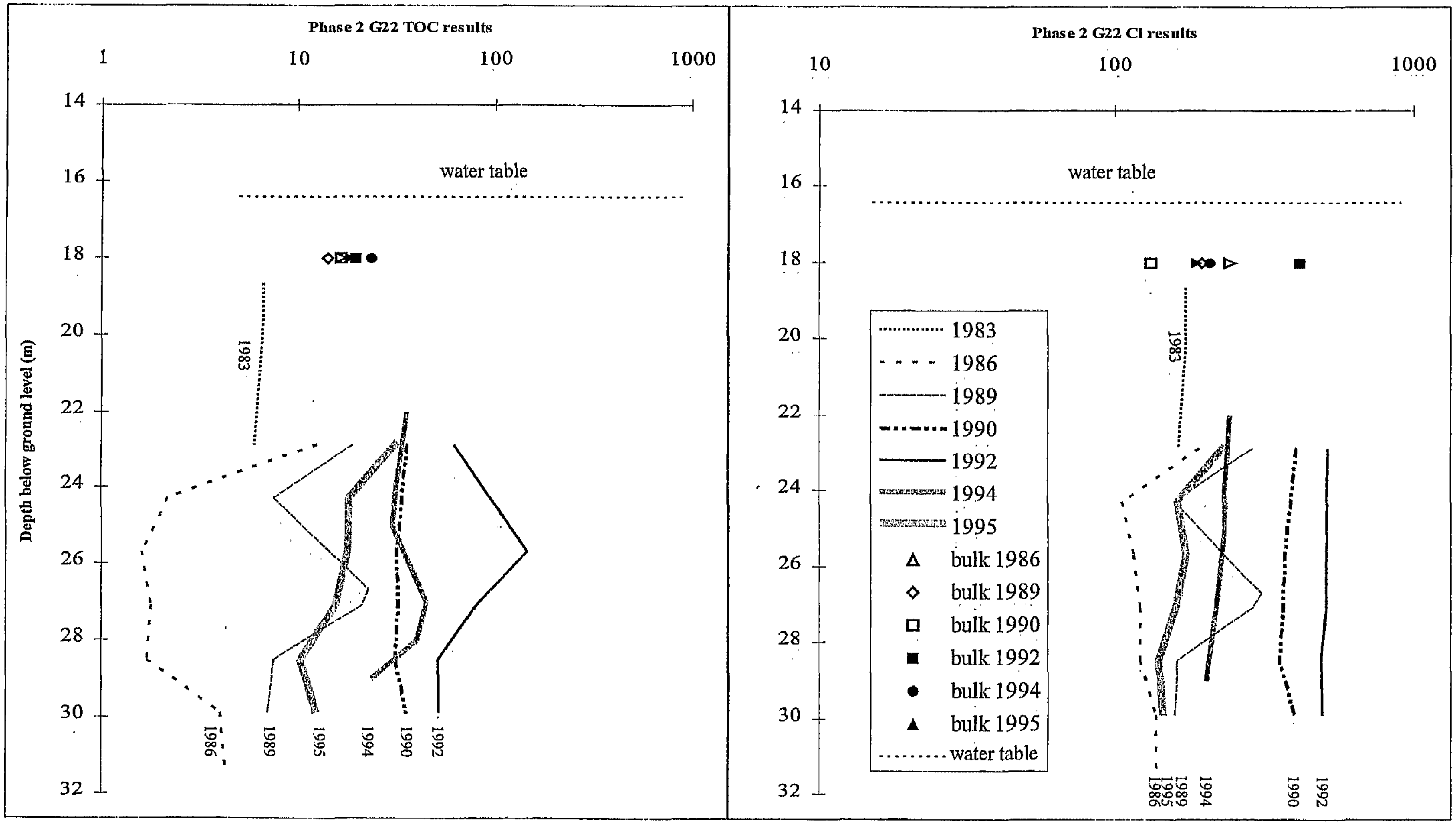


Figure 4.5 Depth profiles of TOC and Cl concentration in groundwater below phase 2

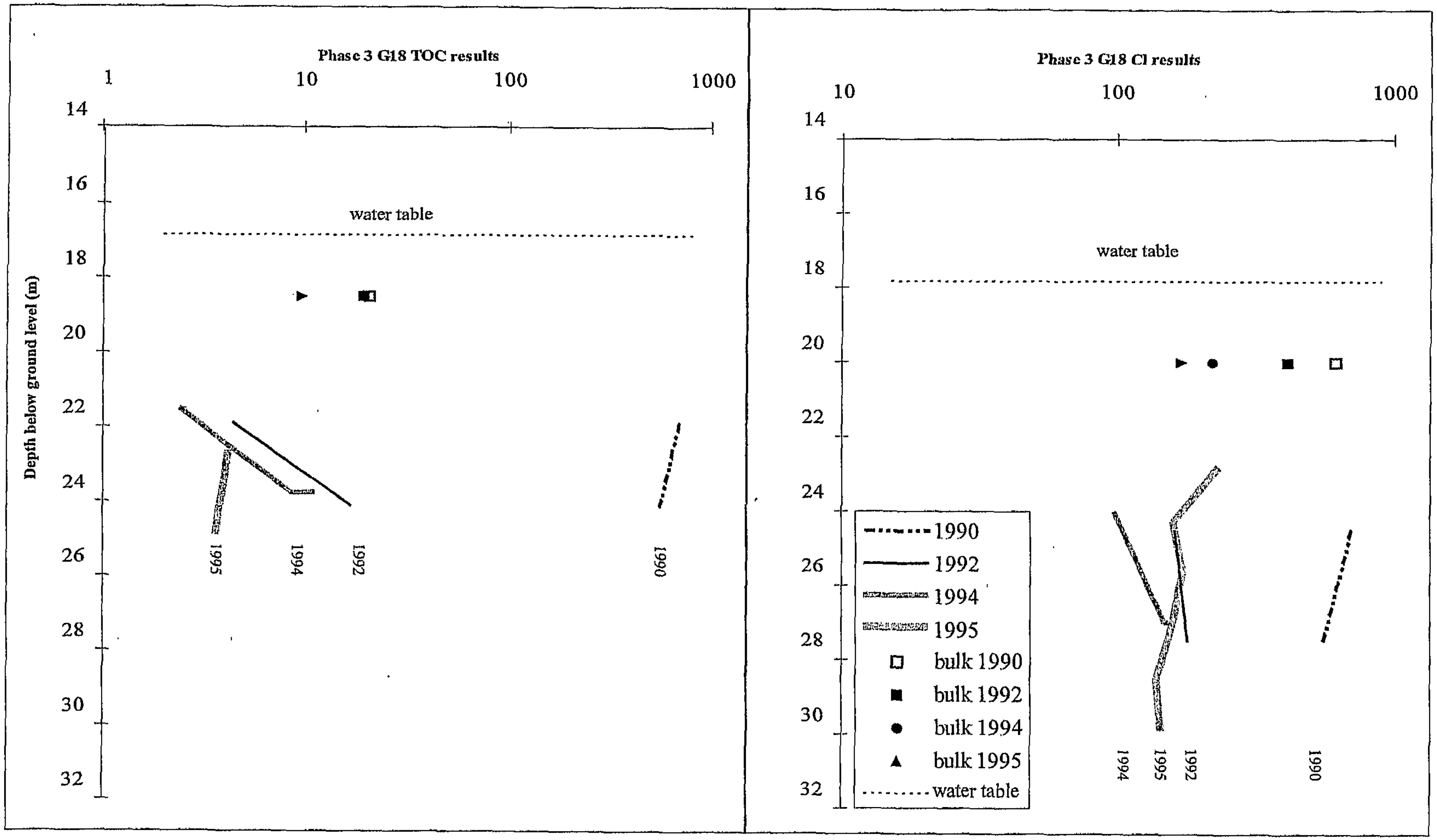


Figure 4.6 Depth profiles of TOC and Cl concentration in groundwater below phase 3

Long-term trends - summary

The depth profiling exercises demonstrated that the groundwater below phase 1 was already contaminated by 1983 but levels of contaminants had almost returned to background levels by 1986 when bulk sampling exercises began. In 1995 levels of TOC and ammoniacal nitrogen were no longer detectable.

The groundwater below phase 2 was not contaminated in 1983 and 1986. Contaminant concentrations rose in 1989 and 1990, peaking in 1992. Although a decrease in leachate contamination was observed in 1992 and 1994, levels of contaminants were still at above-background levels in 1995.

Contamination below phase 3 was already evident when monitoring commenced (G18) in 1990. Chloride levels have decreased sharply since and by 1996 were at background levels. However, TOC was still at above background levels in 1995.

4.1.4 Short-term trends (influence of different purging intervals)

Before samples are collected from any groundwater monitoring borehole, a number of well-volumes are pumped to waste prior to sampling to ensure that all stagnant water has been removed from the borehole. During the long-term monitoring programme at Gorsethorpe (and Burnstump) it has been assumed that purging the borehole of three well-volumes prior to sampling was sufficient to ensure that representative samples of the aquifer were collected on each occasion.

Several monitoring exercises carried out as part of the EC *Life* programme demonstrated that unstable parameters such as pH and temperature in bulk groundwater samples from the Sherwood Sandstone, had equilibrated before 3 well volumes had been pumped.

In February 1996, a waterproof sonde was used to obtain depth profiles of *in situ* pH, Eh, temperature, conductivity and dissolved oxygen before and after purging the boreholes of a number of well volumes. The first depth profile was obtained from the top of the borehole downwards, before pumping was commenced (i.e. purge volume, V_0). After pumping a number of well volumes (1-10) the profiling was repeated. Profiles were obtained for the groundwater in G3 (off-site borehole), below phase 3 (borehole G18) and below phase 2 (G23) and are plotted in Figures 4.7 and 4.8.

By 1996 the groundwater in the off-site and phase 3 borehole was relatively clean as the main phase of leachate contamination has passed. The profiles demonstrate the following:

- **Depth profile obtained prior to purging (V_0):** Within the un-purged water column (V_0) there was a small decrease in dissolved oxygen and an increase in pH as the sonde was lowered through the water column. Headspace in the borehole had been in contact with the water at and just below the water table since the previous sampling event. This had allowed changes in carbonate equilibria as well as diffusion of oxygen into the water column to occur.

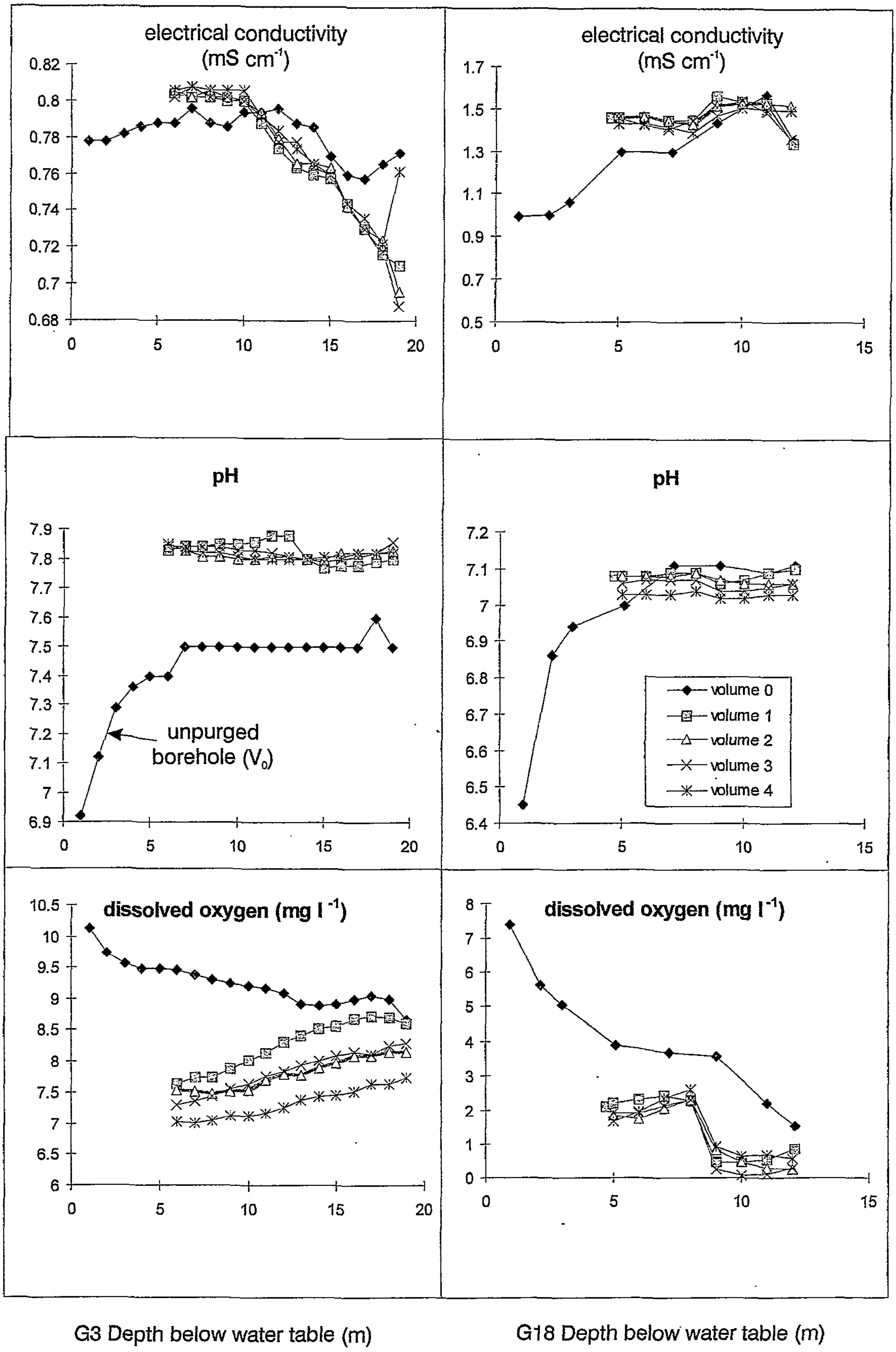


Figure 4.7 Influence of purge volume on groundwater conductivity, pH and dissolved oxygen in bareholes G3 and G18

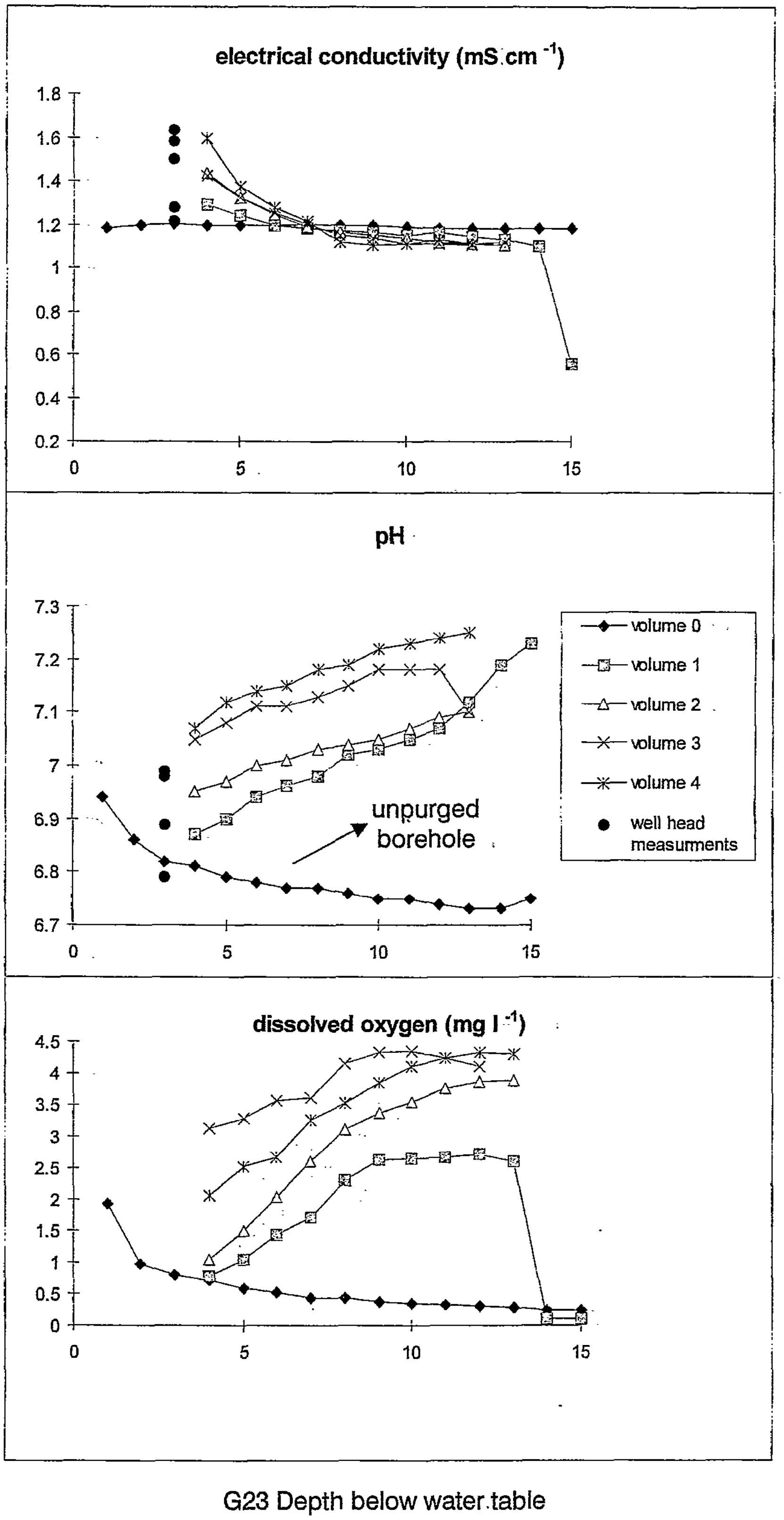


Figure 4.8 Influence of purge volume on groundwater conductivity, pH and dissolved oxygen in borehole G23

- **Depth profile obtained after one-well volume had been purged (V_1) :** (Note that access to the top of the water column was prevented by the pump). After one well volume of groundwater had been removed the actual groundwater depth profile began to emerge. G3 exhibited a decreasing conductivity and stable pH albeit at a higher level. Dissolved oxygen levels were initially lower but converged with the data from the un-purged water column with depth. G18 chemistry was generally more stable although dissolved oxygen levels were lower throughout the profile.

  The greatest change in chemistry was observed at approximately 5 m below rest water level. In G3 the pH of the water had increased from 7.4 to 7.8 and DO had decreased from 9.5 to 7.7 mg l^{-1}. In G18 the difference was more pronounced, DO decreased from 5.1 to 2.1 mg l^{-1} and conductivity increased from 1.3 to 1.4 mS cm^{-1}.

- **Depth profile after 2 to 4 volumes had been purged (V_2-V_4):** After one borehole purge, the chemistry of the water at each depth had stabilised with respect to pH and conductivity (and temperature, which is not shown) as the difference in results after each successive borehole purge was not much greater than the precision of the probes.

  Dissolved oxygen profiles were less clear-cut. Comparative levels with depth had stabilised in G18 after 1 well-volume, but in G3 DO continued to decrease, although by smaller concentrations with each successive purge volume. Over the whole profile of G3 DO levels tended to converge with the results from the unpurged water column with depth.

Borehole G23 again returned a sample of different chemistry after one well-volume purge than obtained in the un-purged borehole. However, both DO and pH continue to increase with increased pumping and do not stabilise within 4 well volumes. As G23 is in the middle of the site, a greater volume of water has to be pumped to draw in fresh water, i.e. continued pumping is gradually diluting the influence of the landfill contamination. The pumping strategy is drawing on the reserves of the more mobile uncontaminated groundwater relative to the less mobile contaminated leachate moving from the landfill above.

The exercise confirms that:

a) the sampling of groundwater without removing the stagnant water column from the borehole will result in unrepresentative sampling of the aquifer (at least in respect of the unstable parameters pH, DO and Eh).

b) groundwater from a Sherwood Sandstone borehole is stable by the time 3 or 4 well volumes have been purged. In the two sandstone boreholes monitored for this study equilibrium with respect to pH and conductivity was attained within 1 well-volume purge.

c) where the influence of a contaminant source on water quality is being examined (for example below a landfill), continued pumping will have a significant effect on the representative nature of the sample, but will not result in a 'stable' sample. In this situation, it is particularly important to agree on an appropriate strategy at the time of developing the sampling plan and then to stick with a consistent strategy of pumping for each subsequent sampling exercise. If the pumping strategy has to be changed, for whatever reason, a record of the adjustments in procedure should be documented in a way that will allow later audit.

4.2 Landfill gas monitoring

Landfill gas monitoring has been conducted in and immediately below the wastes in the three phases of the fill to the north of the site since 1985. The data are plotted and tabulated in Appendix I2, to illustrate gas quality trends with depth and time.

The data represent an almost continuous run of 11 years and show that landfill gases had already reached 16m below the surface of each phase of the fill when monitoring began. No gas extraction for either landfill gas migration control or power generation has been undertaken at Gorsethorpe. The full dataset is included to demonstrate the number of monitoring points that are required to develop a picture of landfill gas levels and flux into the unsaturated zone with time.

Phase 1

The wastes at G14 are 9.7 m deep and the water table (at the time of drilling in 1986, 18.2 m below ground level).

The monitoring probes at 5 m and 8 m appear to have been flooded, influenced by drilling elsewhere on site or otherwise unreliable, however the other probes have provided relatively consistent trends.

When monitoring commenced in 1986-87, approximately eight years after disposal operations in phase 1 ceased, methane levels were already at 70% by volume within the wastes.

At 3 m into the waste relatively stable methane levels of 60-70% by volume were maintained until November 1993. The apparent increase in nitrogen and oxygen in 1994 and 1995 may have been in response to disturbance caused by tree planting on the site. However anaerobic conditions had returned in July 1995 (methane levels of 62% v/v).

Below the wastes, the levels of landfill gas have remained fairly stable since 1986/87: ~50% CH_4 and 20% CO_2 by volume at 11.5 m bgl (2 m below the waste), ~40% CH_4 and 20% CO_2 at 4 metres into the sandstone and 20% CH_4 and 10% CO_2 at 6 m below the waste (3 m above the water table). Although migrating downwards, the landfill gas becomes progressively diluted by aerobic conditions in the unsaturated zone with depth, the levels of landfill gas have remained relatively constant indicating that either:

- landfill gas flux from phase 1 has not decreased significantly, or
- lateral migration in the unsaturated zone from phase 2 is maintaining the elevated levels of landfill gas.

Phase 2

The wastes at G15 in the phase 2 well-field are 13 m deep. The water table at the time of drilling (1987) was 17.3 m bgl.

Methane levels of 63% by volume were recorded at 3 m bgl when monitoring began in 1987. The levels have progressively decreased to 26% CH_4 in July 1995. The erratic profile may be due to sporadic ingress of air from above the wastes through the poor colliery shale cap.

Deeper within the wastes, landfill gas levels have remained relatively constant at 50% CH_4/20% CO_2 at 6 m bgl and 40% CH_4/20% CO_2 at 9 m bgl, decreasing to ~30% CH_4/17% CO_2 at 2 m below the wastes. The same levels were recorded at 4 m bgl until 1991-92 but methane levels have since declined to <10%.

Phase 3

Borehole G16 was drilled into phase 3 in 1986 when the wastes were 10.6 m deep and the water table was at 19.3 m bgl.

The final phase of Gorsethorpe was completed in 1993. However, levels of methane and carbon dioxide have always been lower in phase 3 monitoring ports than those in phases 1 and 2. Within the landfill, methane levels of 50-53% by volume were recorded in 1986-88 but have remained at ~40% by volume since.

The port at 8.6 m bgl exhibits an erratic decline from 47% CH_4 in 1986 to <10% CH_4 in 1995. The probes located 5 and 6 metres into the sandstone indicate that gas flux from the landfill is still fairly strong and stable as methane levels have remained at ~25% over the 11 year period. However, whereas below phases 1 and 2 the CH_4/CO_2 ratio has always been 2-2.5:1, carbon dioxide concentrations below phase 3 were very high at ~20% (i.e. 1.25:1).

4.3 Modelling leachate production

The WRc water balance model has been modified to take account of waste settlement and drainage of leachate from one waste layer to another. The background to the development of the model and its application to Gorsethorpe landfill are described in full in Appendix C. The results are presented briefly below.

The pattern of leachate generation at Gorsethorpe, as predicted by the water balance model, is presented in Figure 4.9.

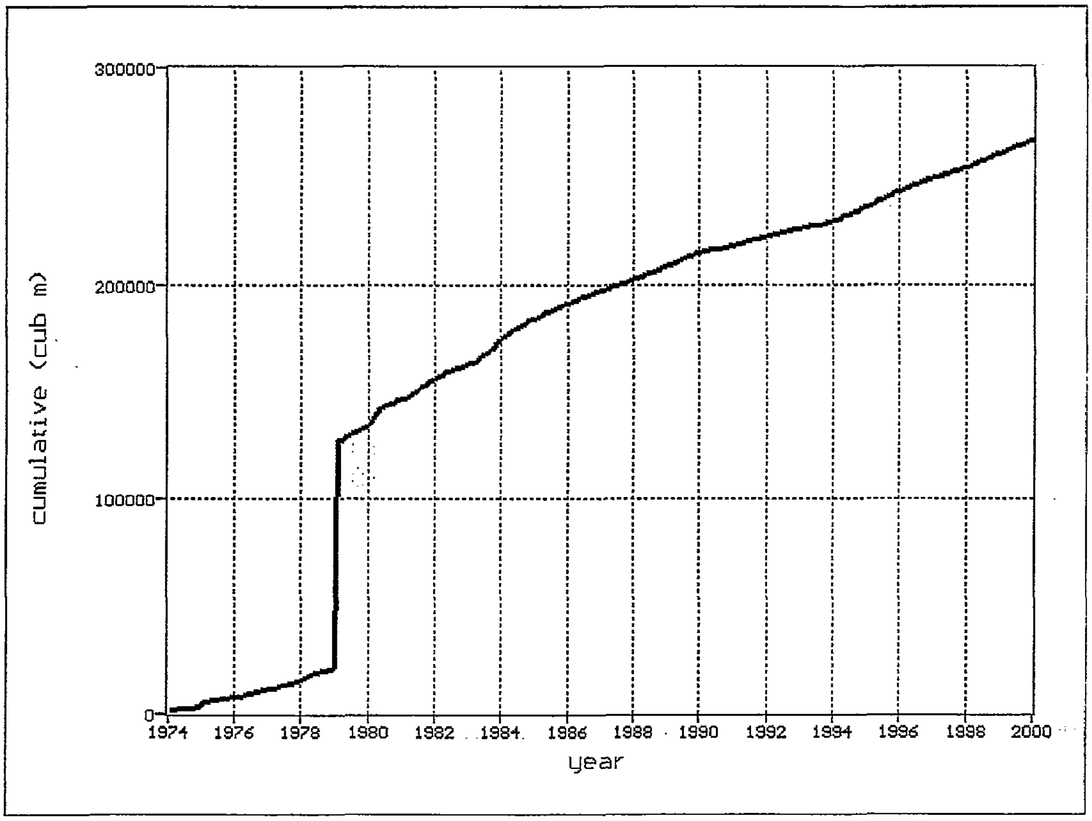


Figure 4.9 **Predicted cumulative leachate production from Gorsethorpe**

Variations in leachate production with time result from:

- the increase through time of the mass of waste;
- water inputs and redistribution throughout the depth of waste; and
- settlement, and consequent reduction in the water holding capacities of the waste.

It is apparent that leachate production in the early years of filling resulted from a relatively low rate of filling, fluctuations in rainfall recharge and reductions in void space arising from the early stages of settlement. Leachate production reached a maximum in the 1980s due to operation of phases 2 and 3 and continued production of leachate from a poorly capped phase 1. The peak in 1980 resulted from exceptionally high rainfall in the winter months of that year.

The total leachate production up to the end of 1995 was predicted to be 243 000 m^3, increasing steadily at a rate of about 4700 m^3 year^{-1}.

The total water content of wastes has also been predicted (Appendix C). Water content increased steadily during emplacement and subsequently declined slowly as settlement continued to reduce the pore space volume. From 1983 onwards, fluctuations in water content were a direct result of changes in rainfall recharge.

5. ANALYSIS AND DISCUSSION

5.1 Preamble

The work recorded in this report represents the output from site investigations, field monitoring and laboratory studies over a period of nearly 18 years (1978 - 1996) at two locations (Burntstump and Gorsethorpe landfills) and represents the largest available set of collated information on the actual and potential environmental impacts of waste disposal operations on the Sherwood Sandstone aquifer. The first 14 years have been reviewed recently (Young *et al.* 1994 and Lewin *et al.* 1994) and the full analysis and discussion of early results is not repeated here. Instead, recent information which reinforces or modifies previous conclusions is considered and discussed, including data arising from intensive groundwater monitoring programmes carried out at the Gorsethorpe site as part of the EC Life programme.

In order to provide a coherent structure to the analysis and discussion, the remainder of this Section, with the exception of a brief review of background information, follows the approach advocated for waste management facility risk assessment, that is:

- source - the landfilled wastes and processes generating leachate and gas;
- pathways - the migration (and attenuation) of contaminants within the unsaturated and saturated zones;
- targets/receptors - the impact of the potential contaminants on groundwater quality.

The outcomes of considerations under each heading are used in Section 6 to examine predictions for future trends in environmental quality at and around existing landfill on the Sherwood Sandstone formation and to assess implications for the design and operation of new waste management facilities, in particular those which may be proposed as 'flushing bioreactor' sites.

5.2 Background

The characteristics of wastes deposited at the sites, and of the local Sherwood Sandstone aquifer, are recapitulated below, for completeness.

5.2.1 Waste disposal histories

The Burntstump landfill has been operational since the 1970s. Initially infill was composed of domestic wastes with builders rubble which was deposited in shallow valleys (phases 1, 2 and 3 Table 5.1 and Figure 3.1). By the early 1980s, disposals had progressed to an adjacent sandpit, with the infill being domestic waste and up to 30% non-hazardous commercial and industrial material (phases 4 to part of 8, Table 1 and Figure 3.1). Phases 1 through 7 are non-contained but it is proposed, by the current operator that the final infill of the western part of phase 8 should be contained by an engineered lining system.

Table 5.1 Summary of waste disposal at Burntstump landfill

phase	Year	Activity
1	1970s	Filled depth c. 6 m. Uncapped.
2	1970s	Filled, c. 6 m deep.
3	1970s	Filled, c. 6 m deep.
2	1970s	Restored with thin cover before 1980.
4	Late 70s	Filled to 10 - 15 m, sand cover.
3	1980s	Restored with thin topsoil (1981)
5	1980-83	Filled, until caught up with sand extraction in c. 1983.
6	1984-86	Valley fill, 10 m in middle, 1 m at edges.
5	1987+/-	Extraction of sand completed, filling resumed.
4	Late 80s	Further 3 - 4 m waste deposited.
7	1986-89	Sand extracted to 85 m AOD. Filled with putrescible household and commercial waste. Intermediate sand cover.
6	1987	Capped
4	1988	Capped, flat finish
5	1989-90	Overtipped with 4 - 5 m waste (settlement).
5	1990	Restored.
7	1990	Restored
8	1990-96	Sand extracted to 85 m AOD, filling from east to west.
1	1990s	Overtipping up to a potential maximum of 9 metres (122 m AOD)

The Gorsethorpe landfill occupies an old sand pit adjacent to the river Maun and the deposition of household waste, incinerator residues and non-hazardous industrial materials began (phase 1, Figure 2.1) in 1969. Phase 1 was filled by 1979 with phases 2 and 3 being completed by 1983. The wastes in all three phases were capped with colliery shale, phases 2 and 3 have a 1 metre thickness applied.

5.2.2 Characteristics of the Sherwood Sandstone

Physical

The sandstone which continues to be exposed in the excavation at Burntstump, and which is confirmed in boreholes at depths of up to 40 and 70 metres respectively at Gorsethorpe and Burntstump, is a massive, generally loose textured, cross bedded, pink sandstone of medium to coarse sand grade. Thin lenses of red and grey/green siltstones and mudstones are present. Petrologically, the material is a well sorted, friable sub-arkose, with K-feldspar. Laboratory measurements of porosity for samples from both sites indicate a range from 21 to 32 %, with a mean of 24.5%. Laboratory determinations of hydraulic conductivity on friable samples indicated values in the range 0.12 to 1.30 m d^{-1}, whilst field assessment suggest a bulk value closer to 3.0 m d^{-1}.

Geochemistry of the formation

The cation exchange capacity of the sandstone was found to be low, with values in the range from 1.72 to 2.10 meq 100 g^{-1}, and a mean value of 1.85 meq 100 g^{-1}. Mean exchangeable ions for the same samples were (in meq 100 g^{-1}) <0.1 K, 0.02 Mn, 0.3 Mg, 0.4 Na, 0.7 NH_3-N, and 1.5 Ca. These values are lower those reported by Morrey (1993) from lithologically apparently similar sandstone from the Bromsgrove area (c. 4.8 meq 100 g^{-1}).

The friable nature of the sandstone is the result of the low proportion of cementing agent. Sullivan (1995) reported that the mean calcite concentration of the Sherwood Sandstone was approximately 1% (dry weight basis). The absence of significant carbonate cement also gives the sandstone a low buffering capacity. However, recent studies by the University of Birmingham (see also Section 5.4) show that MnO_2 coating to the sand grains plays an important role in redox poising. X-ray diffraction studies indicate that clay minerals form up to 5% of the rock (dry weight basis), with expandable clays, particularly a mica-smectite mixed-layered mineral forming 60% of the clay assemblage.

Microbial activity

Characterisation of the distribution of bacterial populations in the Sherwood Sandstone aquifer was carried out on four occasions at Burntstump and twice at Gorsethorpe (Table 5.2). The earliest survey (1985, Burntstump) employed a phenol analine blue stain and direct microscopic counting, but subsequent surveys were made of total viable counts by plating. The stain/direct counting method may enumerate living, dead and dormant forms, and significantly over-estimate the size of viable population. Plate counting to determine viable numbers may under-estimate the true total population because of losses of sensitive forms (in particular anaerobes) in the sample preparation and measurement. Sulphate reducing bacteria are characteristic, sensitive anaerobic forms and their presence or absence was determined in order to provide a measure of the sensitivity of anaerobes to the sampling and measurement procedures.

Table 5.2 Bacterial distribution surveys

Date	Burntstump landfill	Gorsethorpe landfill
1985	Borehole B7. Direct counts and viable counts	
1987	Borehole B9. Direct counts and viable counts	Borehole G16. Direct counts and viable counts
1989		Boreholes G17 and 18.
1991	Borehole B14. Viable count and sulphate reducing bacteria	
1994	Boreholes B15 and 16. Viable counts and sulphate reducing bacteria.	

With the exception of B16 at Burntstump, all sampling points were located in the sandstone directly beneath wastes. B16 was located on the verge of a country road, 600 metres north of B15. The surveys showed evidence of bacterial colonisation to at least 70 metres below ground level (B14, 1991; B15, 1994), that is to about 15 metres below the water table. The greatest numbers for both direct microscopic counts (1985 and 1987) and viable plate counts (1987 onwards) were found at or close to the landfill base, or the base of the soil (B16). Viable counts in the range 10^5 to 10^7 g^{-1} have been found to be typical of this zone beneath the landfills, and to decrease irregularly with depth in the unsaturated zone to counts in the range 10^3 to 10^5 g^{-1}, with very low counts being found in vertical intervals characterised by a low pH (<6.0). An apparent increase in viable counts (to 10^4 to 10^6 g^{-1}) has been noted in the upper 15 metres of the saturated zone. A far greater rate of decline in numbers with depth (to 10 to 10^2 g^{-1}) is characteristic of the unsaturated zone in uncontaminated ground (B16). Sulphate reducing bacteria were found sporadically to depths of up to 70 metres below ground at the landfill sites, but were largely absent at depths of more that about 28 metres in the uncontaminated ground.

Core material from borehole G16 at Gorsethorpe was used in laboratory microbial activity tests which demonstrated that whilst the fatty acids in leachate may be degraded by unsaturated zone bacteria, the process is pH dependent, with active degradation being delayed until pH rose above neutrality. The potential for high acid concentrations to locally overwhelm the buffering capacity of the sandstone and inhibit microbial degradation was recognised.

Groundwater

Groundwaters in the unconfined parts of the Sherwood Sandstone aquifer are typically of a calcium bicarbonate type, but with a higher permanent (sulphate) hardness than that characteristic of limestone waters. The sulphate content typically increases in areas where the formation is confined by the Mercian Mudstone, and the water grades into a calcium sulphate type.

'Uncontaminated' porewater samples from the background borehole (B16) at Burntstump suggested the following general characteristics:

pH	7.2-8.1
EC	450 to 1000 µS cm^{-1}
NH_3-N	0.3 to 0.9 mg l^{-1}
NO_3-N	6-12 mg l^{-1}
Cl	55 to 420 mg l^{-1} (but principally 50-60)
TOC	10 to 15 mg l^{-1}

Similar data are not available for the Gorsethorpe area.

The Sherwood Sandstone outcrop is vulnerable to modification of groundwater quality by anthropogenic activities, which is reflected in general quality parameters in the vicinity of each site (Table 5.3). The Burntstump area is mixed arable and grazing and the principal change over the 19 year period 1975/76 to 1994/95 has been a 130% increase in nitrate concentrations, but with no significant indication of contaminant sources other than agriculture. In contrast, the Gorsethorpe area has been subject to widespread coal mining from the underlying Coal Measures and the effects of influent drainage from rivers carrying mine drainage is reflected in the elevated chloride and sulphates.

Table 5.3 Regional groundwater quality, Burntstump and Gorsethorpe areas (values mg l^{-1}) (from Lewin *et al.* 1994 and Young *et al.* 1994)

Site	Date	SO_4	Cl	NH_4-N	NO_3	TOC
Burntstump (1)	1975/76	nd	25	<0.01	7.0	nd
Burntstump (1)	1986/87	53	28	<0.01	10.4	0.6
Burntstump (2)	1994/95	62	31	<0.3	16.2	0.4
Gorsethorpe (3)	1975/76	89	137	0.005	7.8	nd
Gorsethorpe (3)	1986/87	106	173	<0.01	13.0	0.6

Notes:
(1) Mean annual average values for three closest public supply boreholes.
(2) Mean of values for Cockliff Farm borehole, 500 metres west of landfill.
(3) Mean of annual average values for three closest public supply boreholes.

5.3 Waste characterisation and status (the source of potential contaminants)

Samples of landfilled wastes have been recovered from investigatory boreholes at both sites during each of the surveys undertaken since 1978. Porewaters were extracted from the wastes and analysed to assess the state of maturity of the wastes, but it was not until the 1994 survey at Burntstump that detailed examination and direct testing of wastes was undertaken. The area sampled in 1994 (phase 7) was filled during the late 1980s and the wastes are, therefore, some 10 years younger than those sampled from previous boreholes at Burntstump (located in areas 2/3, filled in the 1970s) and about 5 years younger than the Gorsethorpe wastes (deposited between the late 1970s and 1983).

5.3.1 Waste assay and other analyses

The waste samples obtained from Borehole B15 demonstrated that the mixed household and commercial waste landfilled in this area of the site was very heterogeneous. Composite samples of waste from the upper (1-14 m bgl) and from the lower (16-27 m bgl) parts of the fill contained similar proportions of putrescibles (20% dry weight basis), miscellaneous combustibles (10%) with small proportions of glass (1%) and textiles (0-0.5%). Lignin (15%) and ash (4%) contents were similar at both levels.

However, the characteristics of the upper and lower halves of the landfill were distinctly different in many other respects.

The lower half of the landfilled waste was saturated (moisture content of 79% dry weight) and had a significantly higher metal content than the upper part (ferrous and non-ferrous metals were 9 and 2% of the waste assay, confirmed by the chemical analysis of the processed wastes, with Pb levels a factor of 20 higher than the upper waste and Fe and Cd 2-3 times higher). A similar pattern was noted for other determinands, for example TOC (a factor of 2-3 higher than the upper waste) and volatile matter (49% dry weight). However, the lower wastes were found to retain a smaller proportion of cellulose than the upper wastes (13.7% cf. 32.5% - wet weight) giving a cellulose to lignin ratio of 0.9:1 rather than 2.1:1 and a lower potential for generating methane (56 m^3 methane per dry tonne compared with 77 m^3/dry tonne).

In comparison, the upper wastes were found to be at field capacity (moisture content of 51% dry weight), contained a greater proportion of fines and miscellaneous combustibles, but with a lower concentration of most determinands including volatile matter. The principal exceptions were Mg and SO_4, suggesting a higher input of materials such as plaster board to the upper layers.

The components of landfilled waste will degrade at different rates depending on their physical and chemical properties. Information on the degradability of organic matter in waste is scarce. Several workers (Ham 1979; ERM 1990) sub-divided the components of waste into four descriptive categories according to the estimated rate of degradability - 'readily', 'moderately', 'slowly' and 'biologically inert'. Using a relationship proposed by ERM (1990) between waste components and degradability, workers at the Polytechnic of

East London (1992) re-classified the typical composition of municipal solid waste (MSW) to provide an indication of the proportion of degradable material. Table 5.4 reproduces their analysis, showing that typical UK MSW would consist of 17% 'readily', 12% 'moderately' and 31% 'slowly' degradable, with 40% of the waste stream being biologically inert.

Table 5.4 Biodegradability of typical UK MSW - % of total weight as received (after Polytechnic of East London 1992)

Component	Degradability Category (%)				Total wt (%)
	Readily	Moderately	Slowly	Inert	
Putrescible	15.28	3.82	-	-	**19.1**
Textiles	-	-	3.6	-	**3.6**
Paper and card	-	5.96	23.84	-	**29.8**
Unclassified	-	-	0.33	2.97	**3.3**
Metals	-	-	-	7.8	**7.8**
Plastics	-	-	-	7.7	**7.7**
Glass	-	-	-	8.7	**8.7**
Non-combustibles	-	-	-	5.3	**5.3**
Combustibles	-	-	3.0	-	**3.0**
Fines <20 mm	2.34	2.34	-	7.02	**11.7**
Total	**17.62**	**12.12**	**30.77**	**39.49**	**100**

The relationship between the degradation of the different fractions of MSW is discussed below in relation to the Biochemical Methane Potential (BMP) test results.

Practical and theoretical methods have been applied over the years to estimate the yield of methane from refuse. Although various target figures for total gas yield have been published and summarised there is no clear consensus. Values ranging from 6.2-300 m^3 methane $tonne^{-1}$ wet waste illustrate that estimates can vary considerably depending on the method used and on the assumptions applied.

Recent work by the Polytechnic of East London (1992) has shown how the methods, assumptions and characteristics of the refuse can contribute to this variability. Data from their summary of theoretical maximum methane yields by method is reproduced in Table 5.5 along with derived data, using BMP assays and measured gas release, from the Landfill 2000 accelerated waste stabilisation trials (Blakey *et al.* 1996).

Two main conclusions are drawn from an examination of this data:

- The methane yields estimated from the measured gas production figures and the BMP assays carried out on wastes from the Landfill 2000 trials compare favourably with more recent estimates where factors such as waste characteristics and gas composition have been taken into account. This lends weight to the reliability of the BMP test applied.

- The methane yields estimated from the BMP assays can only relate to the removal of readily degradable organic carbon in the waste, which represents about 18% of the total weight of 'typical' UK municipal solid waste.

The relationships between biochemical methane potential (BMP) and volatile matter, waste age and moisture content and cellulose to lignin ratios have been investigated by a number of authors. Ham *et al.* (1993) demonstrated a positive correlation between volatile matter and BMP as exhibited by the Burntstump wastes and a general negative relationship between waste age and BMP. However, they observed that the degradation of young wastes (of an age similar to that of the wastes in phase 7 at Burntstump) was more likely to be controlled by local conditions (e.g. patches of waste in hydraulic isolation from others) than simply a function of time since deposition.

Wang *et al.* (1994) reported the difficulties associated with estimating potential methane generation and of relating it to lignin content but were able to demonstrate a correlation between the two. Their data, representing the analysis of 13-27 year old landfill wastes, is plotted close to the origin in Figure 5.1 along with data from the Landfill 2000 trials (four year old wastes) and data from the Burntstump investigations.

MSW is composed of many individual components which are degradable to varying extents. The lignin concentration of these substrates varies markedly and its presence is important because it acts as a physical and chemical barrier to microbial attack. The data presented in Figure 5.1 emphasises this characteristic of MSW, where each sample will have contained remnants of different components of refuse leading to differing degrees of degradability. Nevertheless, the data illustrates how the wastes recovered from the basal layers of phase 7 at Burntstump are markedly more degraded and stabilised than those recovered from the upper layers of waste. The fact that the basal waste layers were very much wetter and saturated in comparison with the upper layers of waste may have a significant bearing on this observation.

5.3.2 Leachate generation and characteristics

Rate of generation

Neither Burntstump nor Gorsethorpe landfills are contained and leachate production rates have had to be estimated by the water balance technique, principally through the application of developments of the Blakey and Craft (1986) leachate generation model.

Table 5.5 Summary of theoretical maximum methane yields by method (after Polytechnic of East London 1992)

Method	Assumptions	Yield (m^3 $tonne^{-1}$)	Reference
Volatile solids	Wet refuse is 70% degradable organics 50% of gas is methane 25% moisture content	125 (wet weight)	Pfeffer (1974)
Stoichiometric (model)	Uses extended Buswell equation Assumes 25% net degradable carbon 50% of gas is methane	111 (wet weight)	Environmental Resources Ltd (1990)
Total Organic Carbon	1 mole organic carbon produces 1 mole gas 25-26% waste is organic carbon and is all degradable 50% of gas is methane	190 - 270 (wet weight)	Bowerman *et al.* (1977) Carlson (1977) Leckie *et al.* (1974)
EMCON MGM gas model	Not 100% biodegradable and variable	60 -110 (dry weight)	Augenstein (1991)
Model estimates (1)	Readily degradable	110	Findikakis *et al.* (1988)
	Moderately degradable	45	
	Slowly degradable	10	
Landfill 2000 study (2) - Cell 1	55% of gas is methane	78 (wet weight); 105 (dry weight)	-
- Cell 2	45% of gas is methane	88 (wet weight); 119 (dry weight)	-

Notes:

(1) Assumed that methane yields relate to dry, not wet, weight (un-confirmed in reference paper).

(2) Assuming removal of readily degradable organic carbon, only (Blakey *et al* 1996).

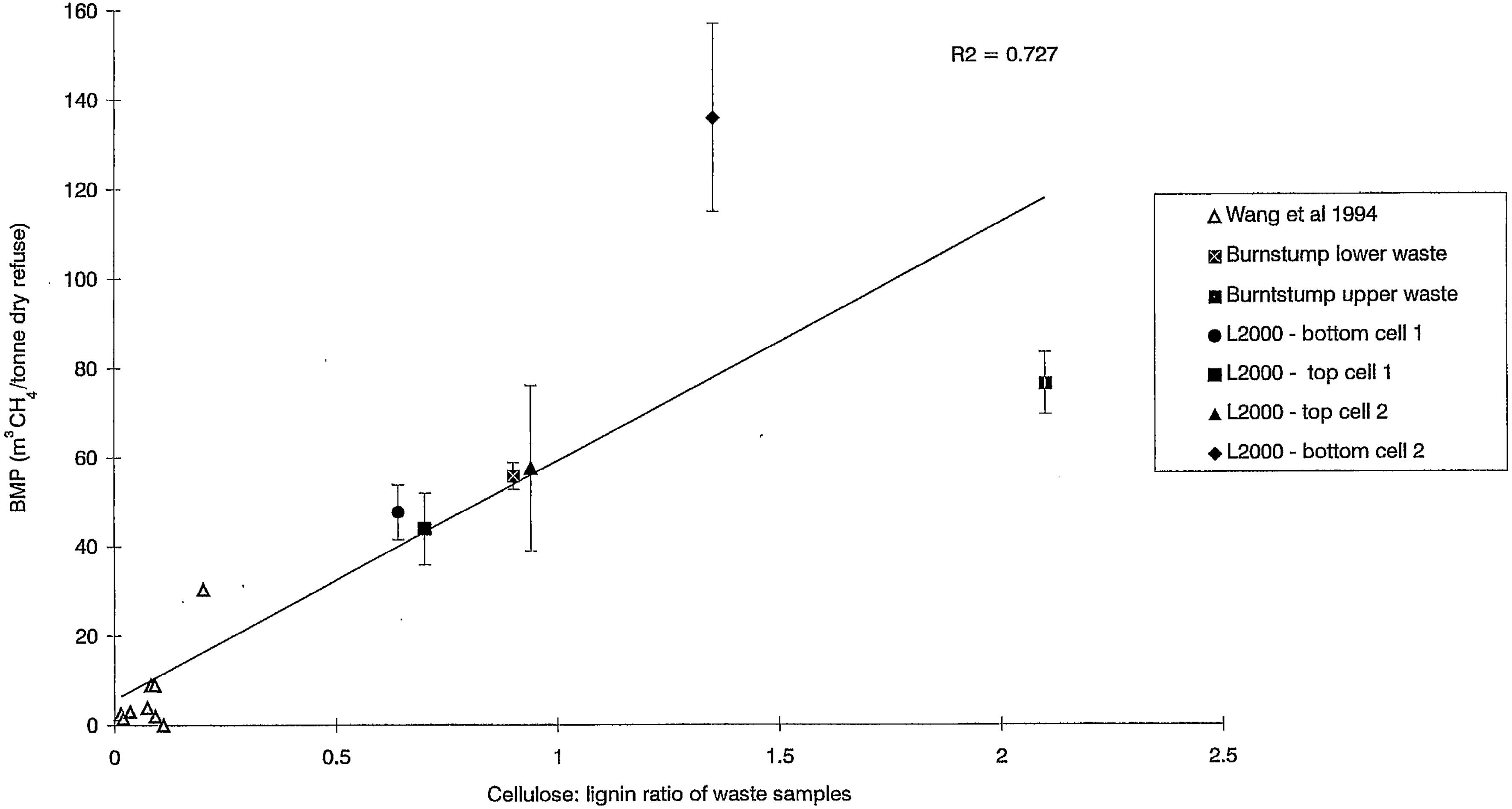


Figure 5.1 A comparison of Biochemical Methane Potential (BMP) with cellulose to lignin ratio for a range of different municipal solid waste samples

The accurate estimation of infiltration is an essential element of water balance calculations. During 1986/87 direct measurements of water flux through the sandy capping of phases 2/3 at Burntstump were made by the Institute of Hydrology, using neutron access tubes and recording tensiometers to define the seasonal development and elimination of zero flux planes. Comparison, over a 15 month period, of the measured drainage with that determined by application of the MORECS estimates of potential evaporation from grass suggested that the latter lie within one Standard Deviation of the measured value (October 1986 - September 1987 evaporation by tensiometer measurements 535.3 mm - Standard Deviation 14.5 mm; MORECS estimate 548.2 mm). The MORECS value appeared consistently to over-estimate the evaporation by between 2 and 4 %, and to under-estimate the potential leachate generation by a similar amount.

The leachate generation model has been applied to provide estimates for three situations:

1. The shallow (<10 m) wastes in phases 2/3 at Burntstump, subject to detailed investigation (1978/91).

2. The deep (c. 30 m) wastes in phase 7 at Burntstump, subject to investigation in 1994.

3. The Gorsethorpe landfill (depth <15 m).

The first simulation (see also Lewin *et al.* 1994) predicted that significant leachate production would be delayed between 6 and 9 years from the start of waste deposition (that is until the mid to late 1970s), with a further 8 to 10 years required to reach equilibrium values. A broad confirmation of this interpretation was found in the analysis of the movement of conservative, mobile dissolved contaminants in the leachate front beneath that part of the landfill, which suggested that whilst leachate was entering the unsaturated zone of the Sherwood Sandstone by 1978, 'steady state' leachate production was not achieved until the mid 1980s.

The second simulation was made using a version of the model which examined the effects of settlement on the porosity of the wastes, and hence their field and saturation capacities. This predicted that leachate production from that phase would not reach an equilibrium rate until about 1997/98, at less than 150 $m^3 y^{-1}$, reflecting the effects of restoration of the phase in 1991. The total production of free leachate by late 1994 was predicted to have been 34 000 m^3, which applied across the base of the phase would indicate a depth of migration into the unsaturated zone of between 2 and 3 metres, consistent with the range estimated from the results of investigations at borehole B15 in August 1994. The importance of making allowance for the effects of settlement on leachate release from deep waste fills was examined by running the model with the final settlement set at zero. Here, the predicted cumulative leachate production reached less than 5% of that described above, which is considered to be inconsistent with the observed situation.

The third simulation (Gorsethorpe) included the effects of waste settlement. As a result of the relatively low rate of waste inputs, and the size of the phase 1, leachate production was predicted to have begun in the early 1970s, with the potential for significant invasion of the shallow underlying unsaturated zone by the time of the first site investigation

(1978). This lead to the conclusion that contaminants were likely to have reached the water table, at a depth of about 6 metres below the landfill base, by 1983. The equilibrium production rate is estimated to be about 5000 $m^3 y^{-1}$. The implications of the simulation for the migration of contaminants from the wastes into the Sherwood Sandstone are consistent with the observed conditions.

The effects of compression of household wastes on their ability to store and transmit water has been investigated in a large-scale (6 m^3) compression cell by Beaven and Powrie (1995). The effects of compressive stress which would be expected at depths of burial of 7, 15 and 30 metres (approximately equivalent to Burntstump phase 2/3, Gorsethorpe, and Burntstump phase 7 respectively) have been found to reduce an initial effective porosity of about 30% to approximately 20%, 12% and 5% respectively, reflected in a 30% reduction in the field capacity of the wastes. These values were derived from short term measurements made on fresh wastes taken from the tipping face of a landfill and subjected to rapid physical compression in the test cell, with pore sizes being changed by mechanical deformation. The settlement experienced by wastes in a landfill includes the effects both of self-weight compression and of compaction due to the loss of mechanical strength of certain of the waste components as they are degraded, so that direct application of the results of rapid compression tests to the prediction of field situations may require the exercise of judgement. Nevertheless, the results of the experimental studies suggest that whilst it may be possible to discount the effects of settlement on leachate production in the case of shallow landfills (<10 m), significant errors are likely to accrue in simulations of landfills with a greater depth.

A schematic of the processes which affect leachate production within a landfill is presented in Figure 5.2.

Leachate composition

In the absence of leachate collection systems, the composition of leachate may be assessed from the results of analyses of porewaters extracted from the wastes. Porewater quality profiles through the wastes show the expected variability of concentrations, but examination of averaged values for key leachate components sampled in the phase 2/3 area at Burntstump (Table 5.6) indicates a progressive reduction of leachate strength over the ten year period 1978/89, with the greatest (>80% reduction) being shown by TOC and the least by (35% reduction) by ammoniacal nitrogen.

Porewater leachate extracted from samples taken in 1994 from phase 7 at Burntstump (Table 5.6) cannot be compared directly with those from phase 2/3 because of the differences in age of the wastes and their depositional history. A significant distinction appears to be present between the strength of leachate in the upper and lower parts of the fill, possibly related to the higher moisture content and assumed greater microbial activity in the lower part leading to enhanced solubilisation. The ratio of ammoniacal nitrogen to TOC is higher in the lower part of phase 7 than in either phases 2/3 at Burntstump, or at Gorsethorpe, and it is suggested that this is due to the more efficient removal of carbon in the gaseous phase by methanogenesis in phase 7 than in other parts of the landfill that have been examined.

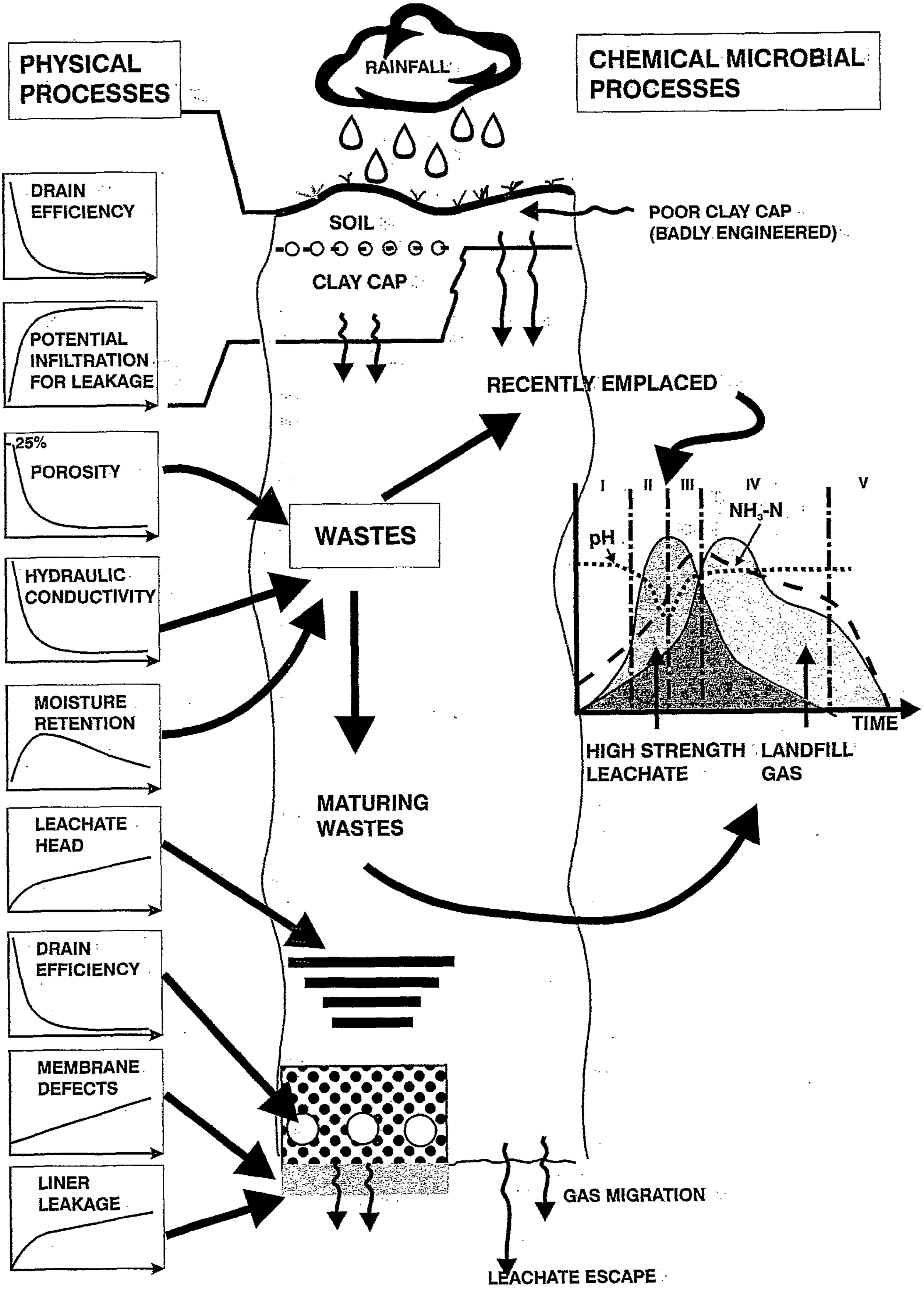


Figure 5.2 Schematic of landfill processes affecting leachate production

Direct sequential comparisons cannot be made of average leachate compositions from surveys at Gorsethorpe, because investigations were made in each of three phases of infill. However, when grouped into the appropriate disposal phases a gradual decrease in leachate strength is apparent in phases 1 and 2, comparable to that found at Burntstump (Table 5.6). The data from phase 3 at Gorsethorpe are equivocal.

Table 5.6 Comparison of averaged porewater leachates, Burntstump and Gorsethorpe landfills (concentrations mg l^{-1})

Site/phase	Date	SO_4	Cl	NH_3-N	TOC	Na	K
Burntstump							
2/3	1978	-	2900	480	11 623	1474	921
2/3	1981	1746	2713	493	10 484	2182	923
2/3	1985	1528	2114	549	6 445	1651	1136
2/3	1987	532	1486	312	1 991	1058	387
7 Upper	1994	821	1481	631	1 813	844	635
7 Lower	1994	1183	3123	1455	2 575	1898	1132
Gorsethorpe							
1	1978	-	4914	475	14 850	3355	829
1	1983	2346	4499	329	1 252	1771	697
1	1986	1727	5191	288	4 189	2063	525
2	1987	1727	5204	531	2 341	2688	684
2	1989	1289	3724	475	2 243	-	-
3	1986	825	1849	521	1 241	974	378
3	1989	3286	3117	526	1 568	-	-

Leaching tests, with deionised water at liquid to solid ratios of 2 and 10, indicated that the majority of the soluble ions (sulphate, chloride etc.) were readily available for leaching. However, metal leaching was minimal at the pH which would be expected to be encountered within the wastes (pH 7-8).

5.3.3 Landfill gas generation

Systematic monitoring of landfill gas at both Burntstump and Gorsethorpe did not begin until late 1985/early 1986, some 7 to 9 years after waste disposal was completed in the areas first investigated. At that time the wastes in area 2/3 at Burntstump and in all three phases at Gorsethorpe were in a fully methanogenic state, producing 60% methane, 40% carbon dioxide with very low oxygen and nitrogen. Subsequent measurements in the wastes have confirmed the continued production of landfill gas at both sites. Non-systematic increases in oxygen and nitrogen have been explained by the creation of partial vacuum in individual sampling probes, which tends to result in ambient air being sucked into the sampling tubes. These partial vacuums are created by saturated conditions in the waste or other blockages. Nevertheless, there is evidence from the deeper probes at both sites that since about 1987 the rate of gas generation in the wastes may have been decreasing as readily available carbon sources became depleted. A marked change in unsaturated zone gas composition in area 2/3 at Burntstump since 1990 is linked to the effects of active gas extraction from adjacent phases. No active gas control measures are present at Gorsethorpe.

Monitoring within and below the deeper, more recently filled part of Burntstump (phase 7) commenced after the construction of Borehole B15 in 1994. Filling was carried out in the late 1980s and by 1994, methane levels were already at 50-60% within the wastes. In 1996 methane and carbon dioxide were recorded at 4% and 15% respectively 47 m below the surface, some 20 m below the base of the landfill, closely reproducing the situation that had been found at depth beneath phases 2/3 in the mid-1980s. The site operators are not currently extracting gas from this part of the site due to problems caused by air ingress and poor quality gas. Continued monitoring would be expected to demonstrate whether the pattern of gas production continues in a similar way to that found in the shallower part of the site, but the greater depth of waste in phase 7 would suggest that the waning of gas production would be delayed beyond 15 years of filling.

In order to provide locally derived information on the natural ('background') pore atmosphere in the unsaturated zone of the sandstone, routine measurements have been made at Burntstump, since 1991, at five depths between 6 and 30 metres below ground level in agricultural land lying immediately to the east of the boundary of phase 6 of the fill via borehole B13. Carbon dioxide concentrations of up to 2% were found in the shallow probes, consistent with the levels that would be expected from aerobic microbial respiration in an active agricultural soil, with lower concentrations at depth. No methane was detected at any depth, indicating:

- a lack of suitable substrate;
- a predominantly aerobic environment not capable of supporting anaerobic degradation processes;
- minimal lateral methane migration from adjacent wastes.

Overall, the pore gases approximated to normal atmospheric composition of c. 80% N_2, 20% O_2 (data in Appendix I).

The changes in generation of landfill gas at the two sites and the effects on the unsaturated zone pore atmosphere are discussed more fully in Section 5.4.

5.4 Migration and attenuation in the unsaturated zone

5.4.1 Preamble

During the 17 year period (1978-95) over which field investigations have proceeded at both sites, the principal findings regarding the movement and attenuation of leachate and landfill gas through the unsaturated zone have been based on measurements in the deep unsaturated zone at Burntstump, but with valuable supporting information from the shallow (<10 m) zone at Gorsethorpe. The most intensive investigations at Burnstump have been conducted in the part of the site which was filled in the 1970s. Some of the waste in this area is now approaching 20 years old, as is that in part of the Gorsethorpe site, and both are close to a decade short of the 'generation' within which the principle of sustainable development indicates that putrescible wastes should become stabilised (for example see Sections 1.26 - 1.31 of Waste Management Paper 26B, DoE 1995). The findings related to the behaviour of leachate and landfill gas components during movement through this zone are considered to be of prime importance both with respect to the future management of operational and restored non-contained landfills, and in conducting risk assessments of existing and proposed contained landfills, including those to be operated as 'flushing bioreactors'.

The field and laboratory data on which this discussion relies have been introduced in Sections 3 and 4 of this report, with detailed listings and graphical representations contained in Appendices E to I.

The processes operating in the unsaturated zone are summarised in Figure 5.3.

5.4.2 Leachate and landfill gas migration at both sites

Phase 2/3 area, Burntstump

A detailed analysis of the migration of leachate through the unsaturated zone has been presented in Lewin *et al.* 1994, which provided evidence of:

- the progressive downwards migration of an essentially coherent leachate 'front' of persistent and mobile contaminants (chloride and, as a less persistent component, TOC);
- the retardation of ammoniacal nitrogen and the substitution of calcium and magnesium for potassium by cation exchange; and
- the influence of the limited buffering capacity of the sandstone formation on microbial attenuation of organic compounds.

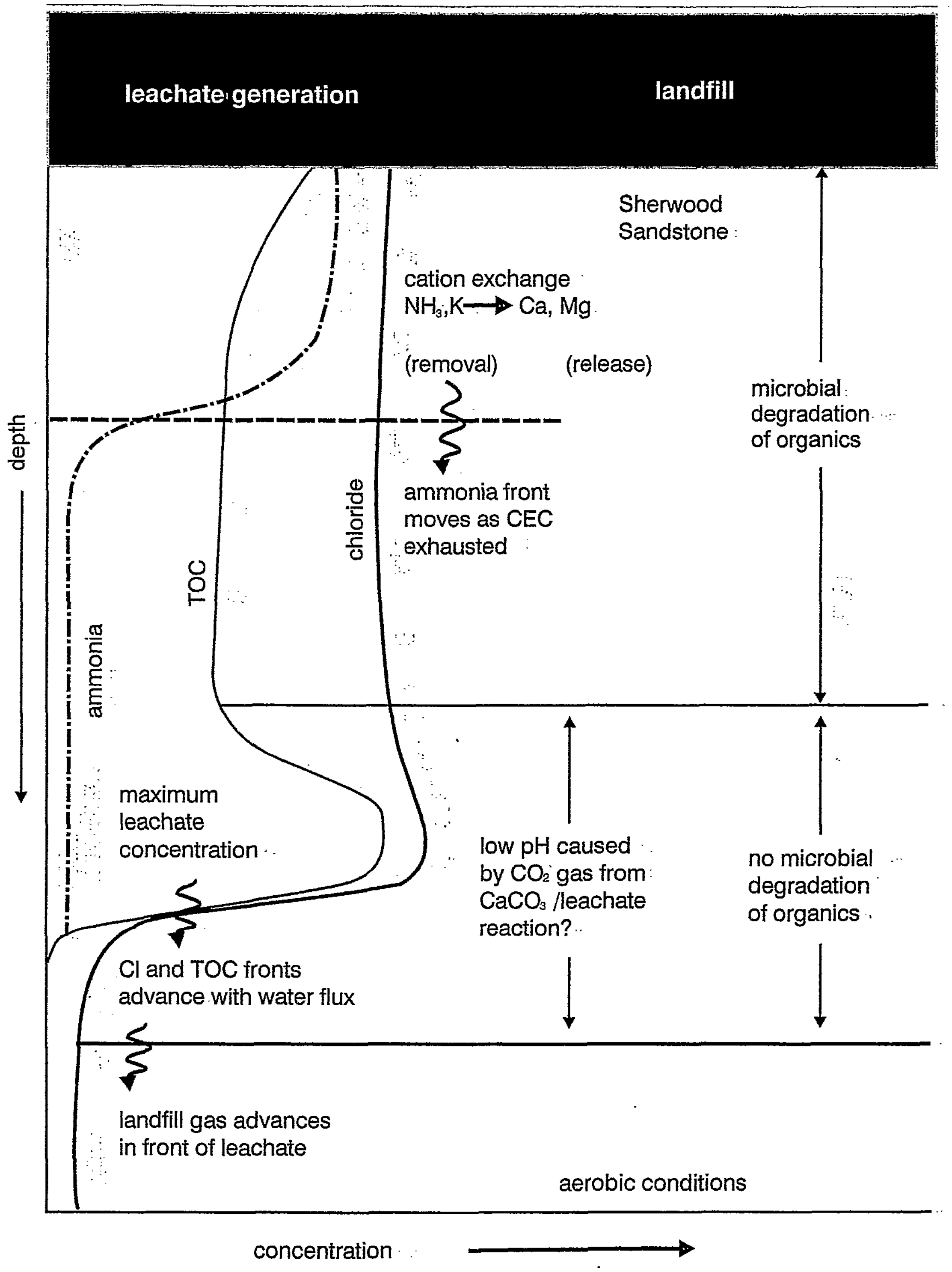


Figure 5.3 Schematic porewater profiles illustrating primary attenuation mechanisms believed to operate in the Sherwood Sandstone

The progressive invasion of the unsaturated zone by landfill gas, ahead of the leachate plume, is illustrated in Figure 5.4. In the figure, quality data are shown for gas monitoring ports at 5 depths within and below phases 2/3. The upper box presents gas quality data for the monitoring port located approximately 1 m below the surface, the second at approximately 2.5 m below the base of the landfill and the next three at depths from 15 to 27 m below the base of the landfill. Filling is estimated to have taken place between 1974 and 1978.

Superimposed on the gas monitoring data is the actual or predicted time at which the mobile, non-retarded leachate components arrived at each monitoring port. Porewater profiling conducted in 1978, 1981, 1985, 1987 and 1991 enabled the depth at which the plume was located and its thickness to be recorded. From this it has been possible to estimate intergranular flow rates for the persistent and mobile components of the leachate.

Between 1978 and 1981, an annual rate of leachate penetration of 0.7 m was estimated, with evidence of an increase to about 1.7 m y^{-1} from 1983 to 1991 (Young *et al.* 1994). This circumstantial evidence has been used to locate the leachate front in Figure 5.4 where more direct measurements and data are unavailable.

These observations are consistent with the outputs from the water balance modelling work (see Section 5.3.2) which predicted that, whilst small quantities of leachate were generated soon after the start of landfilling, significant volumes were not produced until seven or eight years later (i.e. 1980/81) with a slow progression towards a dynamic equilibrium between drainage and infiltration being established around the mid 1990s. Commentary on the schematic representations of leachate and gas changes at the four gas probes in the unsaturated zone is given below (refer to Figure 5.4).

Box 2: 9 m bgl (2-2.5 m below landfill base)

Porewater profiling in 1978 located the chloride front approximately 2 m below the base of the landfill, coincident with a narrow (1 m) zone of low porewater pH (pH 3.5 - 4). Maximum methane levels of 65% v/v were recorded at this depth in 1986-1987 indicating that gas production had already peaked when gas monitoring commenced, approximately eight years after disposal operations in that part of the site had ceased. The proportion of methane continued at this level until 1991/92, when aerobic conditions were rapidly induced by the commissioning of a new landfill gas extraction system in an adjacent phase. The effects of a temporary extraction system failure in late 1995 is seen as a short-lived increase of methane concentrations.

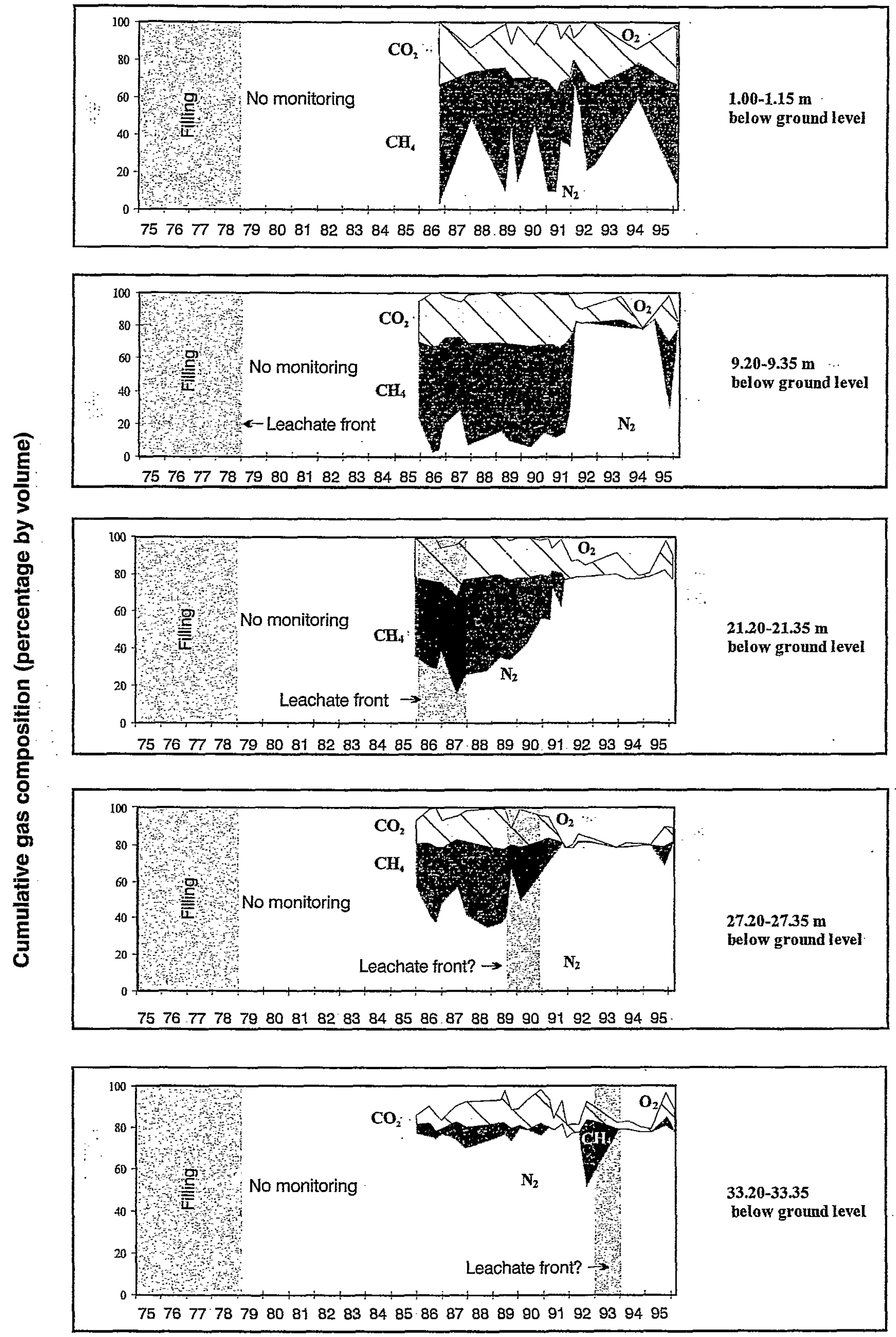


Figure 5.4 Gas and leachate profile below old part of Burntstump landfill (1975-1995)

Box 3: 21 m bgl (~9 m below landfill base)

By 1987 the chloride front was located at 22-23 m bgl and the low porewater pH zone (pH 4.5 - 5.5) straddled a depth of 17-22 m bgl in nearby borehole B9. The leachate front was probably close to the monitoring port at 21-21.3 m in Borehole B7 in 1986/87.

Methane concentrations of 40% by volume were recorded at this port in December 1985 and gradually increased to 50% by volume in 1987/1988 but then began to decline, well in advance of the initiation of local gas extraction measures, with methane concentrations decreasing from 43% in 1989, to 18% in 1991 as the leachate front passed deeper into the unsaturated zone. Carbon dioxide levels remained around 20% over this period. Methane concentrations have remained at undetectable levels since 1992, the exception being a single measurement in 1995. Carbon dioxide has been detectable however, fluctuating at levels of 1-10% by volume since 1991.

Box 4: 27 m bgl (~20 m below landfill)

By 1991 the strength of the leachate had been reduced as it had passed through the unsaturated zone. Consequently porewater chloride levels within the leachate plume were 50% less than those in the leachates recovered in 1978. In addition, by 1991 the pH of the leachate was only marginally lower than background porewater values.

Between 1985 and 1989 methane levels fluctuated between 25-42% v/v. Methane levels appear to have been in the decline from 1990, or earlier, which is the time when the leachate front is predicted to have passed this depth, although it was not possible to collect gas from the ports on three consecutive occasions in 1990. Once the leachate plume had passed further into the unsaturated zone, methane levels decreased to <1% v/v and carbon dioxide to 0-5% v/v. This decrease occurred before the gas extraction system was commissioned in November 1991 and therefore represents a natural decrease in landfill gas flux at this depth. Lateral gas migration was detected at this depth when the extraction system failed briefly in 1995.

Box 5: 33 m bgl (~26 m below landfill)

Landfill gas had already reached 26 m below the base of the site when gas monitoring began, albeit at relatively low levels (~5% v/v methane). Levels remained at 5-10% and 5-15% methane and carbon dioxide respectively until 1990 when methane was no longer detectable. The highest methane level at this probe was a single measurement of 32% v/v determined in September 1992. As no other complementary data was recorded in other ports on that occasion (unlike the 1995 measurement) we have speculated that the methane was being forced ahead by the advancing leachate front which was probably 1-2 m above the port at that time.

Phase 7 area, Burntstump

The porewater profile from Borehole B15 was comparable to those obtained in previous investigations at the site. The location of the leading edge of the leachate front could not be precisely defined as core recovery was not possible from the uppermost part of the Sherwood Sandstone, due to poor consolidation. However, the zone in which the front was located was indicated by a 2-3 order magnitude decrease in TOC, chloride and ammoniacal nitrogen between 28 m (the base of the waste) and 36 m below ground level. This depth interval was found to be consistent with the results of water balance modelling using a revised assessment which makes an allowance for the effects of waste settlement on the storage and release of leachate (see also 5.3.2). The model predicted that by 1994, leachate would have migrated to 2.8 m depth into the unsaturated sandstone, but by the year 2000 would be at 3.7 m below the base of the wastes. The reduction in rate of vertical migration from about 0.4 m y^{-1} (1987-1994), to less than 0.2 m y^{-1} by 2000 is attributed to the effects of restricting infiltration by restoration with a low permeability cap.

Landfill gas monitoring at eight depths between 5 and 47 metres below ground (see Appendix H for details) confirmed anaerobic conditions within the wastes, with penetration of landfill gas components to not less than 32 metres below ground level in 1994.

The porewater profiles of the sandstone at B15 reflect the patterns established elsewhere in the site, with major cations and anions returning to close to background values below the level of the leachate front. In particular, a nearly stoichiometric replacement of ammoniacal nitrogen by nitrate nitrogen is noted (see Figure 3.8) passing downwards through the zone containing the leachate front. However, it was found that viable bacteria within the sandstone below the waste (B15) were generally of the order of 10^3-10^6 counts per gram, which is between two to three orders of magnitude higher than the counts measured on samples taken in the background borehole (B16), suggesting that sufficient additional nutrient material has been transferred from the wastes into the unsaturated zone to maintain the enhanced microbial activity, but without being reflected in a significant rise in porewater concentrations.

Gorsethorpe

Although the unsaturated zone at Gorsethorpe proved to be less than 10 metres deep, the processes observed at Burntstump were found to be operating with, in particular, a clear demonstration of the exchange of ammoniacal nitrogen and potassium for calcium and magnesium (see Section 5.3 and Figure 5.1, Young *et al.* 1994).

A summary of the movement through the unsaturated zones of phases 1, 2 and 3 are given below:

- **phase 1** - This was filled between 1969 and 1979. The wastes at G14 are 9.7 m deep and the water table at the time of drilling in 1986, was 18.2 m below ground level. By 1978 'strong' leachate was present in the phase 1 wastes and TOC and Cl fronts had penetrated the upper 2-4 metres of the unsaturated sandstone. When gas monitoring commenced in 1986-87, approximately eight years after disposal operations in phase 1 ceased, methane levels were already at 70% v/v within the wastes. A reduction in landfill gas concentrations has been observed with depth (~50%, 40% and 20% CH_4 v/v 2, 4 and 6 metres below the base of the fill). However, the concentrations have remained fairly constant at each monitoring port over the 10 year monitoring period, suggesting that either landfill gas flux from phase 1 has not decreased significantly, or lateral migration from phase 2 is maintaining the elevated levels of landfill gas below the phase 1 wastes (but see comments below).

- **phase 2** - The wastes are 13m deep. The water table at the time of drilling (1987) was 17.3 m bgl. Porewater profiling showed that by 1987-1989 the TOC and Cl front had passed through the 4 or 5 metres of unsaturated zone and reached the water table. Methane accounted for 63% v/v of pore gases at the top of the wastes when monitoring began in 1987, but progressively decreased to 26% v/v in 1995. Methane levels deeper in the waste have exhibited smaller decreases over the same time, with a progressive diminution in the unsaturated sandstone beneath the wastes (from 30% v/v in 1986 to <10% v/v since 1991/92).

- **phase 3** - This was completed to a depth of up to 10 m in 1983 with a colliery shale cap of much higher standard than used on phase 1 or 2. The water table is approximately 10 m below the base of the wastes. By 1987, the leachate plume had advanced to the water table and above background levels of TOC and Cl were observed in porewaters from the saturated zone. Landfill gas concentrations have always been lower in phase 3 than in phase 2 even though it was not completed until 1983. For example, 40% methane within the wastes since 1988 and 25% 5-6 metres below the wastes, with a lower methane: carbon dioxide ratio in the unsaturated zone.

5.4.3 Overview of landfill gas generation

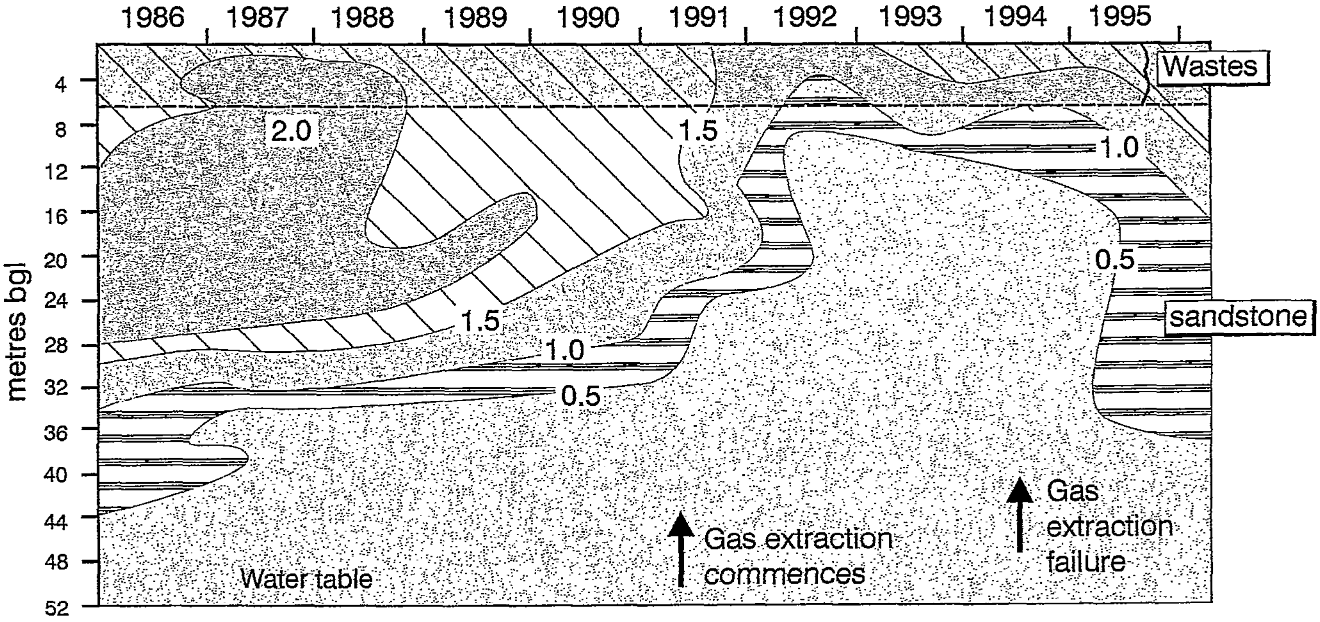
The changes in absolute gas concentrations (as % v/v) within the waste and underlying unsaturated sandstone are described above. Under fully anaerobic conditions, bacterial methanogenesis produces a gas mixture with a CH_4:CO_2 ratio of about 1.5:1 (60% CH_4, 40% CO_2), sometimes rising to about 2.5:1 (72% CH_4:28% CO_2) as the result of the scavenging of gaseous CO_2 to dissolved bicarbonate ions. Examination of the pore gases from a borehole penetrating the unsaturated zone beneath agricultural land (B13) have shown the effective absence of methane and only low carbon dioxide concentrations, so that the presence of any significant methane could be taken as a possible indicator of the presence of landfill gas and it would be expected that in situations where the landfill gas flux is insufficient to displace completely the natural pore gases, the ratio of methane to carbon dioxide would not be significantly different.

A plot of the CH_4:CO_2 ratio against depth and with time, for phase 2/3 at Burntstump (Figure 5.5) tends to confirm the hypothesis, with a significant depth of unsaturated zone containing pore gases with a ratio in the range 1.5-2.0:1, during the interval 1986 - 1990, but with some evidence of a gradual reduction in flux between 1988 and 1990. The effects of the start of the active gas extraction in an adjacent phase in 1991 are clearly shown, with the indication that the initial venting allowed some atmospheric gases to enter the base of the waste mass (1992). The re-establishment of landfill gas flow into the unsaturated zone at the time of a failure of the gas extraction system, late in 1995, is apparent in profiles for the main gas monitoring bores (B7/B8) and for B9 installed in 1987. Gas data from the deeper, more recently filled phase 7 (B15, Figure 5.5) are probably of insufficient duration to determine whether the reduction in ratio between 1994/95 and 1995/96 reflects the re-establishment of active gas extraction from Burntstump, or should be attributed to another cause.

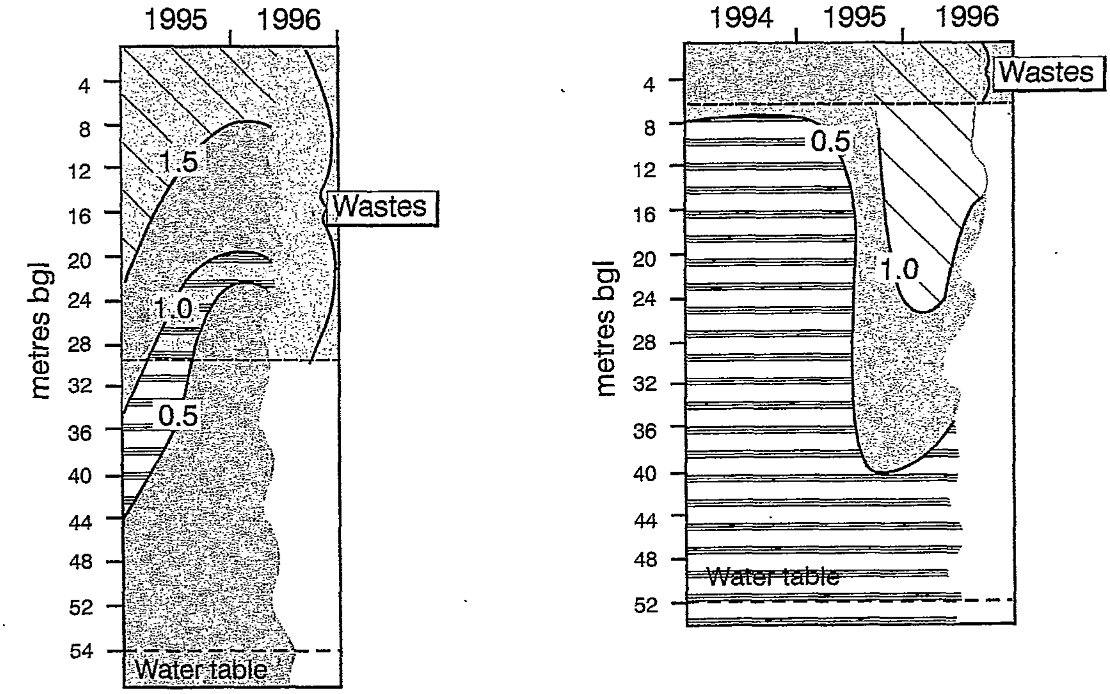
The CH_4:CO_2 ratio plots for the three phases examined at Gorsethorpe (Figure 5.6) appear significantly different from Burntstump, in the extent to which ratios of greater than 2:1 have persisted within the wastes during the monitoring period. The pattern in each phase appears comparable, with a slow decrease in the ratio with time. The depth of unsaturated zone into which landfill gases may migrate is very much less at Gorsethorpe than at Burntstump (c. 18 m total c.f. 54 m total) and the strongly stratified distribution of ratios is believed to reflect this constraint. The high methane proportions in the upper layers of waste suggest that carbon dioxide is depleted from the gas phase more efficiently at this site than at Burnstump. One theory could be that this is related to the constraint on gas flow pathways imposed by the restricted unsaturated zone but this remains unfounded.

5.4.4 Laboratory studies

In addition to routine laboratory determinations of leachate and gas composition by WRc and Severn Trent WA/NRA and microbial laboratory-based assays conducted by Luton University, an important study of leachate/sandstone interactions was completed by the Department of Earth Sciences, University of Birmingham (Thornton *et al.* 1995). The work comprised laboratory flow-through columns packed with sand recovered from the Burntstump quarry and employing both acetogenic (A phase) and methanogenic (M phase) leachates. The data helped clarify the processes deduced from field observations and confirmed that the principal controlling mechanisms over contaminant migration were ion exchange (Na, K, Ca, Mg, NH_4, Fe, Mn), acid-base reactions (Ca, CO_3, pH), redox reactions (Mn/Fe, organics) and sorption (organics). The finding that solid phase natural MnO_2 played a particularly important role in redox poising, with a considerable affect on Fe and micro-organic concentrations was previously unreported.



Phase 2/3; borehole 7 and 8



Phase 7 - borehole 15

Phase 2/3 - borehole 9

Figure 5.5 Methane/carbon dioxide ratios in pore gases - changes with time and depth at Burntstump

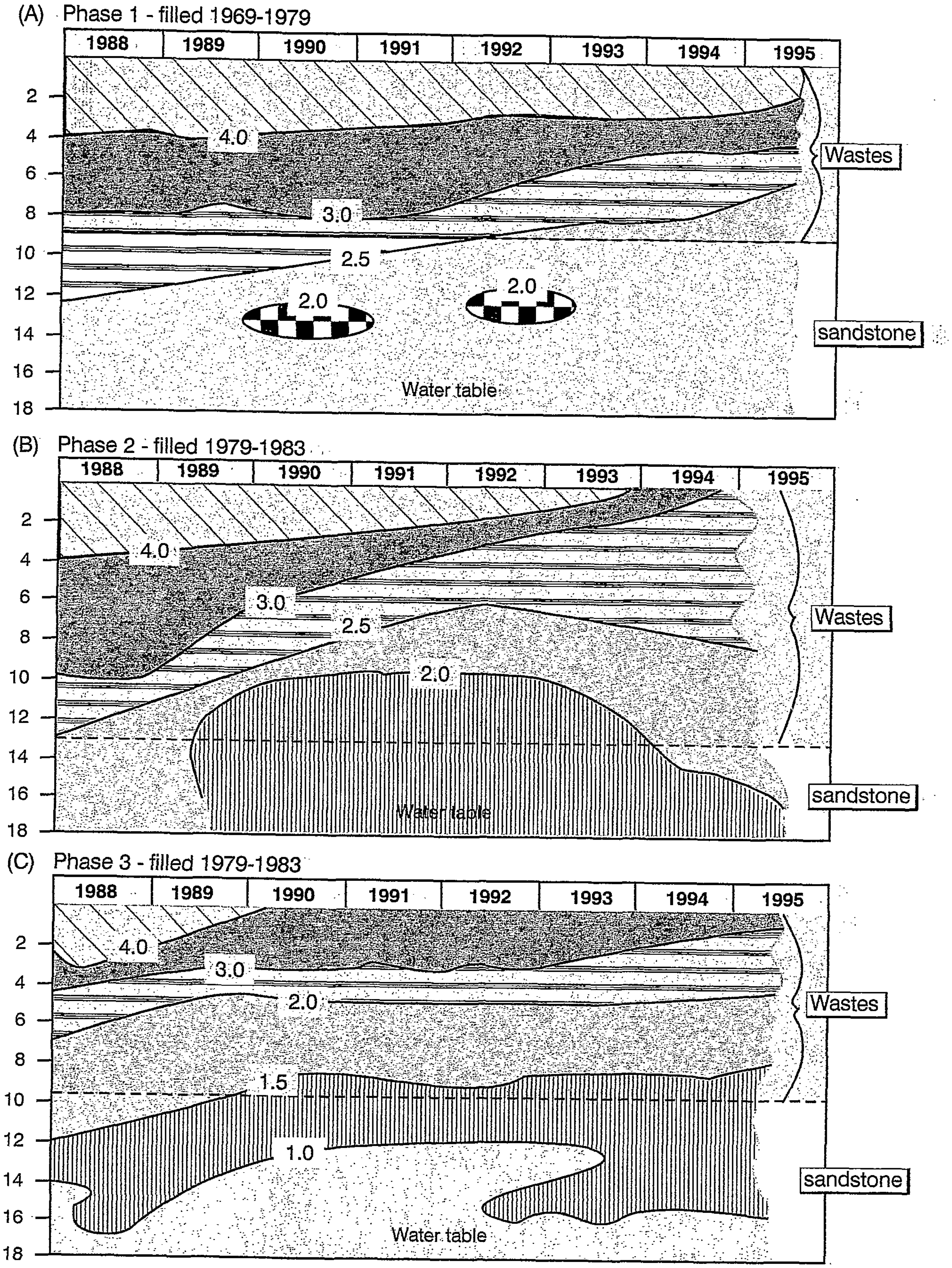


Figure 5.6 Methane/carbon dioxide ratios in pore gases in Gorsethorpe landfill

The amount and quality of data from the laboratory trials were sufficient to be used to calibrate and verify reactive transport models and it is concluded that, given reliable, site specific information, they may prove to become powerful tools in the risk assessment of waste management proposals.

A further, short laboratory study of the mobility of metal species typical of putrescible waste leachate in Sherwood Sandstone was undertaken as part of an MSc project at the Postgraduate Research Institute for Sedimentology, University of Reading (Sullivan, 1995). Batch experiments identified the significance of cation exchange capacity, total organic carbon content, calcite and iron and manganese oxides in the adsorption of four heavy metals. The strength of removal of the metals from the leachate was found to be Pb > Cd ~ Zn > Ni suggesting that these could be adsorbed in the Sherwood Sandstone for a significant period, potentially limiting their potential to reach groundwater. The data also suggest that unsaturated zone characteristics (in addition to cation exchange capacity) need to be incorporated in any risk assessment model for waste disposal on the Sherwood Sandstone.

5.5 Migration and attenuation in the saturated zone

5.5.1 Preamble

The principal information on movement and attenuation of leachate within the saturated zone of the Sherwood Sandstone has been derived from investigations at Gorsethorpe. The processes which control the migration and attenuation of leachate components in the saturated zone are shown schematically in Figure 5.7.

5.5.2 Leachate and gas movement and attenuation

Gorsethorpe

The unsaturated zone at Gorsethorpe is very shallow, ranging from nine to five metres in depth; the wastes are up to 13 m thick. The passage of leachate through the unsaturated zone was observed in drilling programmes conducted between 1978 and 1989, which have been reported in full elsewhere (Young *et al.* 1994) and summarised in previous sections of the report. Groundwater sampling has continued in 1994 and 1996, extending the monitoring dataset to 10 years.

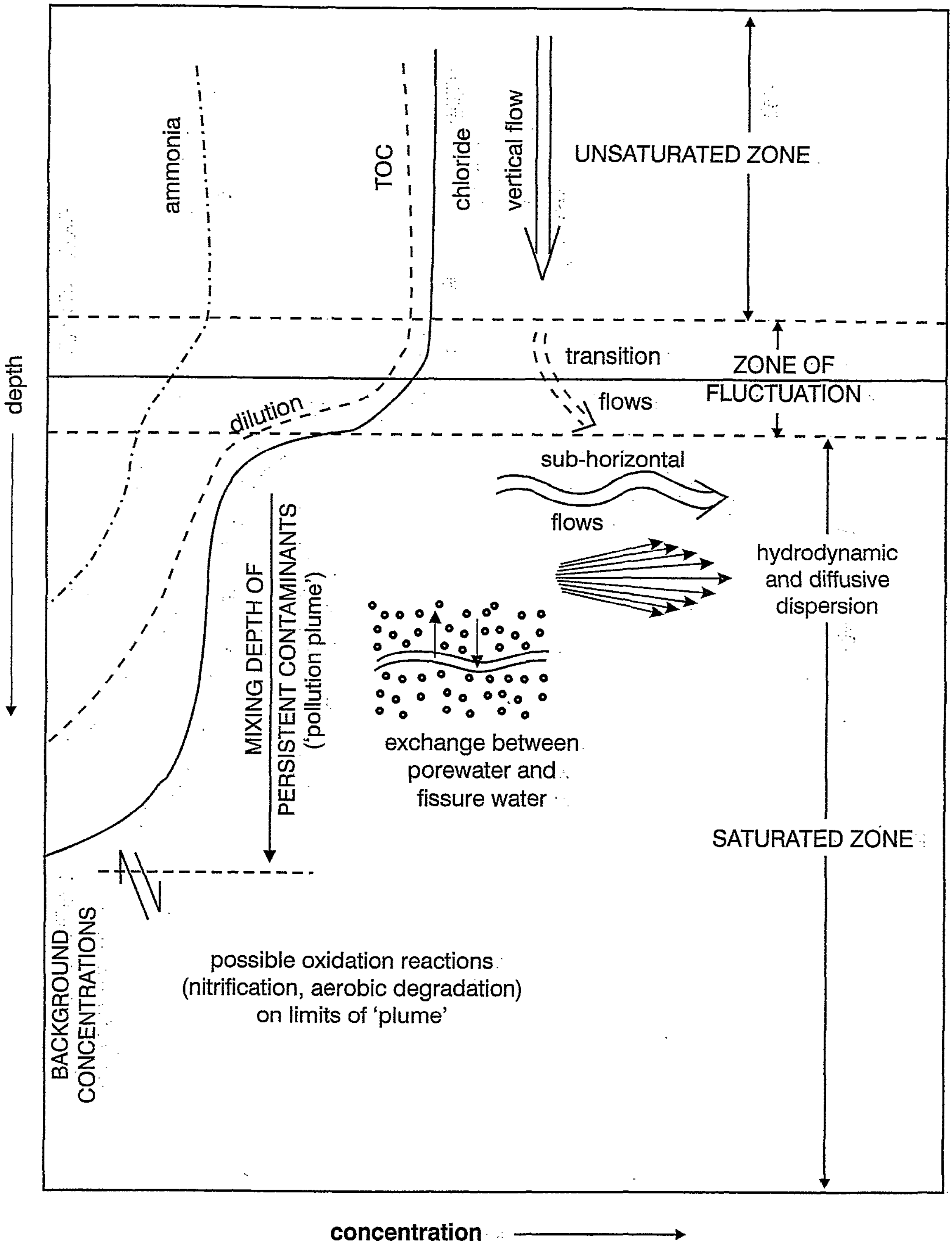


Figure 5.7 Schematic of attenuation processes in the saturated zone

The activity in and below the wastes during the monitoring period is summarised below:

- **Phase 1** (filled 1969-1979). By 1983 the leachate plume had reached the water table and in 1986 the chloride front had advanced at least 5 metres into the saturated zone, while the TOC front decreased sharply at the water table. The ammoniacal nitrogen front was retarded relative to the mobile constituents. Groundwater sampling has confirmed that the groundwater below phase 1 was already contaminated by 1983 but that chloride levels had returned to background concentrations by 1986. Total organic carbon continued to decrease and was no longer detectable in 1995. In 1994 and 1995 ammoniacal nitrogen was below the limit of detection.

- **Phase 2** (completed in 1983). The water table at the time of drilling (1987) was 17.3 m bgl. Porewater profiling showed that by 1987-1989 the TOC and chloride front had reached the water table. An equilibrium position with dilution of the steadily advancing leachate front as it entered the saturated zone appeared to have been attained. The ammoniacal nitrogen front remained retarded at 2 or 3 metres above the water table. The groundwater below phase 2 was not contaminated in 1983 and 1986. TOC, chloride and nitrate concentrations increased in 1989 and 1990, peaking in 1992. Maximum levels of ammoniacal nitrogen (up to 27 $mg\,l^{-1}$ N) were not observed until approximately 2 years later, reflecting the retardation of the migrating ammoniacal nitrogen front through the unsaturated zone, in comparison with the more mobile TOC and Cl. Groundwater levels of TOC and chloride were decreasing during 1992 and 1994, but remained at above-background levels in 1995.

- **Phase 3** (completed in 1983). The water table was approximately 10 m below the base of the wastes at the time of the investigations. By 1987, the leachate plume had advanced to the water table and above background levels of TOC and chloride were observed in porewaters from the saturated zone. Porewater nitrate levels of 0.1 - 1.4 $mg\,l^{-1}$ N persisted in the unsaturated zone, but were undetectable below the water table. As with phases 1 and 2, the migration of the ammoniacal nitrogen front through the unsaturated zone was retarded in comparison with TOC and chloride, with a lag of 1 to 2 m. Contamination of the groundwater below phase 3 was already evident when monitoring commenced (G18) in 1990. Maximum chloride levels (614 $mg\,l^{-1}$) in that year were higher than observed in phase 2 but have decreased sharply since and are now at background levels. However, TOC remained at 10 $mg\,l^{-1}$ in 1995. Levels of NH_3-N in groundwater did not exceed 0.5 $mg\,N\,l^{-1}$ until 1993/94, again caused by the delay in the ammoniacal nitrogen front reaching the water table in comparison with the TOC and chloride fronts. In 1995 the levels had only increased to 2.2 $mg\,N\,l^{-1}$. While this may represent the peak in the ammoniacal nitrogen concentrations, levels could remain detectable for at least another 12 months.

Burntstump

No unequivocal evidence of groundwater contamination by leachates has been recorded. Slightly elevated chloride concentrations were noted at the water table in boreholes drilled in 1985 (phase 2/3 area) and in 1994 (phase 7 area), whilst a small increase in TOC was found at the same level in 1991 (phase 2/3 area). In the case of the 1985 survey, the effects of localised fissure flow through the unsaturated zone were implicated, but not in the other cases and it is possible that the increases record inputs of contaminants from other, up-gradient sources. No evidence of groundwater contamination due to Burnstump leachate has been reported from the downstream monitoring points.

5.6 Quality implications for Sherwood Sandstone Groundwater (the target/receptor of mobile contaminants)

5.6.1 Overview

When the results of the initial investigations into the environmental impact of landfill disposal of wastes on Sherwood Sandstone groundwater were published in the early 1980s (Harris and Parry 1982, Harris and Lowe 1984), they were interpreted to indicate that the natural attenuating capacity of the formation was very slight, particularly with respect to potential organic contaminants. These findings appeared to be contrary to those reached a few years previously in the Department of the Environment's (1978) 'Brown Book' in which, discussing the results of investigations at a representative sample of non-contained landfills, it had been concluded that "extensive experience in the UK over a long period of time has shown very few documented cases of significant groundwater contamination due to landfill have occurred, thus indicating that the controlled disposal of wastes by landfill is acceptable;" and "that sensible landfill is realistic and an ultra-cautious approach to landfill of hazardous and other types of waste is unjustified".

However, subsequent studies have demonstrated that whilst the sandstones possess a significantly lower buffering capacity than the principal limestone aquifers (Chalk, Jurassic limestones) and are often less well endowed with exchange capacity than layer-lattice mineral-rich formations such as the Lower Greensand, they nevertheless exert an attenuating effect on leachates (Blakey and Towler 1988). Recognition of the beneficial effects of the Sherwood Sandstone only became fully apparent with prolonged monitoring, as a consequence of the slow rate of vertical movement of water and dissolved substances through the unsaturated zones of aquifers in which intergranular flow is dominant (Young and Gray 1978, Young 1981). The delay in reaching an understanding of the processes demonstrates the need to take account of the dynamics of contaminant transport and attenuation systems when designing investigations, and when reaching conclusions regarding long-term effects.

The identification of active attenuating processes in the unsaturated zone of the Sherwood Sandstone has important implications for management of both existing landfills (contained and non-contained) and with respect to the planning and authorisation of future sites. This is a consequence of the incorporation into UK legislation of the EC Directive 80/68/EEC

(Protection of Groundwater against Pollution caused by Certain Dangerous Substances) as Regulation 15 of The Waste Management Licensing Regulations 1994, which requires (Reg. 15 (2)) that "possible purifying powers of the soil and sub-soil" should be investigated and taken into account when assessing whether indirect discharge to groundwater provides an acceptable solution from the point of view of the environment. Regulation 15 makes it clear that for the purposes of that regulation, the term groundwater should include only the water in the saturated zone.

The prolonged monitoring period has also allowed observations at both sites which suggest that a systematic decline in anaerobic digestion, as indicated by landfill gas production, began some fifteen to twenty years after the principal disposals took place. A decrease in the strength of leachate forming in the wastes appears to have occurred within a similar time span. Nevertheless, the leachate (and gas) remain a potential environmental threat after about half the length of time for waste stabilisation ("generation" of 30 - 35 years - Waste Management Paper 26B, DoE 1995) which is proposed for sustainable landfilling, with the implication that production of leachate with significant organic components may continue several tens of years, and ammoniacal nitrogen remaining a potential problem for a longer time.

The Sherwood Sandstone is the second most important aquifer in Britain (after the Chalk) with a principal role in the maintenance of both direct groundwater supplies and of surface water supplies, via baseflow, to the Midlands and Northern England. The outcrops of the sandstone have been, and remain, extensively worked for building stone and aggregate with the result that there are large numbers of finished and operational landfills which may contribute actual or potential adverse effects on the quality of the groundwater resource. In addition, there is continued pressure for the development of new sites.

The national landfill geographic information system being developed on behalf of the DoE, could help to identify such sites and target those that might need more monitoring attenuation, if not remedial measures.

5.6.2 Implications for the future management of existing non-contained landfills

The operational histories of the sites at Burntstump and Gorsethorpe suggest that they may provide good analogues for other, post COPA '74, non-contained sites on the sandstone.

In both cases, the principal observations have been made in areas where restoration has, until recently, been with relatively permeable materials, so that the leachate generation and migration rates are likely to have been close to the maximum values for the local meteorological conditions and in the absence of measures to increase the flushing of contaminants from the wastes. In the case of sites with shallow (< c. 20 m) unsaturated zones, exemplified by Gorsethorpe, the attenuating capacity of the formation (buffering and cation exchange capacities in particular) has proved insufficient to prevent significant local groundwater contamination by leachate, although extensive off-site groundwater pollution has not been found.

By contrast, there is now evidence that a thick (> c. 30 m) unsaturated zone can provide significant attenuation of organic leachate components, with an important reduction in ammoniacal nitrogen flux due to the retarding effects of cation exchange. No persistent increases in groundwater concentrations below the old part of the Burntstump site, nor in the groundwater flow direction have been noted. The estimated rate of invasion of the unsaturated zone by leachate (c. $2 \mathrm{~m} \mathrm{y}^{-1}$) suggest that significant contributions to groundwater contamination will not be made before about 2005. Further attenuation of the leachate by the formation is expected to take place and the strength of leachate being generated by the wastes in the non-contained areas of fill should continue to decline, with the result that the introduction of high strength leachate to the groundwater may be short-lived. Water balance models have been employed to simulate and predict leachate generation rates at both Burnstump and Gorsethorpe and the significant reductions in generation rate that would accompany improved restoration/capping has been demonstrated. A reduction in leachate production would be expected to reduce proportionally the flux of contaminants to the water table, with a consequent increase in apparent attenuation by dilution. A negative effect of reducing the moisture flux may be to increase the time over which stabilisation (biodegradation of organic substrates and flushing of persistent compounds) of the wastes takes place.

However, it is considered unlikely that practical, controlled means of accelerating the flushing of wastes in non-contained landfills will be developed and it is suggested that the future management of non-contained landfills on the Sherwood Sandstone should be prioritised by categorising sites on the following basis:

1. Type of waste:
    - putrescible wastes - high;
    - mixed municipal solid waste - intermediate;
    - demolition/inert wastes - low;
2. Mean age of waste:
    - <15 years - high;
    - <30 years - intermediate;
    - >30 years - low);
3. Proportion of fissure flow in local sandstone:
    - >50% - high;
    - <50 >15% - intermediate;
    - <15% - low);
4. Cation Exchange Capacity of the sandstone:
    - <2 meq 100 g^{-1} - high;
    - >2 <5 meq 100 g^{-1} - intermediate;
    - >5 meq 100g^{-1} - low);

5. Mean infiltration rate:

- 100 - 70% effective rainfall - short rooted vegetation - high;
- <70 >20% effective rainfall - intermediate;
- <20% effective rainfall - low).

Within any given area, sites scoring the greatest proportion of 'High' ratings would take top priority for the development of revised management programmes. Such programmes may include the need for additional site investigations and the establishment of a different groundwater monitoring schedule. The most probable effective remedial measure would be to improve the restoration surface to reduce the rate of potential infiltration.

5.6.3 Implications for the future management of existing contained landfills

Existing, engineered containment landfills on the Sherwood Sandstone, as on other UK aquifers, have been designed to operate with a restricted leachate head above the basal lining, and to be progressively restored with low permeability caps in order to minimise infiltration and leachate production. The lining systems employed may be composite (e.g. synthetic membrane laid directly onto clay/bentonite enhanced soil (BES)) or single (membrane, bitumen, concrete or clay layer) and may include multiple liners with intermediate drainage/leak detection layers. Lined landfills require leachate collection and control systems, normally in the form of basal drains and sumps from which leachate may be pumped. In early containment sites the systems often consisted simply of shafts extending to the base of the wastes, from which leachate could be pumped, but more recent examples may be expected to incorporate perforated drains laid in a porous drainage blanket and falling by gravity to one or more abstraction sumps.

In reviewing the knowledge of the performance of membrane liners, Giroud and Bonaparte (1989) have suggested that membranes laid under appropriate quality assurance procedures would not be expected to have less than 5 defects per hectare, and that for small defects (<2 mm diameter) a head of 1 metre would give rise to leakage rate per hole of about 100 litres per day, which amounts, potentially, to 500 litres per day per hectare. However, the estimate assumes that the membrane is laid over a very free draining material (gravel) and it was stated that the leakage rate "would be significantly reduced if the pervious medium in contact with the geomembrane on one or both sides is sand or a less permeable material", which is the situation likely to be present at landfills sited on the Sherwood Sandstone. Shortly after this review, the American Society of Civil Engineers (1990) recommended that, for design purposes a leakage rate of 200 litres per day per hectare should be assumed for a membrane lined landfill, with not more than 1 metre head of leachate, constructed to modern standards, and with third party quality assurance. A recent paper by Colucci and Lavagnolo (1995) on experience gained from the operation of electric geomembrane leak location equipment suggested that from a sample of 25 landfills examined, only one had no liner defects, and that at the remainder there was an average of 15 defects per hectare.

A leakage of 200 l d^{-1} ha^{-1} is equivalent to only about 3% of the drainage that has been assessed as possible at a site such as Burntstump, before improvement of the restoration layers. The continued loss of leachate at that total daily rate through a number of defects would not be expected to have an impact on groundwater comparable to those observed at either Burnstump or Gorsethorpe, and prioritisation and development management strategies on a basis similar to that for non-contained landfills would be appropriate. However, it is possible that greater localised groundwater impacts could develop with time in response to:

1. progressive deterioration in performance of the leachate drainage/control system due to reductions in porosity and permeability by chemical encrustations and biological slime build-up (Brune *et al.* 1991), with a consequential increase of head over the liner, and increased leakage;

2. possible deterioration of the liner system with time, in particular the enlargement of existing defects;

3. progressive reduction in the storativity and permeability of the lower layers of wastes with ageing and settlement (Beaven and Powrie 1995; Bleiker *et al.* 1995), making more difficult the control of leachate levels within the fill.

One, or a combination of these factors could lead to greater point leakage rates (greater head and/or enlarged leak), which could overwhelm the local attenuation capacity of the sandstone, and possibly initiate rapid, fissure flow transfer of contaminants to groundwater.

It is suggested that in addition to the criteria proposed for prioritisation of non-contained landfills, the following additional factors should be incorporated in assessing the need for modification of management plans:

1. liner construction:

    - single liner, membrane or clay/BES <0.3 m - high;
    - single liner, clay/BES >0.3 m - intermediate;
    - composite liner - low;

2. leachate control system:

    - sumps only - high;
    - sumps and drains - intermediate;
    - sumps and drains with continuous granular blanket - low;

3. age of liner/leachate drain system:

    - greater than 30 years - high;
    - <30 >15 years - intermediate;
    - <15 years - low);

4. depth of leachate over liner:

   - greater than 10 m - high;
   - <10 >1 m - intermediate;
   - <1 m - low.

It is considered that although it may be possible to restore the capacity of some leachate drain systems by jetting or rodding, practical methods for repairing leaks in liners will not be available, except in a few circumstances. In those cases where the drainage/liner system appears to be performing to specification and is less than 15 years old, consideration may be given to accelerating the stabilisation of waste by enhancing the moisture content of the wastes by recirculation, but possibly without attempting to achieve the flushing rates which are considered necessary for the flushing bioreactor approach to landfill (i.e. the removal of principal inorganic contaminants following the organics stabilisation phase). Where that option does not exist, it is suggested that improved capping and a suitable performance monitoring programme should be instigated.

5.6.4 The development of sustainable 'bioreactor' landfills on the Sherwood Sandstone

The design of flushing bioreactor landfills is based on both field observations of existing landfills, and field and laboratory scale tests. Conclusions drawn from these trials suggest that a high moisture content is required to optimise the rate of degradation of labile waste constituents and that in order to remove persistent contaminants, such as ammoniacal nitrogen, it will be necessary to flush seven or eight bed volumes of liquid through the waste mass (Knox 1990, Walker 1993). The problem of reduction in the permeability of wastes due to compaction has been noted above. The decrease in permeability would be expected to lead to an increase in the difficulty of ensuring uniform distribution of flushing liquids and an extension of the time needed to pass a bed-volume through the wastes. A possible solution to this problem would be to restrict the depth of such fills to about 10 metres, to limit the self-weight compaction that would affect the basal layers of waste. Alternatively, maintenance of saturated conditions within the main body of the wastes would be expected to maintain high permeability, with a reduction only being noted when the wastes are drained following stabilisation. There would be a high potential for serious environmental damage in the event of a leak developing in a flooded system using current landfill engineering techniques. Research will be required to develop effective hydraulic barrier systems if such an approach were to have any hope of finding favour with waste regulation officers. In view of the potential vulnerability of the Sherwood Sandstone to sudden contaminant loadings, it would be expected that detailed emergency response plans and very significant assurances would be needed before such sites could be developed on the aquifer.

6. CONCLUSIONS

6.1 Preamble

The studies undertaken on the Sherwood Sandstone of Nottinghamshire over nearly eighteen years by staff of the Severn Trent Region of the Environment Agency (and it's predecessor bodies) and by WRc, as an integral part of the Department of the Environment funded national programme of research into long term effects of the landfill disposal of wastes on groundwater, have generated possibly one of the two largest coherent bodies of hydrogeological, geochemical and microbial information related to the impact of waste management practices on the groundwater environment that exist in the United Kingdom. A parallel study on the Chalk in Suffolk, with data extending back twenty one years, forms the other principal data bank.

The history of investigations at the Nottinghamshire sites (and those on the Chalk of Suffolk) neatly span the evolution of environmental control and protection in the UK and in the understanding of landfill processes and hydrogeological dynamics, from the implementation of the Control of Pollution Act, 1974 with a general acceptance of the 'dilute and disperse' philosophy of waste management ('Brown Book'. DoE, 1978), through the development of the 'collect and contain' strategy ('Red Book'. Waste Management Paper 26, DoE 1986) to the recognition of the need for sustainability in landfill practices and the potential requirement to adopt waste management practices that encourage a rapid stabilisation and leaching of degradable materials ('flushing bioreactors' - Waste Management Paper 26B, DoE 1995).

The conclusions to be drawn from the work may be divided into two groups:

1. conclusions related specifically to the Sherwood Sandstone sites examined, and

2. conclusions which are of wider significance.

The second group may be subdivided into those which relate to the Sherwood Sandstone aquifer as a whole and those which, by combining with information from studies of other aquifer types and other waste management practices, are relevant to the protection of groundwaters in all aquifer systems. The conclusions listed below relate only to the first sub-set.

6.2 Sites on the Sherwood Sandstone of Nottinghamshire

- High strength, acetogenic leachates have been generated by the infiltration of rainwater to municipal solids wastes at both sites. Comparison of data from sequential characterisation surveys indicate comparable leachate compositions from low compaction, relatively shallow wastes deposited up to the mid 1980s (phases 1 through 6 Burntstump, and all of Gorsethorpe), with leachate derived from recent deeper, more highly compacted waste deposits (phases 7 and 8 Burntstump).

- The absence of consistent, low permeability final capping of relatively shallow waste deposits (Gorsethorpe and the earlier phases of Burntstump) allowed continuous leachate generation to become established rapidly (by the late 1970s/early 1980s). The leachate produced from those areas provides evidence of the start of a progressive decrease in strength some 15 to 20 years after deposition.

- A concomitant decline in the rate of landfill gas generation has taken place, allowing the re-establishment of aerobic conditions in the deeper part of the unsaturated zone beneath the older part of Burntstump.

- In contrast, field capacity in more recent, deeper and better compacted fill with low permeability capping had not been fully achieved 5 years after completion of filling, with leachate migration from the wastes being controlled by the effects of compression of the lower layers of waste.

- Leachate derived contaminants have entered the unsaturated zone of the Sherwood Sandstone below both Burntstump and Gorsethorpe landfills. Hydrogeological investigations indicate that recharge through the unsaturated zone is dominated by intergranular flow, with the consequence that the rate of vertical penetration of mobile and persistent dissolved contaminants is slow, and directly proportional to the flux of leachate (generally $<2 \text{ m y}^{-1}$).

- Landfill gas is more mobile within the unsaturated zone than dissolved leachate components, and migrates downwards more rapidly, establishing an anaerobic zone in advance of the leachate front. Subsequent re-establishment of aerobic conditions below the leachate front (see above) would be expected to encourage further attenuation of leachate by aerobic processes.

- The Sherwood Sandstone has a generally low buffering capacity, with the result that acidic conditions (low pH) (resulting from the invasion by acetogenic leachate) persist and inhibit methanogenic microbial activity. Consequently, leachate has passed through the shallow unsaturated zone at Gorsethorpe and entered groundwater. However, the deep unsaturated zone at Burntstump has allowed the establishment of conditions conducive to methanogenesis and a progressive and significant reduction in the organic strength of the leachate front. Acclimation of the Sandstone to leachate attenuation is confirmed by the presence of viable bacterial populations beneath waste deposits some two orders of magnitude greater than in the unsaturated zone beneath adjacent farmland.

- The cation exchange capacity of the Sandstone is low (2.0 meq 100 g^{-1} or less), but sufficient to retard the movement of the exchangeable ammonium ion by about 50% when compared with the mobile chloride ion.

- Groundwater contamination by leachate is present beneath the shallow unsaturated zone at Gorsethorpe landfill, but decreasing as a result of the progressive reduction in strength of leachate generated by the ageing wastes. No firm evidence of groundwater pollution by leachate has been recorded at Burntstump, either immediately beneath the landfill area, or in the direction of groundwater flow.

- Where a sufficient depth of unsaturated Sandstone is present and where the rate of leachate generation/release is restricted, natural attenuating processes in the unsaturated zone of the Sherwood Sandstone in Nottinghamshire form a valuable protection of the quality of groundwater resources. The groundwater quality at sites with a shallow unsaturated zone is at risk.

- Laboratory flow-through column studies have been shown to be capable of mimicking the field behaviour of the Sherwood Sandstone with respect to the attenuation of leachate components (see also 6.3 below).

- Direct field measurements of potential leachate generation (moisture flux to wastes) indicate that application of the appropriate MORECS evaporation estimate provides an estimate within 5% of the true value.

- Comparison of intensive monitoring at Gorsethorpe landfill, of leachate-contaminated groundwater, with the results of monitoring carried out to standard protocols confirms that the standard procedures provide reliable information. The value of monitoring data from an unpurged borehole is dubious.

6.3 Landfill facilities elsewhere on the Sherwood Sandstone

- In Sherwood Sandstone areas with a significant fissure flow component, the beneficial attenuating processes operating in the unsaturated zone are likely to be by-passed, with an increased risk of unacceptable groundwater pollution.

- Simple analytical determinations of properties such as buffering capacity and cation exchange capacity of the Sandstone may be used to assist quantification to risk assessments. Further information on which to make assessments may be obtained by appropriate laboratory based column tests to examine leachate/formation attenuation dynamics.

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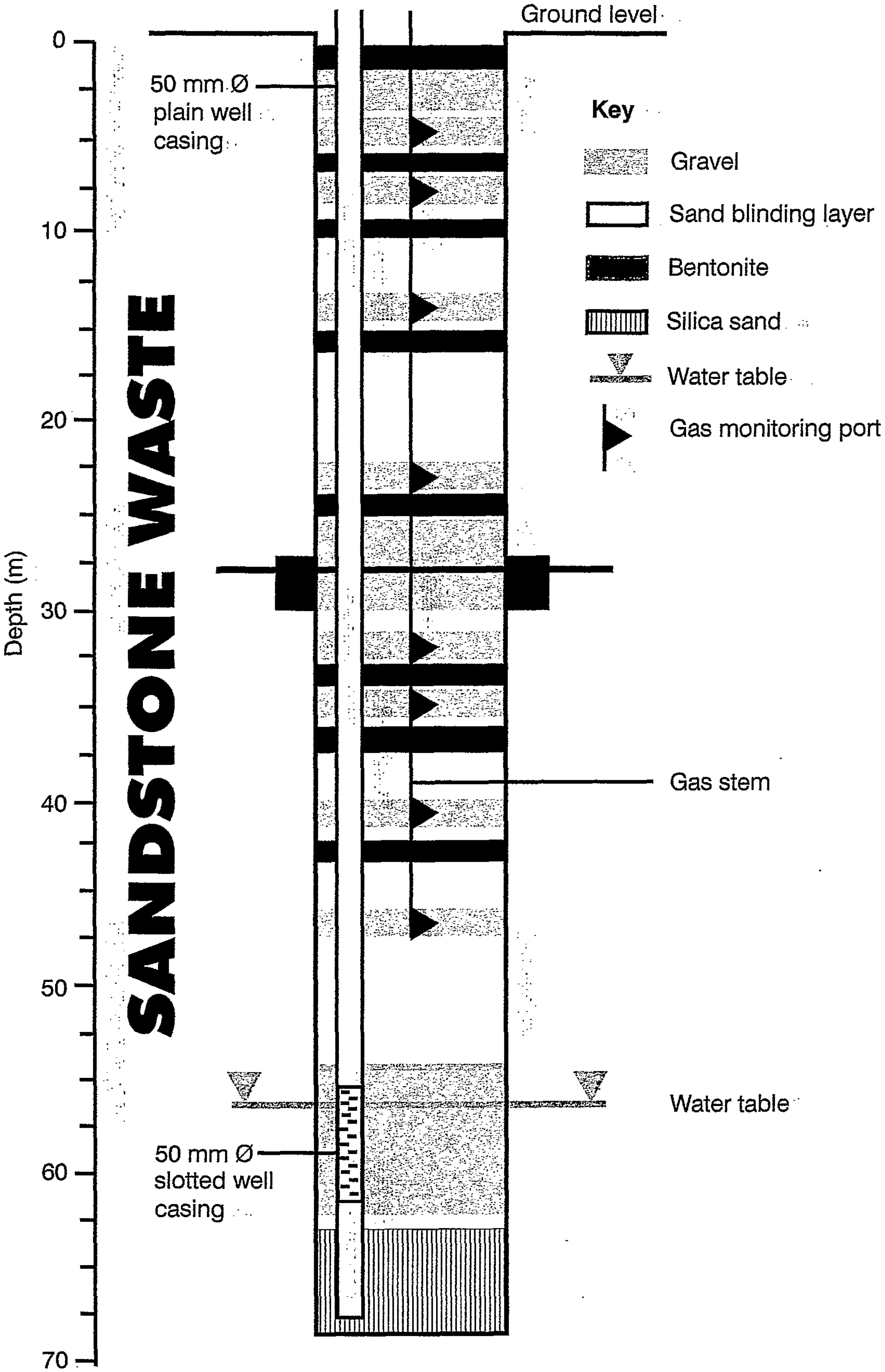
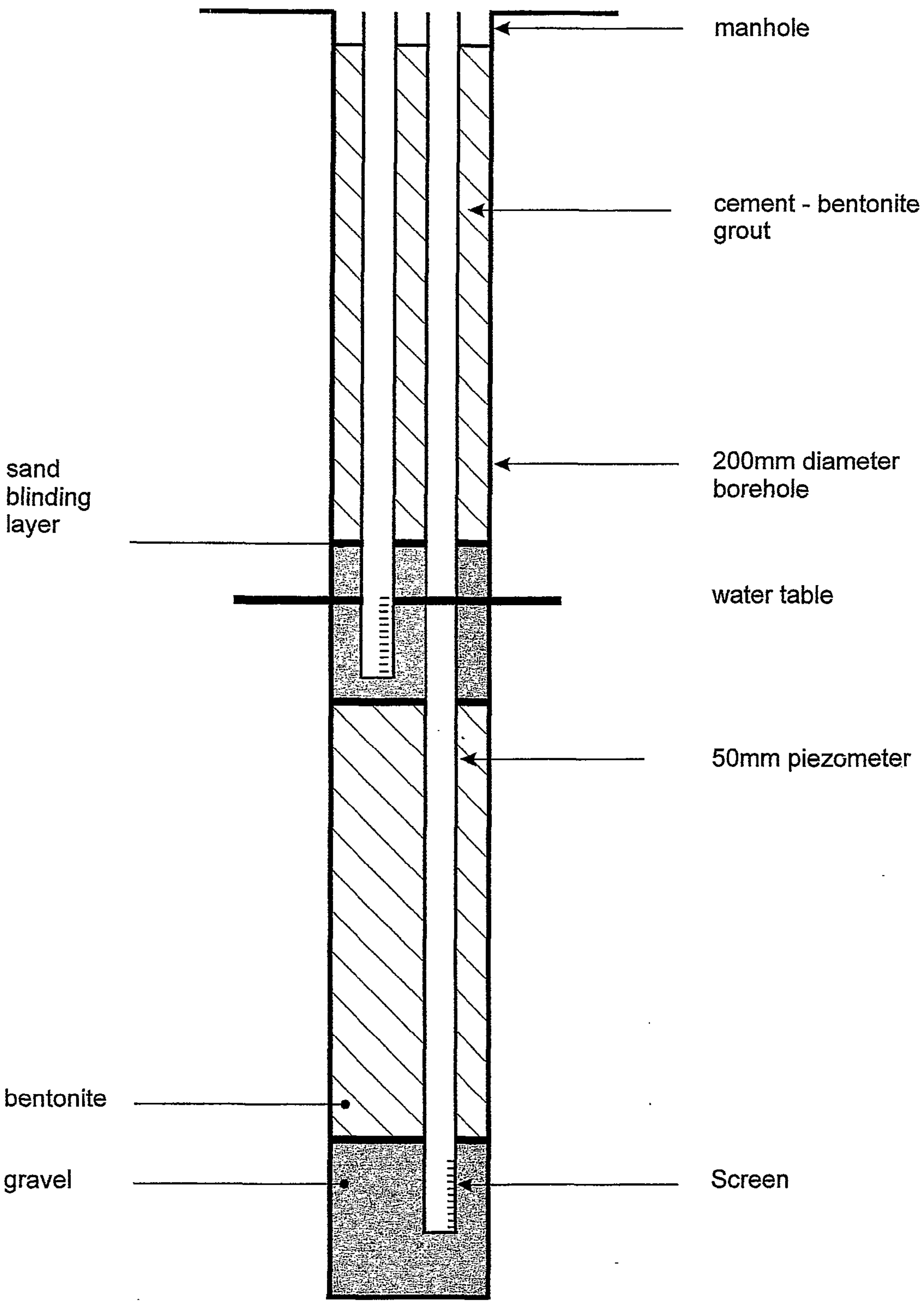
APPENDIX A BOREHOLE CONSTRUCTION

A1 CONSTRUCTION OF BOREHOLE B15 AT BURNSTUMP (AUGUST 1994)

A2 CONSTRUCTION OF BOREHOLE G19 AT GORSETHORPE (1995)



A1 Construction details of Borehole B15 at Burntstump (August 1994)



Not to scale

A2 **Construction of borehole G19 at Gorsethorpe (1995)**

APPENDIX B METHODS AND PROTOCOLS

B1 METHODS FOR SAMPLE PREPARATION AND ANALYSIS (SOLID WASTES, POREWATERS, LEACHATES AND GROUNDWATERS)

B2 LEACHING TESTS (CEN AND DIN): BURNTSTUMP WASTES

B3 BIOCHEMICAL METHANE ASSAY

B4 GROUNDWATER SAMPLING PROTOCOL

B1 METHODS FOR SAMPLE PREPARATION AND ANALYSIS (SOLID WASTES, POREWATERS, LEACHATES AND GROUNDWATERS)

Determinands	Sample preparation method for solid wastes	Analytical technique for waste digests, porewaters, leaching test leachates and groundwaters
Na, Ca, K, Mg, Ca, Fe, Mn	Nitric acid digestion	Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)
Cd, Cr, Pb, Zn, Cu, Ni,	Aqua regia digestion (acid soluble metals)	Flame Atomic Absorption Spectrometry, Graphite Furnace Atomic Absorption Spectrometry (leachates) and ICP-OES (groundwaters)
Mo	Aqua regia digestion	ICP-OES
B	Not determined in wastes	ICP-OES
Hg	Aqua regia digestion(1)	Cold Vapour Atomic Absorption Spectrometry
Cl, SO_4	Water extraction	Ion chromatography
NH_3, NO_3, NO_2	Not determined in wastes	Colorimetry
SRP, TSP	Filtration, acid persulphate digestion for TSP (groundwaters)	Colorimetry
N, P	$Na/CaSO_4$ catalyst/H_2SO_4 acid digestion	Colorimetry
Alkalinity	Not determined in wastes	Titration

B1 Continued

Determinands	Sample preparation method for solid wastes	Analytical technique for waste digests, porewaters, leaching test leachates and groundwaters
Total and dissolved organic carbon	Acidification to remove inorganic carbon	High temperature combustion and non-dispersive infra-red (NDIR)
Carboxylic acids	Not determined in wastes	Direct injection onto GC with FID
Volatile matter	Ignition at 550° C	Weight loss
Moisture content	Oven dry at 105° C	Constant weight

Notes

(1) Leachates from leaching tests were digested ($KMnO_4/H_2SO_4$) prior to analysis.
(2) WRc in house analytical methods are al based on SCA ('blue book') methods.

B2 LEACHING TESTS (CEN AND DIN): BURNTSTUMP WASTES

Samples were subjected to two 24 hour leaching tests to determine the proportion of the elements present in the landfilled waste that was available for leaching with unbuffered deionised water. The exercise enabled a comparison to be made between the single-step DIN leaching test (DIN 3841-S4, October 1994) and the two-step CEN compliance test for granular waste materials (CEN 1994).

The experimental conditions of the two leaching tests are presented below.

Table B1 Leaching tests conducted on the Burntstump waste samples: experimental conditions

Condition	DIN test	Granular leach test
Sample weight	100 g dry solids	100 g dry solids
Leachant volume		
step 1	1000 ml	200 ml
step 2	not applicable	800 ml
Solid to liquid ratio		
step 1	1:10	1:2
step 2 (cumulative)	not applicable	1:10
Period of extraction	24 hours	8 hours (step 1) 16 hours (step 2)
Leachant	Deionised water (allowed to equilibrate over night)	Deionised water (allowed to equilibrate over night)
Agitation	Orbital shaker at 200 rpm	Orbital shaker at 200 rpm
References	DIN 3841-S4 (October 1994)	CEN (1994) van der Sloot *et al.* (1994)

Both the upper and lower waste samples were leached in duplicate. The leachates were vacuum-filtered through 0.45 µm membrane filters and analysed by the methods presented in Appendix B1.

Sufficient leachate was generated by the DIN test and the second step of the CEN test for the duplicate leachates to be analysed separately. However, only a small volume of leachate was generated by the first step of the CEN leaching test due to the low liquid to solid ratio employed (1:2) and the high moisture capacity of the processed waste materials. Equal volumes of second step CEN leachates had to be combined to provide sufficient liquor for the determinations listed above. There was still insufficient volume for NOx and dissolved organic carbon (DOC) to be determined. The CEN leaching test was therefore repeated on further single samples of both the upper and lower waste and the leachates were submitted for DOC and ammoniacal nitrogen. The latter was also determined on a sub-sample of the unfiltered leachates to determine whether any ammonia was lost during the vacuum filtration of the leachates. As the levels of some of the heavy metals was lower than expected in the leachates, the repeat samples were submitted for analysis by graphite furnace, which has a superior detection limit to flame AAS or ICP for Cr, Cd and Pb.

Test blanks - leachant only - were shaken and filtered in an identical manner to the samples to determine whether the reagents, equipment or air-borne contamination contributed to the leachate determinations. A sample of leachant (stabilised deionised water) was also submitted for analysis straight from the carboy into appropriately preserved bottles as a reagent blank. During the repeat CEN leaching exercise, blanks were submitted for NH_3-N, DOC and Cr, Cd and Pb.

The analyses of the unfiltered and filtered CEN leachates demonstrated that in the dilute leachates where levels of ammoniacal nitrogen were low ($\sim$5 mg l^{-1}) up to 50% of the NH_3-N was lost during filtration. This was not observed at higher level ($\sim$20 mg l^{-1}).

B3 BIOCHEMICAL METHANE POTENTIAL ASSAY

B3.1 Scope

The International Standard, ISO 11734, specifies a method for the evaluation of biodegradability of organic compounds at a given concentration by anaerobic micro-organisms. The conditions described in this test do not necessarily correspond to the optimal conditions allowing the maximum value of biodegradation to occur, since a relatively concentrated sludge is used with a relatively low concentration of test material. The test allows exposure of sludge to the chemical for a period of up to 60 days, which is longer than the normal sludge retention time (25-30 days) in anaerobic digesters, though digesters at industrial sites can have much longer retention time.

B3.2 Field of application

The method applies to organic compounds of known carbon content which are:

- soluble;
- insoluble, provided that a method of exact dosing is applicable;
- are non-volatile, or having a negligible vapour pressure under the conditions of the test.

B3.3 Apparatus

In addition to the normal laboratory facilities the following specialised equipment is required:

- Incubator or thermostatically controlled water or sand bath.
- Pressure resistant glass reaction vessels, nominal size 0.1 to 1 litre, each fitted with a gas-tight septum, capable of withstanding 2 atmosphere (e.g. Figure 1). 160 ml serum bottles were used for the purpose of this study. These will be closed with No. 25 Suba-seal septa.
- Pressure-measuring device, e.g. pressure transducer connected to a syringe needle (gauge 12-18 or 2.65-1.24 mm OD), 3-way gas-tight valve, which also facilitates the release of excess pressure,). Gas pressure were measured with a hand-held precision pressure meter (John Watson and Smith Ltd, Leeds) attached to a miniature three-way inert valve (Aldrich Chemical Co. Ltd, Gillingham) and male Luer fitting.

B3.4 Reagents

B3.4.1 Distilled or de-ionised water

Reagents were added to distilled or de-ionised water containing less than 2 mg DOC l^{-1}.

B3.4.2 Dilution medium

Only reagents of recognised analytical grade were used. For each test sample, 600 ml of the dilution medium was prepared as presented in Table B2.

Table B2 Dilution medium for BMP assay

Constituent		Amount
Anhydrous potassium dihydrogen phosphate	KH_2PO_4	0.27 g
Disodium hydrogen phosphate dodecahydrate	$Na_2HPO_4.122H_2O$	1.12 g
Ammonium chloride	NH_4Cl	0.53 g
Calcium chloride dihydrate	$CaCl_2.2H_20$	0.075 g
Magnesium chloride hexahydrate	$MgCl_2.6H_2O$	0.1 g
Ferrous chloride tetrahydrate	$FeCl_2.4H_2O$	0.02 g
Distilled or deionised water		1 litre

A total of 20 litres of media in two separate 10 l glass container was prepared One was used to resuspend the centrifuged sludge, the other was for the test media.

The pH of the medium was adjusted to 7.0 ± 0.2 with dilute mineral acid or alkali. The medium was sparged with oxygen-free nitrogen for approximately 1h before use.

B3.5 Primary digesting sludge

B3.5.1 Definition

A mixture of the solid phases of sewage which has been incubated in a digester at about 35 °C to produce an active syntrophic consortium of fermentative and methanogenic bacteria producing carbon dioxide and methane.

B3.5.2 Sludge Collection

Digesting sludge was collected from a primary digester at a sewage treatment works treating predominantly domestic sewage. 5 litres of digested sludge were collected in wide-necked bottles constructed from high density polyethylene. The bottles were filled to within 1 cm of the top and sealed tightly. After transport to the laboratory, measurement of the total solids was carried out directly. The bulk sample of digested sludge can be held at room temperature for 24 hours without loss of activity.

B3.5.3 Total solids determination

Total solids determination were carried out according to the Standard Operating Procedure "Determination of the concentration of suspended solids, SOP No 370".

B3.5.4 Preparation of sludge

This test procedure requires digested sludge to contain a low DIC concentration, resulting in a concentration below 10 mg DIC l^{-1} in the final test solution. This is achieved using the following procedure:

a) Transfer 1 litre of seeding sludge into six 250 ml centrifuge tubes supplied with sealable caps; flush the headspace with oxygen-free nitrogen for 1 minute; seal tube taking care to exclude air;

b) Weigh each centrifuge tube plus contents;

c) Centrifuge at 3000 rpm for 5 minutes;

d) Re-suspended the pellet in oxygen-free dilution medium. The pellet is resuspended by sparging the media with nitrogen gas;

e) Repeat steps a - c until sludge has been centrifuged and re-suspended a total of three times.

The above operations was conducted in such a way that the sludge had minimal contact with air. The centrifuged digested sludge was finally diluted by the addition of one volume of sludge to nine volumes of dilution media as described below in Section 5.5.

B3.5.5 Sludge addition to test medium

The final manipulation to take place with the sludge is to re-suspend the pellet in the requisite volume of dilution medium to give a concentration of solids in the range 1 to 5 g l^{-1}. This is most easily achieved by adding 500 ml of washed digested sludge (if the dry weight of the original sludge solids is between 10 and 50 g l^{-1}) into 4500 ml of dilution media contained in a aspirator (5 litre volume). The dilution media/sludge mixture headspace was sparged for 30 minutes with oxygen-free nitrogen whilst mixing the vessel contents prior to dispensing into serum vials. The pH was adjusted as necessary to 7.0 ± 0.2.

B3.5.6 Mode of dispensing dilution media containing digested sludge

100 ml aliquots of dilution media/sludge mixture were transferred to each serum vial containing the measured volume of test material. The transfer of liquid under anaerobic conditions was carried out as described in the following step procedure:

a) Sludge should be stirred in the aspirator at a speed which keeps it dispersed but does not create a vortex. Gas should be flowing through the gassing needles and the sintered sparger.

b) Place three serum bottles under the gassing needles and leave for three minutes.

c) Fill the pipette with digesting sludge using an automatic pipette filler.

d) Repeat c for the remaining two bottles.

e) Whilst removing the first bottle from the gassing needle, stopper with a Suba-seal. Fold the Suba-seal over the neck of the bottle and place in an incubator at 35 °C. Lubricate the Suba-seal with a few drops of distilled/deionised water.

f) Swirl bottle to mix contents.

g) Place a new bottle beneath the gassing needle.

h) Repeat procedure for the remaining two bottles.

i) Dispense the remainder of the sludge.

B3.6 Test and reference material

B3.6.1 Test chemical addition

0.5 g of each refuse composite sample was added to the test vessels prior to the addition of media and seed.

Table B3 **Amounts of test and reference substance added to serum vials**

Vial number	Test substance	Amount of test sample required (g or ml)
1-3	Control	Zero
4-6	Control	Zero
7-9	B1	0.5
10-12	B2	0.5
13-15	Sodium benzoate	5 ml

B3.6.2 Reference chemical addition

Sodium benzoate was used as the reference compound. A stock solution of 1 g C per litre was prepared (pH 7.0 ± 0.2). 100 ml of the stock solution was placed into a serum vial of 160 ml capacity. The solution was initially degassed for a period of 10 minutes with nitrogen prior to addition to test bottles. 5 ml of the reference compound was then be added by syringe to the stoppered test vessel prior to incubation.

B3.6.3 Experimental design

Addition of test or reference chemicals will be performed in the following fashion:

Table B4 **Experimental Design**

Bottle Number	Test Compound Addition	Analysis
1-3	Control	pH
4-6	Control	Pressure
7-9	B1	Pressure
10-12	B2	Pressure
13-15	Sodium benzoate	Pressure

B3.7 Incubation and gas measurements

B3.7.1 Incubation of test vessels

The vessels were incubated at 35 ± 2 °C in the dark for about 1 hour to allow equilibration and release excess gas to the atmosphere.

B3.7.2 Calibration of pressure meter

Gas pressure readings were related to volume of gas produced using a standard curve produced by injecting known volumes of gas at room temperature into serum bottles containing 100 ml of dilution medium. Calibration of the pressure meter was carried out as follows:

a) Dispense 100 ml aliquots of medium into five serum bottles. Close serum bottles with Suba-seals. Place into a water bath at 37 °C. The water level should be no higher than the neck of the bottle.

b) Switch on pressure meter and allow to stabilise.

c) Zero instrument.

d) Insert syringe needle through seal of one bottle and open miniature Hamilton valve until pressure reads zero. Close Hamilton valve.

e) Repeat for other bottles.

f) Inject a 2 ml of gas through the seal of one bottle, allow gas to reach temperature of the water (2 mins) record pressure and then open Hamilton valve until pressure reads zero. Close Hamilton valve.

g) Repeat for other bottles.

h) Repeat using 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 22, 25, 28, 30 and 50 ml of air (allow 2 minutes for air to equilibrate in the bottles).

i) Plot a calibration curve of pressure (bar) against gas volume (ml).

B3.7.3 Pressure measurement

Gas production was monitored at least two times per week. The contents of the vessels were mixed by shaking for a few minutes before each pressure measurement. Gas pressure was measured by inserting a syringe needle through seal of one bottle, allowing the pressure to stabilise, and then recording the pressure reading.

B3.8 Calculation and expression of results

B3.8.1 Course of biodegradation

If intermediate pressure measurements have been taken, plot accumulated pressure increase (dP) against time to obtain a biodegradation curve. This will serve the purpose of demonstrating the lag time prior to biodegradation. This graph will appear in the final test report. Actual gas volumes produced were calculated by comparison to a standard curve of pressure measurements as described above in Section 7.2. The test is invalid if the reference chemical(s) is not degraded in excess of 70% within 28 days of incubation with digested sludge.

B3.9 References

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ISO 11734. Water quality - evaluation of the ultimate anaerobic biodegradability of organic compounds in digested sludge. Method by measurement of biogas production.

WRc SOP No.370. Determination of the concentration of suspended solids.

B4 WRc PROTOCOL FOR SAMPLING GROUNDWATER FROM AN OBSERVATION BOREHOLE (AFTER CLARK 1992)

B4.1 Equipment/Apparatus

The following list is not exhaustive but includes the main elements:

- Site map and borehole diagram (background information on the monitoring array is highly desirable);
- Tool kit (to serve the monitoring equipment as well as the closure cover of the borehole);
- pH meter and probe;
- Conductivity meter and probe;
- Dissolved oxygen (DO) meter and probe;
- Eh meter and probe (optional);
- Flow through cell for pH, conductivity, Eh and DO measurements (optional);
- Sample bottles;
- Plastic sheet;
- Groundwater level dipper;
- Sample recovery equipment;
- Totalising water meter (optional);
- Deionised or distilled water for rinsing equipment.

B4.2 Preparation for sampling

The requirements of the sampling exercise will be documented in the Sampling Plan. Before developing the Sampling Plan, the objectives of the exercise must be defined. This protocol only covers the basic sampling methodology, but the following check list will assist the development of the Sampling Plan and hence the preparations for the sampling exercise.

1. Read the Company/organisation health and safety policy statement and prepare a Site Operating Procedure (SOP) for inclusion in the Sampling Plan. (NOTE: The SOP should take account of the employer's responsibility with respect to the Control of Substances Hazardous to Health (COSHH) Regulations 1988. Each SOP should be assigned a specific hazard/risk code which can be used to identify appropriate Personal Protective Equipment (PPE) for the task.)

2. Check the access route and ground conditions for the field vehicle and discuss with the site owner or other responsible person. Agree conditions of entry to the site in writing and add these to the Sampling Plan.

3. Discuss the sample analytical requirements with the analyst (e.g. determinands, sample type and condition, bottles, sample storage, reception arrangements) and collect the prepared bottles in good time for the sampling exercise. (NOTE: Other sample requirements like filtration, preservation, bottle head space should be discussed at this stage).

4. Obtain all information relating to borehole construction and rest water levels. (NOTE: a geophysical log of the borehole provides additional valuable information, if available).

5. Calculate the volume of water to be pumped from the borehole in order to remove at least three borehole volumes of water. (NOTE: It is often helpful at this stage to create a quick look up table for later use in the field).

6. Decide on the depth at which the pump is to be set. (NOTE: the decision will be based on the borehole characteristics, the position of the screen, the type of pump and the objectives of the exercise. Always check the Sampling Plan and discuss with the supervisor.)

7. Before packing the sample recovery equipment, check the cleaning procedure records and repeat to the appropriate standard, if not satisfied.

8. Check the calibration of the pH, temperature, conductivity, Eh and DO probes. (NOTE: Ensure that calibration and standard solutions are taken on the sampling exercise.)

B4.3 Procedure for taking a groundwater sample from an observation borehole

1. Open the observation borehole and check the depth to the water table and the total depth of the borehole using a groundwater level dipper. Record the results using field documentation.

2. Lay out all the sample recovery equipment on a clean plastic sheet or in trays.

3. Check the volume of water to be pumped (see Preparation for Sampling, item 5) and set up arrangements for disposing of the purged groundwater (see the Sampling Plan).

4. Assemble the sample recovery equipment, tape all cables and rising main together to avoid tangling and damage, and lower the assembly into the borehole. For large diameter observation boreholes a tripod and winch assembly may be required. (NOTE: Secure any loose cables to the rising main to avoid tangling and damage.)

5. Slowly lower the assembly to the required depth and secure in position (e.g. by locking the cable drum or by using a catch-plate). The sample inlet should be 1-2 meters above the screen (if present).

6. Connect the discharge hose to the top of the rising main. A totalising water meter can be fitted onto the discharge hose to aid the measurement of discharge volume. (NOTE: The discharge hose should be sufficiently long to prevent water returning to the borehole head works.)

7. Consult the Sampling Plan for the required purge volume, start the pump and run until the borehole has been purged. (NOTE: see item 3 above.)

8. Check the calibration of probes for on-site determinations. Measurements of temperature, pH, conductivity, Eh, and DO should all be carried out in a flow-through cell connected to the reduced-flow discharge line, after removing air bubbles from the cell. Alternatively pH, temperature and conductivity can be measured in a clean beaker full of groundwater, but on no account should Eh and DO be measured in this way. Record the results in the field log, with any comments on appearance and odour.

9. Fill the sample bottles direct from the discharge tubing where possible. Rinse the bottles which do not contain preservative with groundwater and fill to the top. Bottles containing preservatives should not be rinsed and only filled to the 'fill-to-mark'. Filter the samples for metal determinations through 0.45 μm membrane filters (after discarding the first aliquot of filtered sample).

10. Reduce the pumping rate to <2 l min^{-1} when sampling for volatile determinands. Fill the glass vial to the brim and screw on the cap with PTFE-lined septum. There should be no headspace within the vial. Store the vials upside-down in a coolbox to minimise the loss of volatiles.

11. Check that the sample bottles are labelled correctly, then pack them into a coolbox containing ice packs for transport.

12. When QA/QC samples are needed, 'trip' blanks should remain unopened and 'field' blanks should be transferred from their bottles into fresh bottles containing the relevant preservative. 'Equipment' blanks are prepared by running organic-free/deionised water through the sampling equipment.

13. Rinse the sampling accessories with organic-free, deionised water before packing them away.

14. Slowly withdraw the sample recovery equipment from the borehole so as to avoid damage to the rising main or any cables. Disassemble the equipment on the plastic sheet, rinse with deionised or distilled water and pack the equipment away.

15. Secure the closure cover of the borehole.

16. Deliver the sample bottles to the laboratory, completing sample custody forms.

17. All field equipment should be thoroughly cleaned using a proprietary cleaning fluid on return to the laboratory (NOTE: It is prudent practice to set up a record of this activity and get a colleague to authorise the completion of the cleaning before the equipment is returned to storage.)

B4.4 Additional informative notes

- Pump sets and dippers used for contaminated water should be appropriately marked and must not be used for routine groundwater monitoring.

- Where dedicated sampling equipment for each borehole is not available, and previous monitoring data demonstrate that a range of levels of contamination will be encountered during a sampling exercise, attempt to commence the sampling exercise with the least contaminated borehole, finishing with the most heavily contaminated borehole.

- Where piezometers are being sampled, the 'active' water column will be equal to the distance from the sample inlet of the recovery equipment to the bottom of the borehole.

- For large diameter observation boreholes, a dual pump array for purging and sampling may be required.

- Conditions in the borehole (e.g. presence of silt or other heavy particulates) may affect the temporal variations in the data, or be responsible for systematic trends. Where changes in borehole conditions are encountered, the field technician must discuss his observations with his supervisor and any agreed changes in monitoring strategy logged in the Sampling Plan.

- The principle of removing three well volumes to purge boreholes is a good general guide. However, detailed knowledge obtained during a monitoring programme might indicate that a change to this strategy is appropriate.

B4.5 Reference

Clark, L. (1992) Methodology for monitoring and sampling groundwater. NRA R&D Note 126.

APPENDIX C WATER BALANCE MODEL

C1 DEVELOPMENTS IN LEACHATE GENERATION MODELLING

C2 THE CONCEPTUAL MODEL

C3 APPLICATION TO BURNTSTUMP LANDFILL

C4 APPLICATION TO GORSETHORPE LANDFILL

APPENDIX C WATER BALANCE MODEL

C1 DEVELOPMENTS IN LEACHATE GENERATION MODELLING

A model to simulate water movement through a landfill, and the consequent production of leachate, was originally developed at WRc in 1986 in response to the need to fully understand the flow of leachate from the Edmonton Test Cells (Craft and Blakey 1986). The original model was adapted to landfill leachate production in 1989. The model embodied the concepts of water mass balance and drainage of water through a partially saturated medium. Until 1994, only minor changes had been made to the original model, which had been applied with varying degrees of success to numerous landfills. In the past year, it has been possible to re-assess the concepts in the model, to develop an improved version and to test it against better field data. This report describes the new model, and its application to the Burntstump landfill.

C2 THE CONCEPTUAL MODEL

The model includes the concepts of:

- the filling of cells at a monthly resolution;
- user-specified water content in the input waste;
- simulation of the landfill as a sequence of layers, each comprising one month's input;
- addition of each month's rainfall recharge to the top layer of waste;
- capping of the landfill with consequent modification of rainfall recharge;
- settlement of the waste, dependent on age since placement;
- drainage of water from one layer into the next, dependent on water content of waste and the field capacity and saturation capacities of the waste;
- calculation of leachate production on a monthly basis.

The model currently works with at a monthly resolution as indicated above, but the size of the time step can be reduced if required.

The concepts outlined above are considered to represent the key physical processes involved in the generation of leachate. The way in which each of these concepts is handled in the model will now be described.

C2.1 Waste input

In order to be able to calculate leachate production, data on waste inputs are required from the start of filling, through to completion. Older data are generally less reliable, and in some cases it may be necessary to estimate rates of waste input for earlier years from current knowledge of site conditions. The effects of an error in waste input volume for a particular year on leachate production in later years diminishes with time. However, model runs show that such effects may persist for 5-10 years, so that good data for the early years of filling can be important.

Annual filling rates are required by the model in units of m^3, dry tonnes or wet tonnes. The model converts the input data into dry tonne per month which is the basic unit of calculation. For what-if predictions of leachate generation in future years, the proposed filling sequence must be specified up to completion.

The model assumes that filling occurs in a number of separate stages, corresponding to landfill cells. Filling of cells can run consecutively, concurrently or as a combination of the two. At any time the cells can be partially or completely capped.

C2.2 Water content of waste

The moisture content of fresh waste can be specified by the user. The default value is 35% by dry weight.

C2.3 Layer structure

Each month's waste input is represented in the model as a layer of uniform composition. The first month's input into the cell comprises the first layer, and the number of layers in the model increases with time until the cell is completed.

C2.4 Rainfall recharge

Monthly rainfall recharge data are used to calculate the volumes of water added to the cell. The monthly input will normally be the area of the cell multiplied by the bare soil rainfall recharge, and will be added into the top layer of waste. The model includes the facility to calculate rainfall recharge inputs using pre-specified functions, so that specific algorithms may be used for particular cases.

The normal source of recharge data is MORECS. This will need to be obtained as monthly values for a sequence of years spanning the period of landfilling, and extending to a total of at least 10-15 years. The model uses the sequence, repeated many times if required, to simulate leachate generation into the future.

C2.5 Capping of the landfill

The model can simulate capping of the landfill by using the pre-specified recharge functions described in C1.4. A complex sequence of capping operations, including for example temporary cover and subsequent removal to permit continuance of filling, can be simulated.

For each type of capping, the resultant modification of the rainfall recharge data must be calculated and built into the pre-specified functions used by the model.

C2.6 Settlement of the waste

Settlement of the waste is simulated as a gradual compaction over a number of years following emplacement. Each month's waste input is modelled as a separate layer, so that a settlement factor is required for each layer for each month. Settlement is assumed to be solely a function of age of the waste, and in the model is characterised by the final compaction ratio. An exponential equation is used, as illustrated in Figure C1. This shows compaction stabilising after about 7 years to 80% of the original thickness. It is assumed in the model that as the waste skeleton compacts, so does the void space in a similar way. This is manifested in commensurate reductions in the field and saturation capacities of the waste.

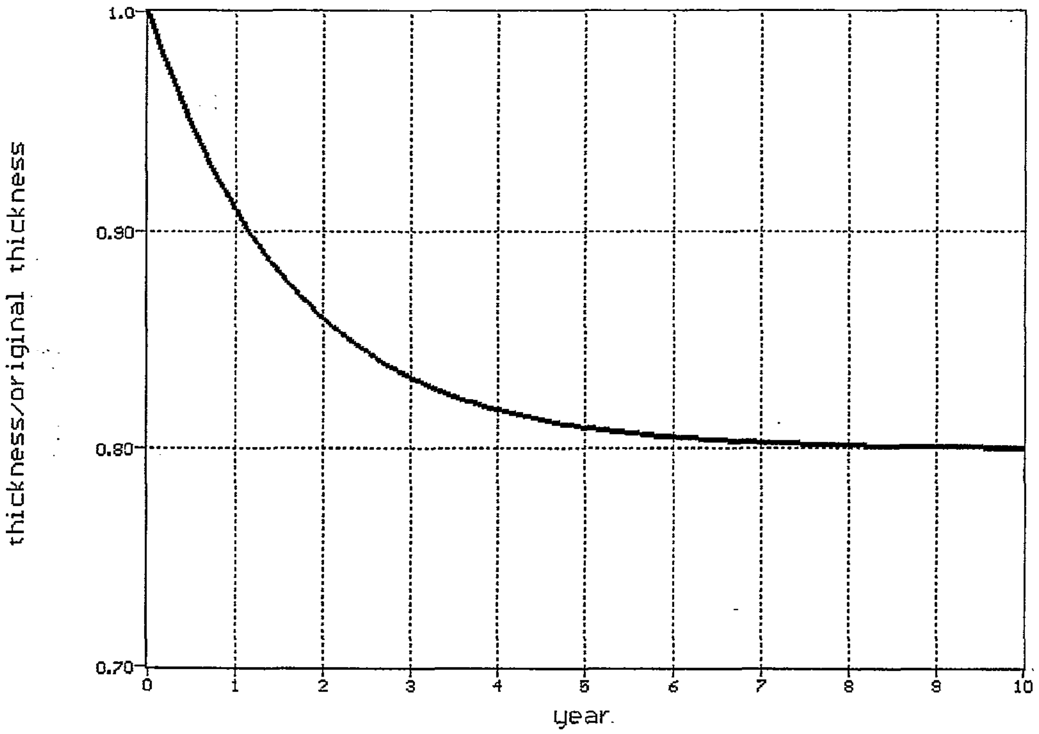


Figure C1 Model representation of waste settlement as a function of age

C2.7 Drainage of water

In partially saturated media rates of water drainage depend on the difference between the water content and the field capacity, where the latter is defined as the water content which can be held against gravity. The equation used in the landfill model is:

$q_n = (c_n - fc) * t_n * r$

where: q_n = water draining out of layer n during month (m^3),
c_n = water content, by dry weight, of waste in layer n,
fc = field capacity of waste, by dry weight,
t_n = mass of dry waste in layer n (te),
r = drainage rate constant (1/month).

The drainage out of layer n becomes an input to the layer below, or in the case of the bottom layer, the leachate produced in the month. A value of r = 1 means that the waste cannot hold any water above the field capacity level. A value of r = 0 indicates that the waste can retain any volume of water so that drainage will not occur. In reality, the value of r must lie between 0 and 1, and is at the users discretion. The value of r to be used in any case may be inferred by comparing the model predictions with the measured leachate production time series. The default value of r is 0.75 which has been used in a number of studies, and given satisfactory simulations of leachate generation.

If the wastes in any layer become super-saturated, that is if the moisture content exceeds the saturation capacity, then instantaneous drainage occurs to reduce the moisture content to equal the saturation capacity. The quantity of water draining is given by:

$q_n = (c_n - sc) * t_n$

where: q_n = water draining out of layer n during month (m^3),
c_n = water content, by dry weight, of waste in layer n,
sc = saturation capacity of waste, by dry weight,
t_n = mass of dry waste in layer n (te).

Super-saturation of the wastes will not normally arise unless a very large water input due to rainfall recharge occurs in some month or succession of months.

C2.8 Leachate production

In the above calculation, the drainage out of a layer normally becomes an addition to the layer below. For the bottom layer the drainage can be equated to leachate production from the landfill for the month in question.

The overall calculation scheme is shown in the flow chart of Figure C2.

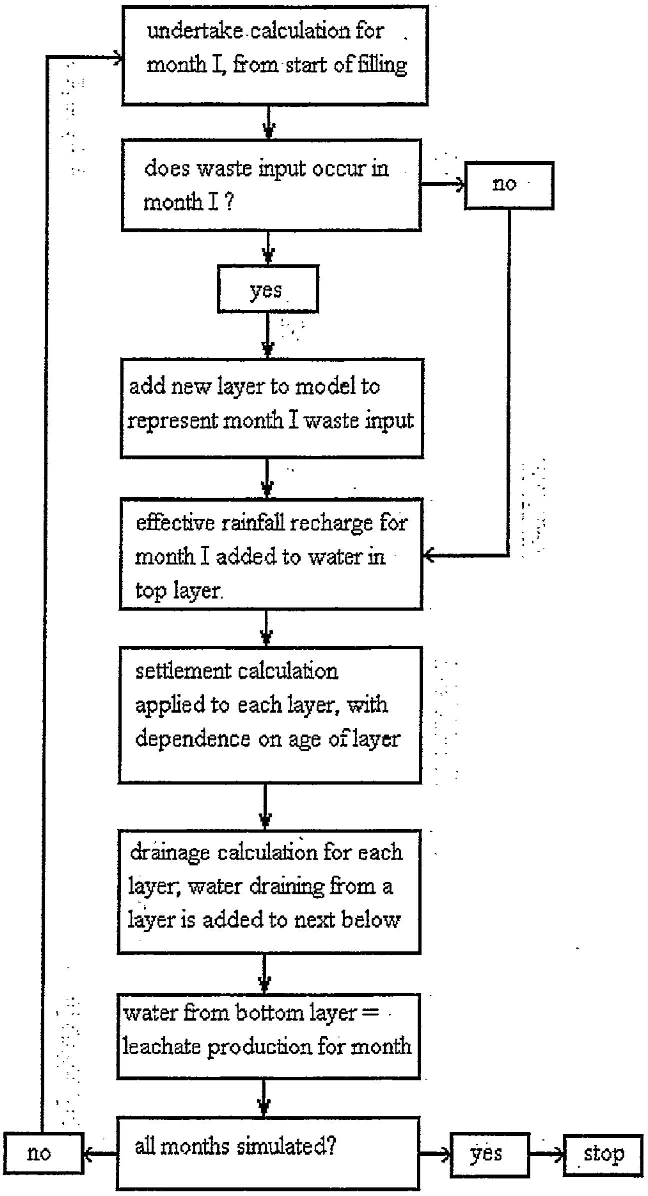


Figure C2 Leachate generation model flow chart

C3 APPLICATION TO BURNTSTUMP LANDFILL

The model described in Section C1 has been applied to Cell 7 of the Burntstump landfill, for which reasonably good data on filling rates were available. In addition, penetration of the underlying sandstone by leachate had been measured to provide an estimate of total leachate generation.

C3.1 Model input data

The filling and restoration sequences applied to the model were as in Table C1.

Table C1 Filling and restoration sequence used in Burntstump model

Date (month/year)		Fill rate	Area (m^2)		Cap
start	end	(wet te/year)	exposed	capped	function*
1/87	12/87	22750	62000	0	1
1/88	12/88	27500	62000	0	1
1/89	12/89	366900	62000	0	1
1/90	12/90	287100	62000	0	1
1/91	12/94	0	0	62000	2
1/95	12/99	0	0	62000	3

Notes: cap functions

1. no cap; rainfall recharge equal to MORECS values for bare soil.
2. temporary capping; rainfall recharge equals 30% of MORECS values for bare soil.
3. final capping; rainfall recharge to wastes equals zero.

Other parameters used in the model were as follows:

- moisture content of fresh waste, by dry weight = 0.35
- field capacity of fresh waste by dry weight = 0.45
- saturation capacity of fresh waste by dry weight = 0.85
- total final settlement = 20%
- drainage rate constant = 0.75 1/month

Rainfall recharge values were taken from MORECS for bare soil, grid square 117, as shown in Table C2.

In order to allow simulations up to 1999, data for 1995 - 1999 were equated to the sequence of values for 1985 -1989.

Table C2 Effective rainfall recharge data for Burntstump landfill model

	Effective rainfall (mm/month)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1985	38.8	4.4	11.8	13.9	10.6	12.8	6.7	9.0	2.3	4.0	8.7	25.1	148.1
1986	50.6	16.3	6.7	34.5	11.8	4.2	7.6	14.0	1.8	7.3	9.2	25.0	189.0
1987	24.3	26.7	33.4	28.9	5.2	13.7	6.7	10.2	6.7	15.2	13.7	20.7	205.4
1988	76.4	17.9	37.9	4.8	7.0	5.4	16.9	6.2	4.5	6.0	4.8	3.4	191.2
1989	3.8	5.1	6.8	17.4	3.1	9.3	5.1	4.6	4.4	8.3	5.5	23.8	97.2
1990	40.3	53.6	2.2	3.0	1.9	8.5	3.9	6.0	3.7	9.8	6.6	8.3	147.8
1991	28.6	30.5	11.6	6.8	1.5	8.5	5.4	1.7	10.7	4.6	5.8	3.8	119.5
1992	7.6	4.4	17.4	5.0	6.4	6.5	12.8	11.3	12.5	11.1	59.8	32.0	186.8
1993	32.9	1.6	3.3	17.2	7.0	7.7	10.4	7.3	15.4	20.9	40.9	63.1	227.7
1994	55.3	31.2	10.2	11.9	7.0	1.8	7.2	7.5	17.1	7.6	26.3	57.6	240.7

C3.2 Model results

The model was run over the period 1987 to 1999 inclusive to provide results during the time months of leachate production. Rainfall recharge input to cell 7 is shown in Figure C3.

The results show the reduction in inputs from 1991, when a temporary cap was applied, and the cessation of inputs from 1995 when the final capping was installed. Water input with the wastes is shown in Figure C4, which mirrors the changes in waste loadings during the 4 years of filling.

The predicted leachate production is shown as monthly quantities in Figure C5, and as the cumulative total in Figure C6.

The variations in leachate production with time result from:

- the increase through time of the mass of waste,
- water inputs and redistribution throughout the depth of waste,
- settlement, and consequent reduction in the water holding capacities of the waste.

Each tonne of fresh, wet waste added to the cell requires the input of a further 74 l of water before drainage will commence. As the wastes age and the void space is reduced by settlement so the extra water needed to initiate drainage falls, to a long term value of 7 l.

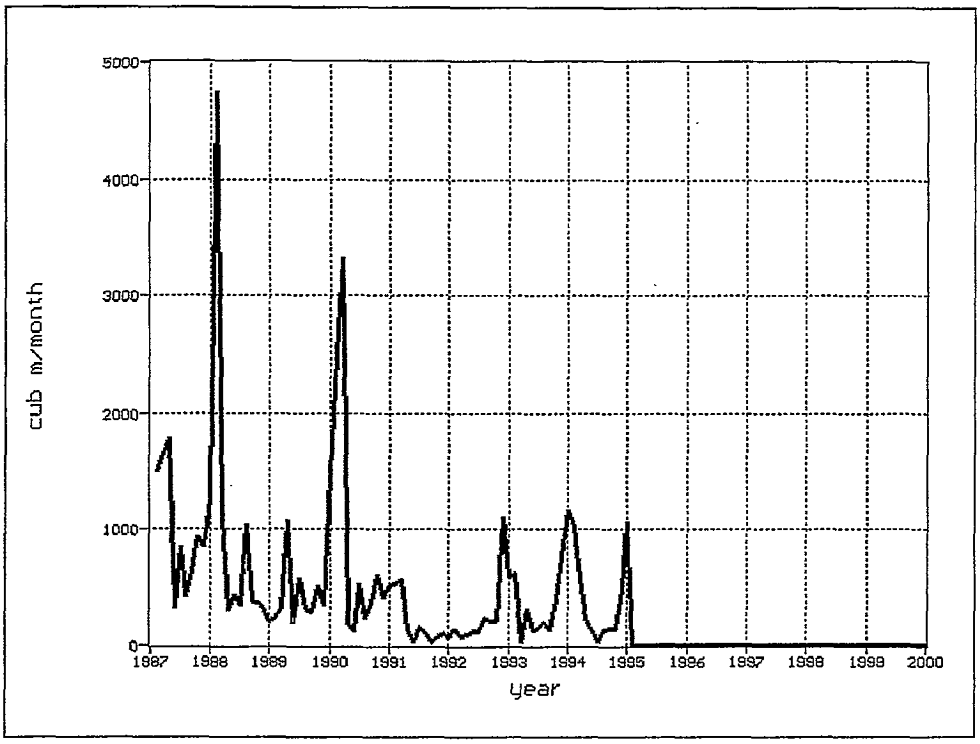


Figure C3 Rainfall recharge inputs to cell 7, Burntstump

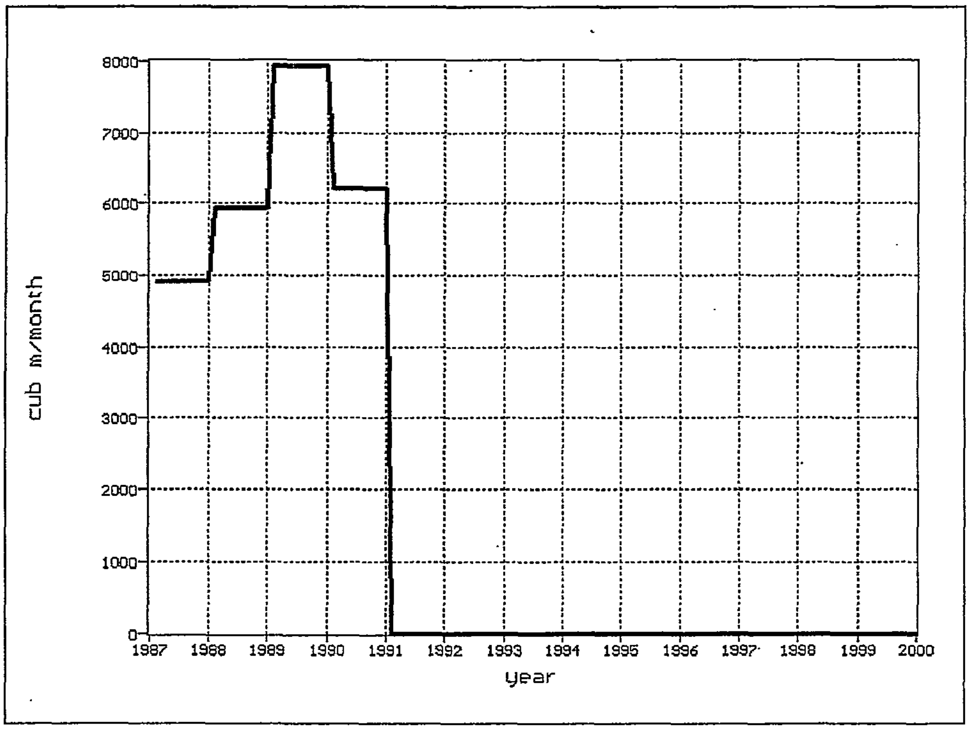


Figure C4 Water in waste input to cell 7, Burnstump

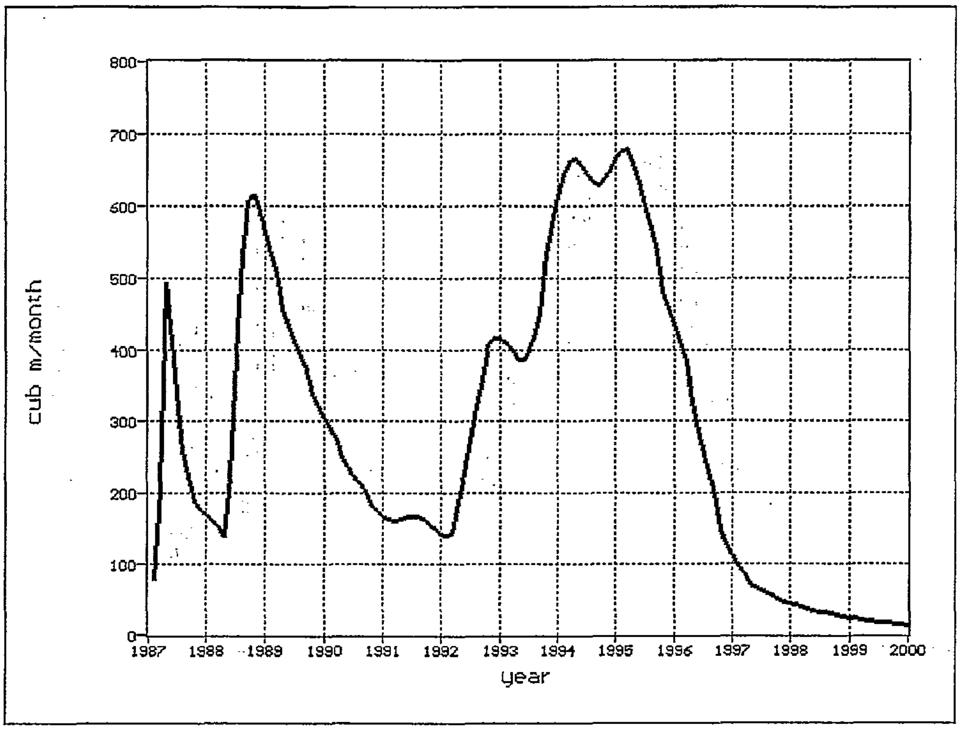


Figure C5 Predicted monthly leachate production from cell 7, Burntstump

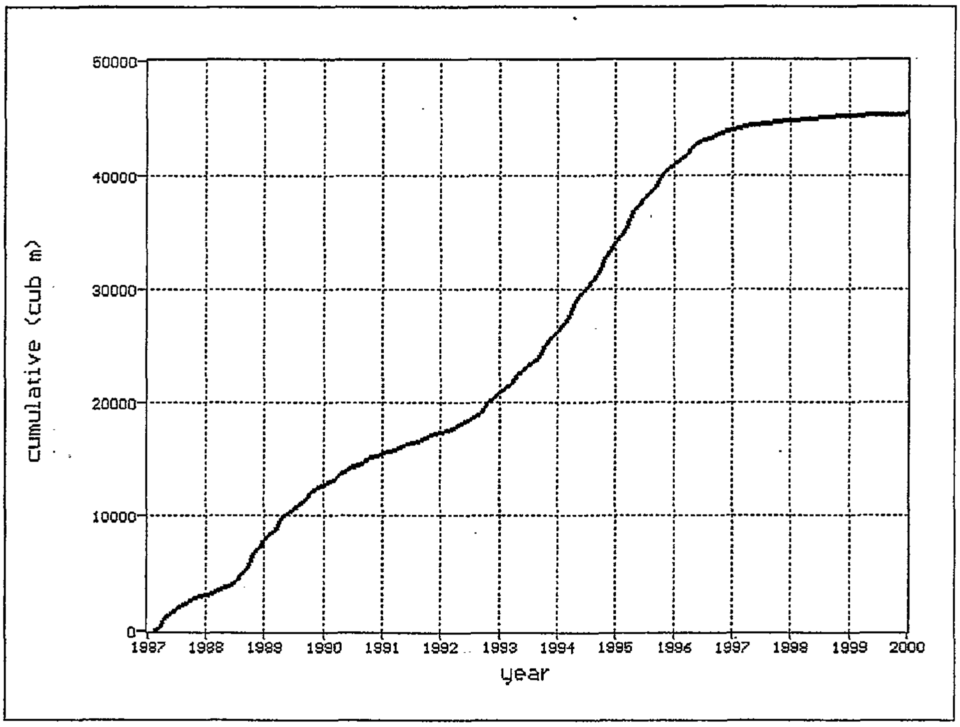


Figure C6 Predicted cumulative leachate production from cell 7, Burntstump

At relatively low rates of waste input, rainfall recharge can make up the water deficit in the waste and initiate leachate production. At relatively high rates of waste input, rainfall recharge may be insufficient to raise the waste moisture content above field capacity so that no leachate is produced. It is apparent that leachate production in the early years of filling resulted from a relatively low rate of filling, fluctuations in rainfall recharge and reductions in void space arising from the early stages of settlement. From early 1989, leachate production fell as waste inputs to the cell increased significantly. The subsequent rise through the early 1990s was due to approximately equal contributions from continued settlement and the reduced, but still significant, rainfall recharge inputs. This is illustrated in Figure C7 which shows the total water content of the wastes. This increased steadily during the years of filling up to a maximum of 325 000 m^3, and subsequently fell under the effects of settlement to an asymptotic value of 308 000 m^3.

The total leachate production up to the end of 1994 was predicted to be 34 000 m^3, Figure C6. This equates to an effective depth of 0.55 m, averaged over the area of the cell, and hence a depth of leachate penetration of about 2.8 m (assuming a porosity of 0.2). The depth of leachate penetration is likely to vary across the cell because of the heterogeneity of the waste and fluctuations in the base level.

Due to poor core recovery in the sandstone directly below the landfill, the exact depth of penetration of the leachate front could not be established during the drilling of borehole B15. However, the porewater profiling did demonstrate that leachate had infiltrated less than 8 m into the sandstone by 1994, and therefore a modelled infiltration depth of 2.8 m is not in conflict with the field observations.

It is predicted that by the year 2000, leachate production would be at 45 400 m^3 equivalent to leachate penetration of 3.7 m (assuming a porosity of 0.2 and the absence of fissures).

To illustrate the effect of settlement on leachate production, the model was also run with the total final settlement equal to zero. The predicted cumulative leachate production was as shown in Figure C8, reaching just 3% of that predicted with settlement of 20%, and clearly inconsistent with the expected depth of leachate penetration.

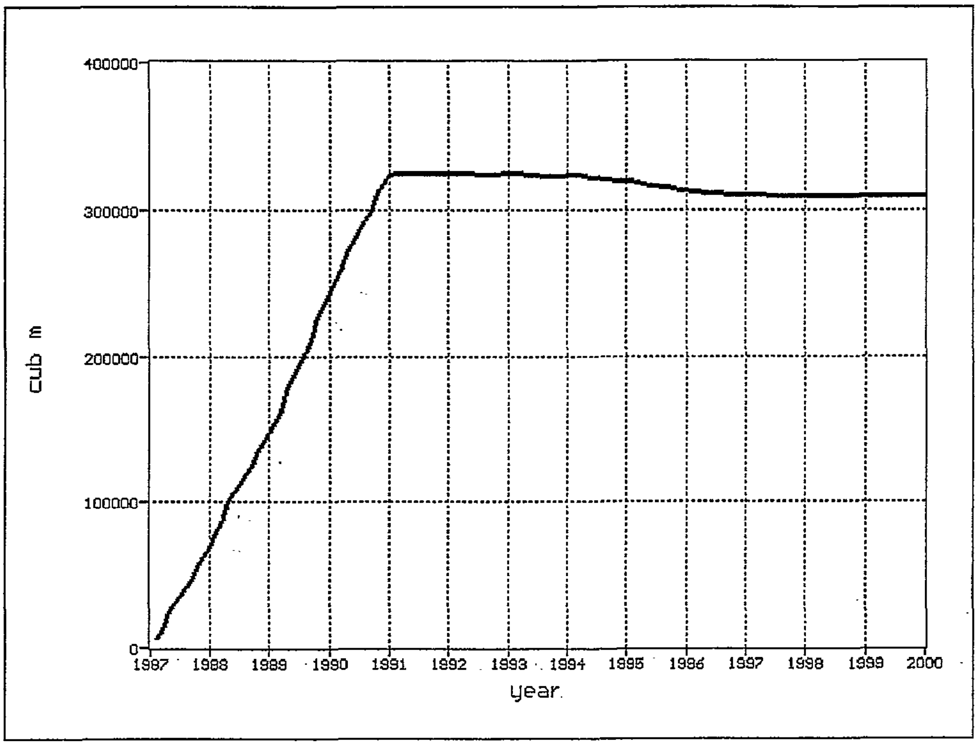


Figure C7 Predicted water content of the wastes in cell 7, Burntstump

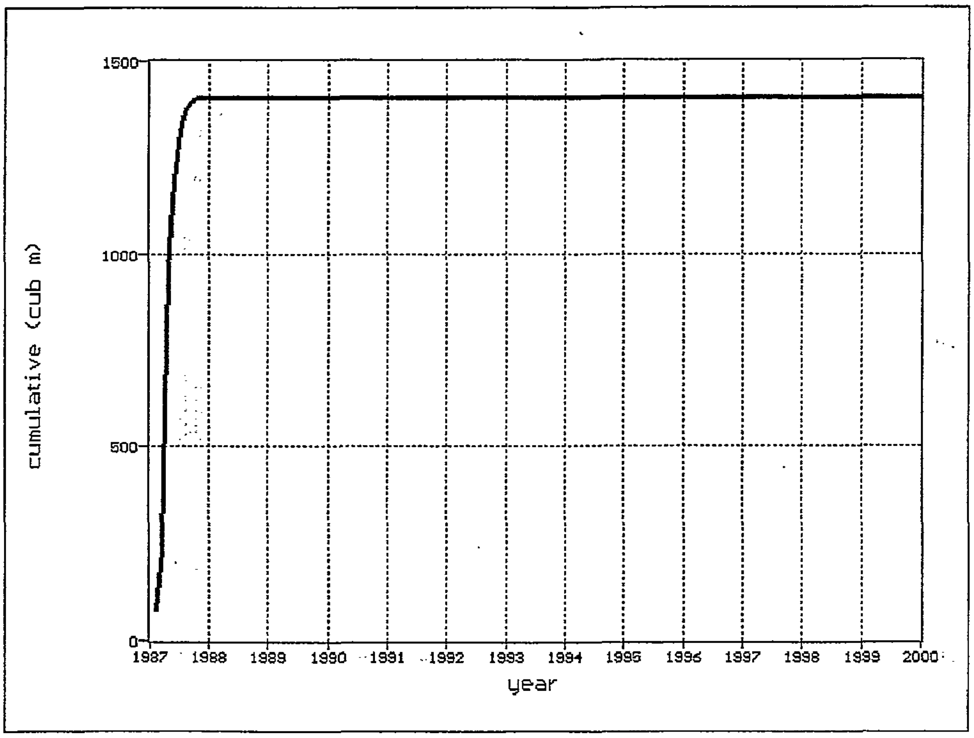


Figure C8 Predicted cumulative leachate production without settlement

C3.3 Conclusions from Burnstump modelling

The WRc leachate generation model has been substantially modified and now includes:

- the representation of monthly inputs as separate layers,
- calculation of water flows downwards through the layers,
- modification of rainfall recharge by user specified capping functions,
- the effects of age on settlement and water holding characteristics of the waste.

The model has been applied to the Burntstump landfill, cell 7, and has given predictions of leachate production which are not refuted by partial field data.

Runs of the model with settlement set to zero predicted very small volumes of leachate production which were inconsistent with the field data.

The model needs to be further tested by application to other landfills where field data are available for comparison with predictions.

C4 APPLICATION TO GORSETHORPE LANDFILL

C4.1 Model input data

The filling and restoration sequences applied to the model were as in Table C3.

Other model parameters, including the MORECS rainfall recharge values, were as for Burntstump.

C4.2 Model results

The model was run over the period 1974 to 1999 inclusive.

Water inputs are shown in Figures C9 and C10 for the rainfall recharge and waste respectively.

Table C3 Filling and restoration sequence used in Gorsethorpe model

date (month/year)		fill rate	area (m^2)		cap function
start	end	(wet te/year)	exposed	capped	
Phase 1					
1/74	12/78	18816	28000	0	1
1/79	12/99	0	0	28000	4
Phases 2 & 3					
1/79	12/82	64680	77000	0	1
1/83	12/99	0	0	77000	5

Notes: cap functions

1. no cap; rainfall recharge equal to MORECS values for bare soil.
4. 0.5 m colliery shale; rainfall recharge equals 50% of MORECS values for bare soil.
5. 1.0 m colliery shale; rainfall recharge equals 20% of MORECS values for bare soil.

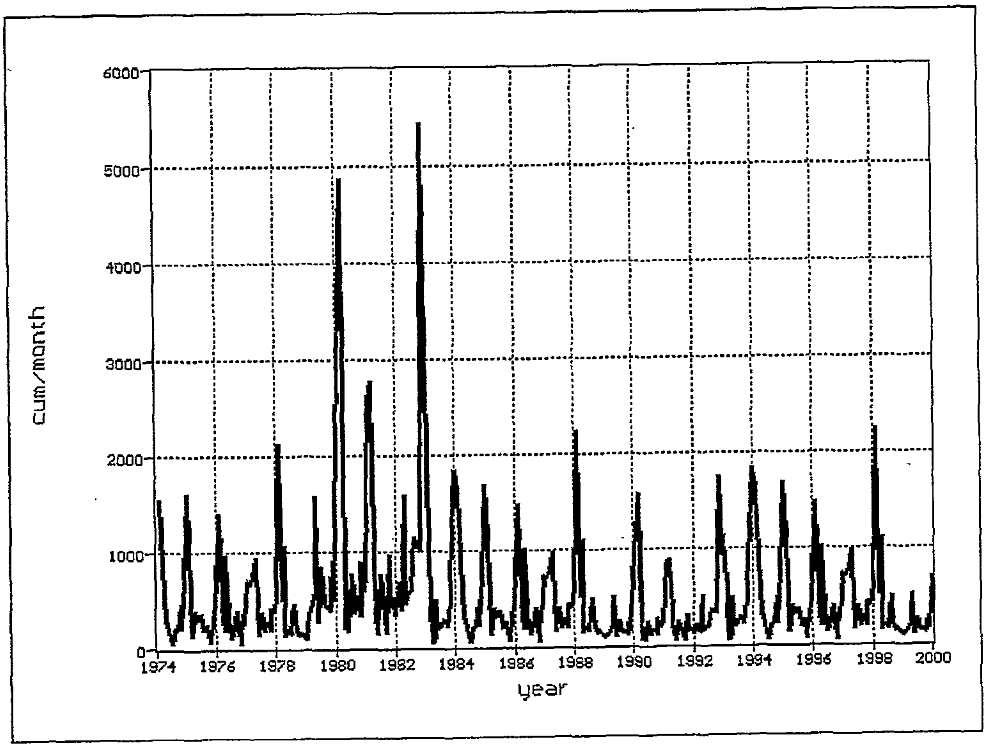


Figure C9 Rainfall recharge inputs to Gorsethorpe

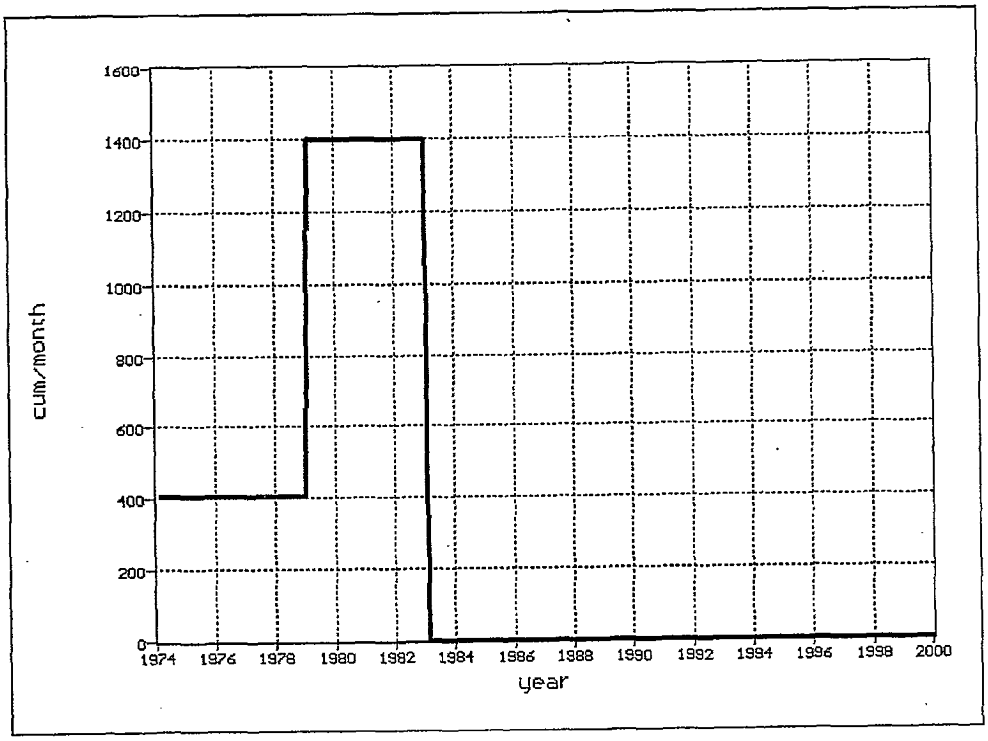


Figure C10 Water in waste input to Gorsethorpe

The results show the reductions in inputs in 1983, and subsequent capping. Water inputs with the wastes mirror the changes in waste loadings during the 9 years of filling.

The predicted leachate production is shown as monthly quantities in Figure C10, and as the cumulative total in Figure C11.

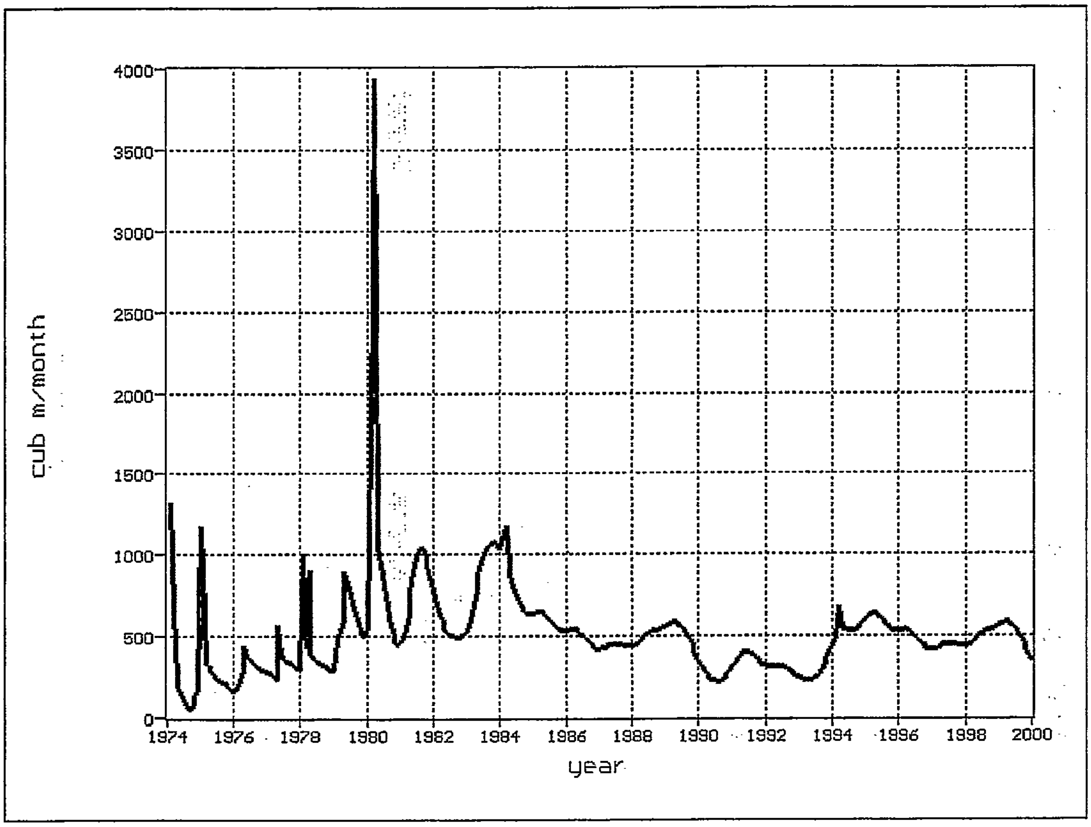


Figure C11 Predicted monthly leachate production from Gorsethorpe

The variations in leachate production with time result from:

- the increase through time of the mass of waste,
- water inputs and redistribution throughout the depth of waste,
- settlement, and consequent reduction in the water holding capacities of the waste.

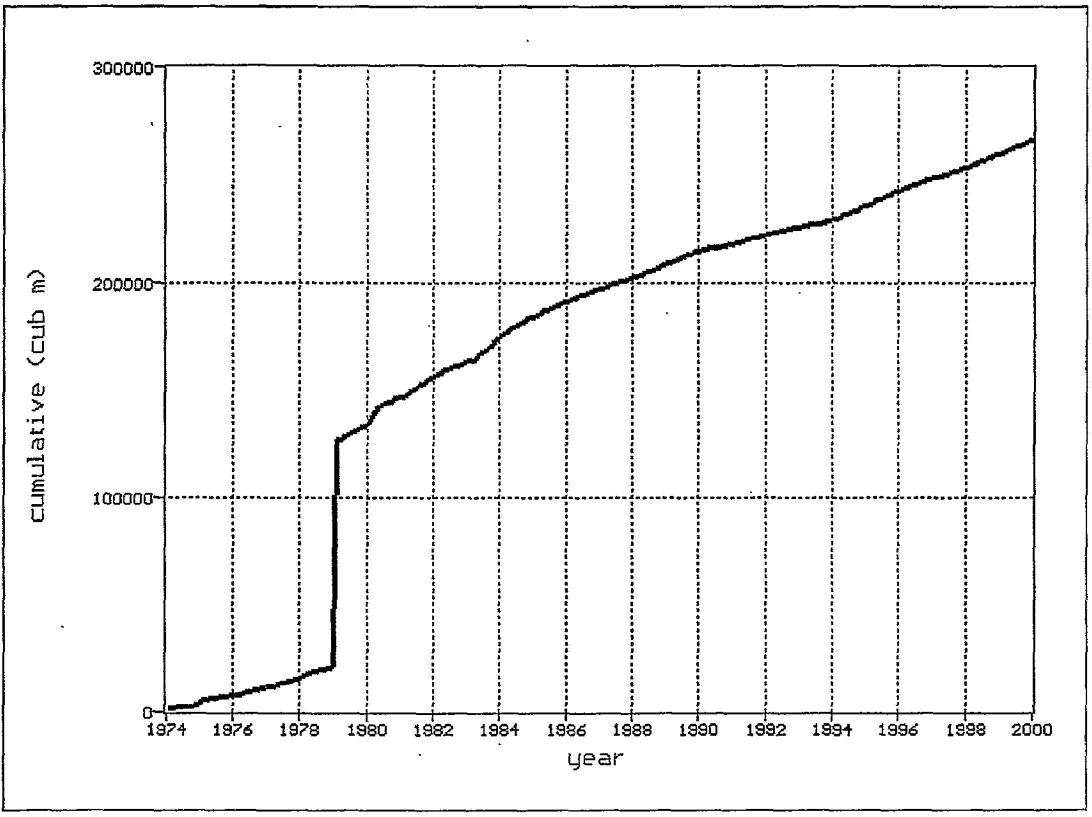


Figure C12 Predicted cumulative leachate production from Gorsethorpe

It is apparent that leachate production in the early years of filling resulted from a relatively low rate of filling, fluctuations in rainfall recharge and reductions in void space arising from the early stages of settlement. Leachate production reached a maximum in the 1980s due to operation of Phases 2 and 3 and continued production of leachate from a poorly capped Phase 1. The peak in 1980 resulted from exceptionally high rainfall in the winter months of that year.

The total leachate production up to the end of 1995 was predicted to be 243000 m^3, and increasing steadily at a rate of about 4700 m^3 $year^{-1}$ (Figure C12).

Figure C13 shows the predicted total water content of the wastes. The value increases steadily during emplacement and subsequently declines slowly as settlement continues to reduce the pore space. The fluctuations from 1983 onwards are due to changes in rainfall recharge.

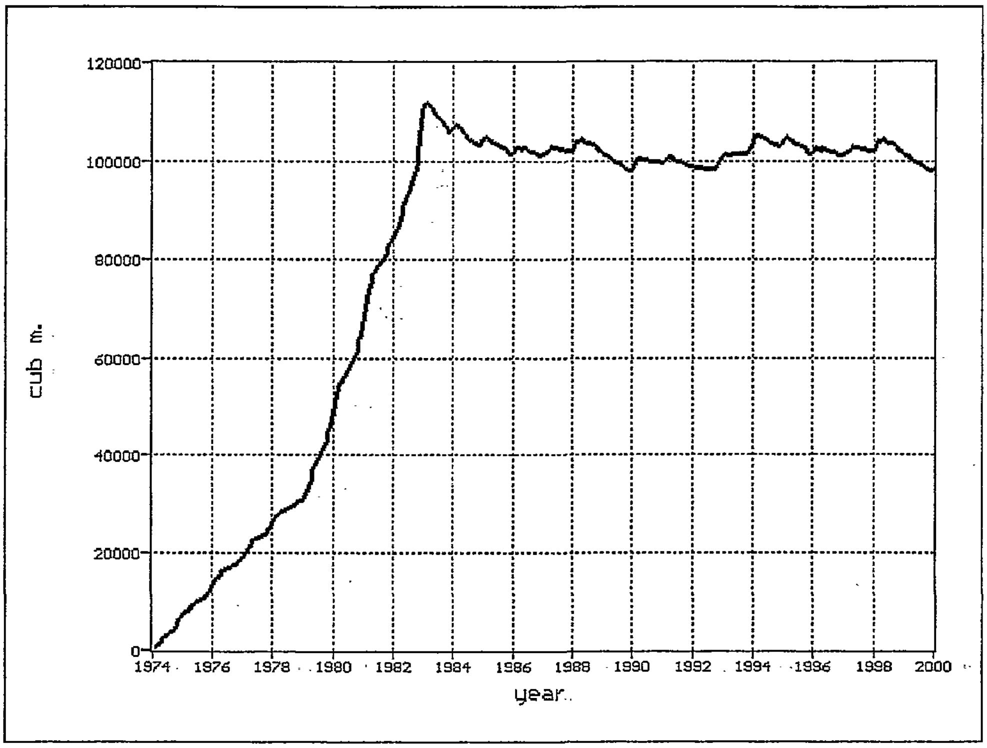


Figure C13 **Predicted water content of the wastes in Gorsethorpe**

APPENDIX D CHARACTERISATION OF BURNTSTUMP WASTE (B15, 1994)

D1 WASTE ASSAY - UPPER BURNTSTUMP WASTE SAMPLE

D2 WASTE ASSAY - LOWER BURNTSTUMP WASTE

D3 ELEMENTAL COMPOSITION OF BURNTSTUMP WASTE

D4 LEACHING TEST DATA (MG L^{-1})

D5 LEACHING TEST DATA - MG PER DRY KG^{-1} LEACHED

Notes Appendix D4

- In Appendix D4 the leachate concentrations are compared with the example leachate criteria for landfill completion (DoE 1993). At a liquid to solid ratio of 10 (DIN) the leachates failed the criteria for DOC by a factor of 20.
- Leaching tests involve the removal of the leachate from the solid by filtration. In a comparison of unfiltered and filtered leachates, ammoniacal-nitrogen loss of up to 50% was observed in the dilute leachates (2-5 mg l^{-1} N). No loss was observed at higher concentrations.

Notes Appendix D5

The mg kg^{-1} data for the CEN granular leaching test (D3) represent the concentration leached:

- during the first leaching step; and
- the cumulative leaching over both leaching steps (the calculation allows for the small diluting contribution of the 'first step leachate' in the 'second step leachate').

D1 WASTE ASSAY - UPPER BURNTSTUMP WASTE SAMPLE

Burntstump bulk waste samples (B15, 1-14m): assay by waste category and by particle size

Upper waste: each waste category classed by size fraction (% wt)

size (mm)	paper & card	plastic film	dense plastic	textiles	miscel. combustible	miscel. non combustible	glass	putrescible	ferrous metal	non-ferrous metals	<10mm fines	total %
>160	13.8	10.4	16	0	16.3	0	0	0	0	0	0	
160 - 80	11.2	9.9	32	0	30.9	7.4	0	7	52.2	0	0	
80 - 40	38.3	30.7	28.4	0	31.2	23.1	6.9	18.4	30.9	0	0	
40 - 20	20.6	36.7	6.3	0	16.3	34.6	44	21.2	0	0	0	
20 - 10	16	12.3	17.3	0	5.3	34.9	49.1	53.3	16.9	100	0	
<10	0	0	0	0	0	0	0	0	0	0	100	
total	*99.9*	*100*	*100*	*0*	*100*	*100*	*100*	*99.9*	*100*	*100*	*100*	

Upper waste: each size fraction classified into waste categories(%)

size (mm)	paper & card	plastic film	dense plastic	textiles	miscel. combustible	miscel. non combustible	glass	putrescible	ferrous metal	non-ferrous metals	<10mm fines	total %
>160	31.9	11.3	8.7	0	48.2	0	0	0	0	0	0	*100.1*
160 - 80	11.4	4.7	7.6	0	40.2	14	0	15.3	6.7	0	0	*99.9*
80 - 40	20.5	7.7	3.6	0	21.4	23	0.4	21.4	2.1	0	0	*100.1*
40 - 20	11.8	9.9	0.8	0	12	36.7	2.4	26.4	0	0	0	*100*
20 - 10	7.3	2.6	1.8	0	3.1	29.4	2.1	52.5	1	0.2	0	*100*
<10	0	0	0	0	0	0	0	0	0	0	100	*100*

Acid digestible fibre and other analyses on wet weight basis (not normalised)

	Moisture % wet wt	total nitrogen (%)	first relux loss %	cellulose (%)	lignin (%)	ash (%)	cell/lig ratio	cell/VM ratio	volatile matter dry wt%
1-14m	33.6	0.7	18.1	32.5	15.4	4.2	**2.11**	**0.66**	**48.90**

D2 WASTE ASSAY - LOWER BURNTSTUMP WASTE SAMPLE

Burntstump waste samples (B15, 16-27m): assay by waste category and by particle size

size (mm)	paper & card	plastic film	dense plastic	textiles	miscel. combustible	miscel. non combustible	glass	putrescible	ferrous metal	non-ferrous metals	<10mm fines	Total %
Lower waste: each waste category classed by size fraction (% wt)												
>160	0	0	0	0	0	0	0	0	0	0	0	
160 - 80	52.2	16.8	24	0	49.3	0	0	0	24.5	0	0	
80 - 40	32	49.3	37.7	100	29.7	16.8	4.3	13.5	27.8	1.5	0	
40 - 20	15.9	23.8	20	0	19	47.4	20.9	21.3	20.9	98.5	0	
20 - 10	0	10.1	18.3	0	2	35.8	74.8	65.2	26.7	0	0	
<10	0	0	0	0	0	0	0	0	0	0	100	
total	*100.1*	*100*	*100*	*100*	*100*	*100*	*100*	*100*	*99.9*	*100*	*100*	
Lower waste: each size fraction classified into waste categories(%)												
>160	0	0	0	0	0	0	0	0	0	0	0	*0*
160 - 80	46.2	8.8	3.4	0	28.4	0	0	0	13.3	0	0	*100.1*
80 - 40	22.8	20.8	4.3	5.9	13.8	6.2	0.2	13.7	12.1	0.1	0	*99.9*
40 - 20	12.5	11.1	2.5	0	9.7	19.4	0.1	24.1	10.1	9.5	0	*99*
20 - 10	0	4.2	2	0	0.9	12.9	3.6	65	11.3	0	0	*99.9*
<10	0	0	0	0	0	0	0	0	0	0	100	*100*

Acid digestible fibre and other analyses on wet weight basis (not normalised)

	Moisture % wet wt	total nitrogen	first reflux loss %	cellulose	lignin	ash	cell/lig ratio	cell/VM ratio	volatile matter dry wt%
15-27m	45.0	0.47	25.5	13.7	15.1	3.6	0.91	0.50	27.2

D3 ELEMENTAL COMPOSITION OF BURNTSTUMP WASTE SAMPLES

Sample	pH	TOC	Na	K	Mg	Ca	SO_4	Cl	N	P	Fe	Mn	Ni	Cd	Cr	Cu	Pb	Zn	Hg	Volatile matter %
		% w/w	<------------------------------ concentration of Na to Hg in mg kg^{-1} ------------------------------>																	
Upper waste	7.3	9.38	1500	2830	6840	30800	5090	1370	1300	400	19500	376	27.3	1.97	74.7	79.2	101	604	<2.49	47.9
	7.9	11.7	1540	3030	5820	30500	4460	1300	1700	423	21200	383	35.5	1.76	87.8	105	150	975	<2.47	54.9
	-	-	-	-	-	-	-	-	-	-	-	-	38.6	1.91	99	300	133	701	<3.0	44.1
	-	-	-	-	-	-	-	-	-	-	-	-	40.4	1.57	105	796	174	723	<3.1	48.8
mean value	*7.6*	*10.5*	*1520*	*2930*	*6330*	*30650*	*4775*	*1335*	*1500*	*412*	*20350*	*380*	*35.5*	*1.80*	92	*320*	*140*	*751*	<3.1	48.9
Lower waste	7.9	29.0	2690	3030	5610	31600	2320	2660	3240	769	32200	544	34.8	2.43	95.5	243	2840	606	<2.45	27.8
	8.1	26.3	2810	3230	5610	34100	2410	2840	2900	644	29600	581	42	3.95	136	265	1970	899	<2.47	28.5
	-	-	-	-	-	-	-	-	-	-	-	-	52.6	2.95	110	159	2340	712	<3.1	22.6
	-	-	-	-	-	-	-	-	-	-	-	-	52.5	2.82	121	167	1670	872	<3.1	30.0
mean value	*8.0*	*28*	*2750*	*3130*	*5610*	*32850*	*2365*	*2750*	*3070*	*707*	*30900*	*563*	*45.5*	*3.04*	*116*	*209*	*2205*	*772*	<3.1	27.2

Notes

Results of replicate digests (not replicate determinations of single digest)

Upper wastes = composite samples of 7 wastes retrieved from top 14m of B15

Lower wastes = composite samples of 7 wastes retrieved from 16 - 27m bgl in B15

D4 LEACHING TEST DATA (mg l^{-1})

Sample/ leaching test	Liquid/ solid ratio	Cond μS cm^{-1}	pH	DOC	Na	K	Mg	Ca	SO$_4$	Cl	Alk CaCO$_3$	NH$_3$ as N (F)	NH$_3$ as N(3) (UF)	NO$_3$ as N	NO$_2$ as N	TSP as P	B	Fe	Mn	Ni	Cd	Cr	Cu	Pb	Zn	Mo	Hg
					<------								leachate concentration in mg l-1											------>			
Upper waste																											
CEN step 1(1)	2	3810	7.8	-	417	303	90.9	670	1670	523	746	19.7	-	-	-	1.27	1.8	0.38	1.1	0.2	<0.04	<0.10	0.19	<0.50	0.24	-	-
CEN step 1 dup. (2)	2	4580	-	*1100*	-	-	-	-	-	-	-	*19.0*	*21.5*	-	-	-	-	-	-	-	*0.001*	*0.012*	-	*0.007*	-	-	-
mean CEN step 1	2	4195	7.8	1100	417	303	90.9	670	1670	523	746	19.35	21.5	-	-	1.27	1.8	0.38	1.1	0.2	0.001	0.012	0.19	0.007	0.24	-	-
CEN step 2	2-10	845	7.5	-	56.1	49	12.8	94	215	61.5	79.5	3.3	-	-	-	0.185	0.4	<=0.04	0.14	<=0.1	<0.04	<0.10	0.09	<0.50	<=0.04	-	-
CEN step 2	2-10	646	7.34	-	41.6	39	9.6	71	152	41.5	119	2.7	-	-	-	0.175	0.5	0.15	0.10	<=0.1	<0.04	<0.10	0.06	<0.50	<=0.04	-	-
CEN step 2 dup.	2-10	-	7.4	138	-	-	-	-	-	-	-	2.9	5.0	-	-	-	-	0.10	0.12	<=0.1	0.002	0.004	0.08	0.012	<=0.04	-	-
mean CEN step 2	2-10	745.5	7.413	138	48.85	44	11.2	82.5	184	51.5	99.25	3.0	5.0	-	-	0.18	0.45	0.075	0.12	<=0.1	0.002	0.004	0.0767	0.012	<=0.04	-	-
DIN	10	1210	7.4	243	88.0	71.5	20.8	151	344	101	208	3.1	-	0.73	<=0.1	0.185	0.61	<=0.004	0.29	0.11	<=0.02	<=0.05	0.10	<=0.3	0.11	0.04	<=0.2
DIN	10	1205	7.3	244	88.4	71.1	20.5	153	344	100	204	2.8	-	0.79	<=0.1	0.205	0.65	<=0.004	0.27	0.07	<=0.02	<=0.05	0.05	<=0.3	0.08	0.03	<=0.2
mean DIN	10	1208	7.4	244	88.2	71.3	20.7	152	344	101	206	2.9	-	0.76	<=0.1	0.195	0.63	<=0.004	0.28	0.09	<=0.02	<=0.05	0.075	<=0.3	0.10	0.04	<=0.2
Lower waste																											
CEN step 1(1)	2	4960	7.8	-	671	386	48.4	246	880	1390	378	17.8	-	-	-	1.21	2.3	0.23	0.44	<=0.1	<0.04	<0.10	<=0.04	<0.50	0.16	-	-
CEN step 1 dup. (2)	2	6920	-	1350	-	-	-	-	-	-	-	20.94	19.0	-	-	-	-	-	-	-	0.0015	0.044	-	0.033	-	-	-
mean CEN stepl	2	5940	7.8	1350	671	386	48.4	246	880	1390	378	19.4	19.0	-	-	1.21	2.3	0.23	0.44	<=0.1	0.002	0.044	<=0.04	0.033	0.16	-	-
CEN step 2	2-10	803	7.9	-	92	62	7.3	45	89	119	84	2.8	-	-	-	0.17	0.5	<=0.04	0.06	<=0.1	<0.04	<0.10	<=0.04	<0.50	<=0.04	-	-
CEN step 2	2-10	807	7.9	-	112	74	7.8	45	92	148	99	3.2	-	-	-	0.9	0.7	0.65	0.07	<=0.1	<0.04	<0.10	<=0.04	<0.50	0.08	-	-
CEN step 2 dup.	2-10	-	-	248	-	-	-	-	-	-	-	4.3	8.1	-	-	-	-	-	-	-	0.004	0.008	-	0.027	-	-	-
mean CEN step 2	2-10	805	7.9	248	102	68	7.6	45	90	134	91	3.4	8.1	-	-	0.54	0.6	0.33	0.07	<=0.1	0.004	0.008	<=0.04	0.027	0.08	-	-
DIN step 1	10	1265	7.4	207	154	91.7	12.4	75.4	131	226	113	2.06	-	0.58	<=0.1	0.46	0.84	<=0.004	0.15	0.10	<=0.02	<=0.05	0.06	<=0.3	0.07	0.07	<=0.2
DIN	10	1546	7.4	254	193	117	14.8	84.5	155	291	137	2.56	-	0.58	<=0.1	0.21	1.03	<=0.004	0.20	0.06	<=0.02	<=0.05	0.03	<=0.3	0.10	0.08	<=0.2
mean DIN	10	1406	7.4	231	173.5	104.35	13.6	79.95	143	259	125	2.31	-	0.58	<=0.1	0.335	0.94	<=0.004	0.175	0.08	<=0.02	<=0.05	0.045	<=0.3	0.09	0.075	<=0.2
blanks																											
unfiltered leachant	-	-	-	1.4	0.97	0.2	<0.01	0.6	-	-	-	-	<0.50	-	-	-	<0.01	<0.004	<0.002	<0.01	<0.0002	<0.005	<0.004	<0.002	<0.004	-	-
filtered leachant	-	15	-	1.2	1.03	0.2	0.02	0.7	-	-	-	<0.50	-	-	-	-	<0.01	<0.004	<0.002	<0.01	<0.0002	<0.005	<0.004	<0.002	<0.004	-	-
CEN 1 blk	-	14	-	1.7	-	-	-	-	-	-	-	<0.50	<0.50	-	-	-	-	-	-	-	0.001	<0.005	-	<0.002	-	-	-
CEN 2 blk	-	15	-	0.97	-	-	-	-	-	-	-	<0.010	<0.50	-	-	-	-	-	-	-	<0.0002	<0.005	-	<0.002	-	-	-
WMP26a Example completion criteria for leachates																											
		4000	**6.5-7.5**	**10**	**1500**	**120**	**500**	**1000**	**2500**	**2000**	**-**	**5**	**5**	**500**	**1**		**-**	**2**	**0.5**	**0.5**	**0.05**	**0.5**	**1**	**0.5**	**1**	**-**	**0.01**

Notes (1) The first step of the CEN test is at a low liquid to solid ratio (2:1) yielding a small volume of leachate.
As the wastes had a high absorption capacity, equal volumes of leachate from the duplicates were combined to yield sufficient liquor for analysis.
(2) At a later date, the leach test was repeated, and samples analysed by more sensitive methods for the heavy metals.
Filtered (F) and unfiltered (UF) leachates were submitted for amoniacal nitrogen determination to investigate potential loss of ammonia. NB No loss at ~20 mg l^{-1}, 50% loss at ~5 mg l^{-1}
(3) The leachates are separated from the solid by vacuum filtration through a 0.45 um membrane filter.

D5 LEACHING TEST DATA (mg per dry kg leached)

Sample/ leaching test	TOC	Na	K	Mg	Ca	SO_4	Cl	N	P	B	Fe	Mn	Ni	Cd	Cr	Cu	Pb	Zn
	------------ waste, porewater and leachate concentration in mg kg^{-1} ------------>																	
Upper waste																		
Waste conc.	105000	1520	2930	6330	30650	4775	1335	1500	412	-	20350	380	35.5	1.8	92	320	140	751
Porewater	645	306	236	39	43	240	507	232	-	-	1.02	0.08	-	-	-	-	-	-
CEN step 1	2200	834	606	182	1340	3340	1046	43.1	2.54	3.6	0.76	2.20	0.4	0.024	0.024	0.38	0.014	0.48
CEN total	2622	963.0	867	221	1635	3411	1015	98.5	3.5	8.7	1.425	2.36	<=1.97	0.039	0.079	1.52	0.206	<=0.79
DIN	2440	882	713	207	1520	3440	1005	29	1.95	6.3	<=0.04	2.80	0.9	<=0.2	<=0.5	0.75	<=3.0	1.0
Lower waste																		
Waste conc.	277000	2750	3130	5610	32850	2365	2750	3070	707	-	30900	563	45.5	3.04	116	209	2205	772
Porewater	1196	873	520	44	25	544	1434	668	-	-	4.03	0.14	-	-	-	-	-	-
CEN step 1	2700	1342	772	96.8	492	1760	2780	38.7	2.42	4.6	0.46	0.88	<=0.2	0.004	0.088	<=0.4	0.066	0.32
CEN total	4712	1934	1292	143.5	855	1763	2705	153.1	10.17	11.4	6.5	1.235	<=1.9	0.0665	0.152	<=0.76	0.513	1.52
DIN	2305	1735	1044	136	800	1430	2585	23.1	3.4	9.4	<=0.04	1.75	0.8	<=0.2	<=0.5	0.45	<=3.0	0.9

Conversion from mg l^{-1} to mg per dry kg leached.
The leaching test leachates have been multiplied by the appropriate dilution factor.
The concentrations of porewaters from each horizon in the waste have been divided by the moisture content and a mean calcultated for the upper and lower waste samples (Appendix E1)

APPENDIX E POREWATER CHEMISTRY AND SHERWOOD SANDSTONE MICROBIOLOGY

E1 POREWATER CHEMISTRY - INORGANICS

E2 POREWATER CHEMISTRY - ORGANICS

E3 POREWATER CHEMISTRY - MG KG^{-1}

E4 MICROBIOLOGY OF SANDSTONE CORE

E1 POREWATER CHEMISTRY- INORGANICS

Depth m bgl	Cond µS cm^{-1}	pH	moist content %	TOC	Na	K	Mg	Ca	SO$_4$	Cl	Alk CaCO$_3$	NH$_3$ as N	NO$_3$ as N	NO$_2$ as N	SRP as P	Fe	Mn	Cl: TOC	Ion Bal. %
										porewater concentration in mg l^{-1}									
B15: Upper waste																			
3	7330	7.9	24.3	2170	605	668	104.0	135	237	1350	2612	584	0.12	0.03	0.018	0.47	0.25	0.62	2.6
5	11220	8.4	45.7	1380	1030	874	96.7	17.4	337	1455	5109	1075	<=0.10	<=0.10	0.28	5.30	0.09	1.05	1.1
9	7870	7.9	46.4	2500	912	668	103.0	88.4	630	1425	2303	435	0.19	0.14	0.26	3.30	0.27	0.57	0.7
14	7620	8.0	22.0	1200	827	329	180.0	413	2080	1695	729	431	<=0.01	0.13	<=0.03	0.14	0.39	1.41	-2.9
B15: Lower waste																			
18.5	14750	8.5	44.4	2700	1660	987	35.7	13.9	170	2970	5540	1348	0.06	0.36	0.56	8.10	0.09	1.10	-6.0
22	17500	8.4	-	1090	1940	1280	64.6	29.6	3400	3220	3307	1470	<=0.01	0.17	0.85	8.20	0.08	2.95	-5.6
25.1	16500	8.2	45.4	1360	1940	1140	75.6	14.2	590	3140	5734	1560	<=0.01	0.10	0.14	6.50	0.05	2.31	-2.1
27.7	15900	7.6	47.9	5150	2050	1120	204	152	570	3160	6314	1440	<=0.01	0.21	<=0.03	12.1	0.96	0.62	0.2
B15: Sherwood Sandstone																			
36-36.5	437	8.0	-	15.7	20.1	3.9	18.9	38.1	35.1	42.0	127	0.237	9.7	<=0.01	0.13	0.11	0.07	2.68	-7.5
37-37.5	440	8.1	4.9	7.5	19.1	3.5	19.8	40.1	38.7	41.1	122	<=0.50	8.5	<=0.01	<=0.03	<=0.004	0.07	5.48	-2.8
40.6-41.4	*1246^*	*7.9^*	*6.1^*	*33.5^*	*144^*	*12.3*	*41.2*	*78.3*	*206^*	*189^*	*122*	*2.6^*	*31.2*	*0.13*	*0.04*	*0.02*	*0.15*	*5.64*	*-0.8*
42.2-42.3	703	7.9	4.5	7.1	13.6	5.4	35.9	73.2	39.0	55.0	96.3	0.37	44.7	0.02	<=0.03	0.00	0.13	7.75	-2.0
50-52	771	7.6	4.4	10.0	14.9	7.8	39.3	80.7	43.0	68.5	187	0.60	50.4	0.03	<=0.03	0.14	0.12	6.85	-12.2
56-57	650	7.9	6.9	9.4	16.6	7.3	32.4	65.4	37.5	59.0	96	<=0.10	35.7	1.19	<=0.03	0.70	0.10	6.28	-2.6
57-58	614	7.6	6.1	10.4	17.2	5.8	30.1	59.8	48.0	39.3	113	<=0.10	46.4	0.21	<=0.03	0.21	0.17	3.78	-11.2
58-59	610	8.1	7.8	10.1	43.2	6.2	23.8	48.7	40.5	112	131	<=0.50	6.07	0.20	0.029	0.057	0.04	11.10	-9.2
59.7-60	709	7.9	8.2	10.3	52.9	10.8	27.1	49.1	40.0	142	122	<=0.50	5.63	0.14	0.83	0.05	0.05	13.80	-8.3
61-62	822	7.7	8.7	11.7	35.0	8.9	39.0	76.4	59.5	101	140	<=0.50	34.8	0.16	<=0.03	0.022	0.09	8.64	-6.1
64-65	854	7.9	6.5	11.9	23.1	14.4	40.5	81.1	48.0	129	92.3	<=0.50	35.5	<=0.10	0.117	<=0.008	0.07	10.80	-3.3
67-68	551	7.8	9.3	7.3	14.3	5.8	26.6	55.7	60.0	58.0	93.3	<=0.10	25.0	<=0.10	0.08	<=0.008	0.04	7.95	-8.2
B16: Background borehole- Sherwood Sandstone																			
24.9	1000	7.6	5.0	15.5	11.5	10.8	31.4	135.0	26.0	282	76.3	0.28	12.0	0.020	0.04	0.02	0.100	18.2	-4.4
35.1	1250	7.8	3.9	10.5	16.0	11.9	52.5	159.0	18.1	422	70.7	0.34	6.0	0.021	0.39	0.05	0.074	4.4	-4.0
41.1	465	7.9	5.0	13.6	13.9	7.4	16.3	51.6	30.6	59.4	89.3	0.53	11.4	0.068	0.06	0.00	0.051	5.7	-14.7
45.1	507	8.1	4.0	14.6	17.7	8.0	18.2	51.4	25.4	84.0	88.2	0.88	-	-	0.02	0.11	0.070	5.8	4.6
47.1	451	7.7	4.9	13.9	13.9	7.0	17.2	47.0	25.5	55.3	82.9	0.29	-	-	0.08	0.07	0.040	4.0	9.8
49.1	445	7.2	5.0	14.7	22.4	6.6	16.0	41.0	24.9	59.7	106.6	0.62	-	-	0.18	0.29	0.070	4.0	2.3
^27.8	*3100*	*7.7*	*4.5*	*16.5*	*43*	*24.1*	*131*	*457*	*31.3*	*1215*	*53*	*0.8*	*14.3*	*0.400*	*<=0.005*	*0.00*	*0.220*	*73.6*	*-2.0*
^43.1	*9800*	*8.1*	*9.8*	*861*	*1420*	*515*	*157*	*47.7*	*297*	*2980*	*1577*	*470*	*5.7*	*0.110*	*0.012*	*0.55*	*0.037*	*3.5*	*-7.5*

^ Core contaminated with drilling foam

Negative ion balance indicates cation deficiency

E2 POREWATER CHEMISTRY- ORGANICS

Depth (mbgl)	Ethanoic acid	Propanoic acid	i-Butanoic acid	n-Butanoic acid	i-Pentanoic acid	n-Pentanoic acid	i-Hexanoic acid	n-Hexanoic acid	Sum of VFAs	TOC mg l^{-1} C	ΣVFA/TOC %	Proportion of acids to total Ethanoic %	Propanoic %	Butanoic %	pentanoic %	hexanoic	sum %
	porewater concentration mg l^{-1} C																
B15 Upper waste (1-14m bgl)																	
3	224	117	6.8	39	17	12	0.8	17	433	2170	20.0	52	27	11	6	4	100
5	75	11	2.2	16	2.2	3.0	<0.2	9.2	118	1380	8.6	63	9	15	4	8	100
9	212	50	8.3	21	8.9	12	0.6	13	327	2500	13.1	65	15	9	6	4	100
14	49	7.8	1.4	5.6	1.4	1.4	0.2	3.9	71	1200	5.9	69	11	10	4	6	100
mean	*140*	*47*	*5*	*21*	*7*	*7*	*1*	*11*	*237*	*1813*	*12*	*62*	*16*	*11*	*5*	*5*	*100*
B15 Lower waste (18.5-27.7m bgl)																	
18.5	78	10	2.3	17	3.2	1.4	0.3	5.7	119	2700	4.4	66	9	17	4	5	100
22	20	1.5	<0.3	1.2	<2	<0.2	<0.2	1.2	24	1090	2.2	83	6	5	0	5	100
25.1	44	4.2	1.1	2.2	0.9	0.8	<0.2	3.9	58	1360	4.2	77	7	6	3	7	100
27.7	356	81	15	152	15	50	1.1	148	818	5150	15.9	44	10	20	8	18	100
mean	*125*	*24*	*6*	*43*	*6*	*17*	*1*	*40*	*254*	*2575*	*7*	*67*	*8*	*12*	*4*	*9*	*100*
B15 *Sherwood Sandstone*																	
36.25	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	7.5							
41	2.0	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<4.2	33.5							
41	0.6	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.8	33.5							
42.6	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	7.1							
51	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	10.0							
56.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	9.4							
57.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	10.4							
58.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	10.1							
59.8	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	10.3							
61.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	11.7							
64.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	11.9							
67.5	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	7.3							
B16 Sherwood Sandstone																	
24.9	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	15.5							
27.8	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	16.5							
35.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	10.5							
41.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	13.6							
43.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	861							
45.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	14.6							
47.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	13.9							
49.1	<0.4	<0.3	<0.3	<0.3	<0.2	<0.2	<0.2	<0.3	<2.2	14.7							

Average total volatile fatty acid concentration of fresh and aged leachates (mg/l C) source: WMP26a

Fresh	5688
Aged	5
Wet sites	12

E3 POREWATER CONCENTRATIONS (mg kg^{-1} dry weight)

Depth m bgl	conductivity µS cm^{-1}	pH	moisture dry weight %	TOC	Na	K	Mg	Ca	SO_4	Cl	Alk $CaCO_3$	NH_3 as N	Fe	Mn
porewater concentration in mg l^{-1}														
3	7330	7.9	32.1	2170.0	605	668	104.0	135.0	237.0	1350.0	2612	584.0	0.47	0.25
5	11220	8.4	84.2	1380.0	1030	874	96.7	17.4	337.0	1455.0	5109	1075.0	5.30	0.09
9	7870	7.9	86.6	2500.0	912	668	103.0	88.4	630.0	1425.0	2303	435.0	3.30	0.27
14	7620	8.0	28.2	1200.0	827	329	180.0	413.0	2080.0	1695.0	729.0	431.0	0.14	0.39
18.5	14750	8.5	79.9	2700.0	1660	987	35.7	13.9	170.0	2970.0	5540	1348.0	8.10	0.09
22	17500	8.4	170.3	1090.0	1940	1280	64.6	29.6	3400.0	3220.0	3307	1470.0	8.20	0.08
25.1	16500	8.2	83.2	1360.0	1940	1140	75.6	14.2	590.0	3140.0	5734	1560.0	6.50	0.05
27.7	15900	7.6	91.9	5150.0	2050	1120	204.0	152.0	570.0	3160.0	6314	1440.0	12.10	0.96
converted to mg kg^{-1}														
3				697	194	214	33	43	76	433	838	187	0.15	0.08
5				1162	867	736	81	15	284	1225	4302	905	4.46	0.08
9				2165	790	578	89	77	546	1234	1994	377	2.86	0.23
14				338.4	233	93	51	116	587	478	206	122	0.04	0.11
mean				**1090**	**521**	**405**	**64**	**63**	**373**	**843**	**1835**	**398**	**1.88**	**0.12**
18.5				2157	1326	789	29	11	136	2373	4426	1077	6.47	0.07
22				1856	3304	2180	110	50	5790	5484	5632	2503	13.96	0.14
25.1				1132	1614	948	63	12	491	2612	4771	1298	5.41	0.04
27.7				4733	1884	1029	187	140	524	2904	5803	1323	11.12	0.88
mean				**2469**	**2032**	**1237**	**97**	**53**	**1735**	**3343**	**5158**	**1550**	**9.24**	**0.28**

E4 MICROBIOLOGY OF SHERWOOD SANDSTONE CORE

	Borehole B15		Borehole B16	
Depth m bgl	Aerobes B15	SRBs B15	Aerobes B16	SRBs B16
notes	aerobes	total viable aerobe count/gramme sandstone		
	SRBs	sulphate reducing bacteria (presence/absence)		
	-	core not sampled at this depth		
6.5	-	-	310,000	present
8.1	-	-	483	present
24.5	-	-	4,700	present
25.6	-	-	180,000	present
27.1	-	-	655	present
28.6	-	-	92,000	-
31.6	-	-	610,000	present
32.6	-	-	250	absent
33.6	-	-	59,000	absent
34.6	-	-	62	absent
35.6	-	-	62	absent
35.75	360,000	present	-	
36.25	1,100	present	-	-
36.25	320,000			
36.6	-	-	2	absent
36.75	2,000	present	-	-
37.25	19,000,000	present	-	-
37.6	-	-	1,900	absent
37.75	130,000	-	-	-
38.6	-	-	3	absent
39.6	-	-	696	absent
40.6	-	-	9	absent
41	67,000,000	present	-	-
41.6	-	-	6	present
41.8	12,000	present	-	-
41.8	21,000	-	-	-
41.8	-	-	-	-
42.6	41,000	present	1	absent
43.6	-	-	6	present
44.6	-	-	4	present
44.9	4,000			
44.9	29,000	present	-	-
45.6	-	-	4	absent
46.6	-	-	295	absent
46.75	678	present	-	-
47.6	-	-	3	present

E4 contd. MICROBIOLOGY OF SHERWOOD SANDSTONE CORE

	Borehole B15		Borehole B16	
Depth m bgl	Aerobes B15	SRBs B15	Aerobes B16	SRBs B16
49.6	-	-	259	present
52.5	490,000	present	-	-
55	36,000	present	-	-
57.05	3,200	present	-	-
58.95	6,500	present	-	-
60.05	841	absent	-	-
61.025	240,000	present	-	-
62	1,100,000	present	-	-
63.1	656	absent	-	-
64.1	1,000	absent	-	-
65	42,000	present	-	-
66.1	460,000	present	-	-
66.7	250,000	present	-	-
68	320,000	absent	-	-
70.1	470,000	present	-	-
71	140,000	absent	-	-

APPENDIX F GROUNDWATER QUALITY - BURNTSTUMP (1991-1996)

F1 BURNTSTUMP GROUNDWATER QUALITY - INORGANICS

F2 BURNTSTUMP GROUNDWATER QUALITY - CARBOXYLIC ACIDS

F3 BURNTSTUMP GROUNDWATER QUALITY - SOLVENTS

F1 BURNTSTUMP GROUNDWATER QUALITY:INORGANICS

BURNTSTUMP FIELD AND INORGANIC GROUNDWATER DETERMINATIONS

<------ on-site measurements ----> (Cond to alkal); results in mg l⁻¹ unless stated otherwise (Na to B)

Bore hole	Date	RWL m AOD	Cond µS cm⁻¹	pH	Eh mV	Temp °C	DO mg l⁻¹	Diss CH_4 mg l⁻¹	alkal $CaCO_3$ mg l⁻¹	Na	K	Mg	Ca	SO_4	Cl	Lab. alkal $CaCO_3$	NH_3 As N	NO_3 As N	NO_2 As N	TSP As P	TOC	Fe	Mn	Ni	Cd	Cr	Cu	Pb	Zn	B	Ion Balance %(1)
B14	Nov-91	54.37	-	7.0	-	9.5	-	<=0.01	-	15.6	2.8	22.4	52.4	37.4	41.5	110	<=0.1	13.8	<=0.05	0.07	1.4	0.005	<=0.002	<=0.01	<=0.004	<=0.01	0.006	<=0.05	0.007	-	9.2
B14	Feb-92	54.30	-	-	-	-	-	<=0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B14	Sep-92	54.02	490	7.6	-	-	-	0.01	-	12.0	2.3	20.4	47.7	32.6	42.2	87.1	<=0.1	13.9	<=0.1	0.01	0.7	<=0.004	<=0.002	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	0.055	-	9.1
B14	Sep-92 D	54.02	-	-	-	-	-	<=0.01	-	12.1	2.4	20.8	47.8	32.6	42.6	85.2	-	13.8	<=0.1	0.03	0.7	0.009	0.003	<=0.01	<=0.004	<=0.01	0.007	<=0.05	0.063	-	9.7
B14	May-94	53.74	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B14	Oct-94	53.92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B14	Feb-95	54.32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B14	Oct-95	54.86	532	6.9	-	12.1	6.68	-	104	12.2	2.8	23.4	55.2	31	45.5	125	<=0.05	17.7	0.124	0.042	1.7	<=0.004	<=0.002	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	<=0.004	<=0.01	5
B14	Aug-95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B14	Jan-96	55.32																													
B11	Nov-91(2)	53.93	-	9.6	-	-	-	-	-	93.5	181	<=0.1	761	9.5	446	2219	<=0.1	0.150	0.09	0.1	33.3	0.08	<=0.02	<=0.1	<=0.04	<=0.1	0.09	<=0.5	<=0.04	-	11.0
B11	Feb-92	52.85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B11	May-94	53.34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B11	Oct-94	53.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B11	Feb-95	53.48	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B11	Sept-95(3)	53.48	1310*	7.5*	-	-	2.10*	-	-	70.8	123	2.0	153	45.1	354	138	0.24	0.2**	-	-	7.40	23.1	0.78	<=0.10	<=0.005	<=0.10	<=0.10	<=0.10	<=0.10	-	18.3
B11	Jan-96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B11	Feb 96(3)	-	1200	7	-	10.2	-	-	-	68.1	105	1.1	127	84.0	53		0.37	30.1**	-	-	6.40	14.8	0.86	<0.02	<0.0005	<0.02	<0.02	<0.005	<0.02	-	52.7
B12	May-91	52.97	-	-	-	-	-	-	-	15.3	2.4	36.8	70.3	55.0	42.2	-	0.08	9.23	<=0.01	0.08	0.93	0.321	0.019	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	0.014	-	1.0
B12	Nov-91	52.61	-	7.1	-	-	<=0.01	-	-	16.5	2.5	38.6	77.3	45.4	47.7	282	<=0.1	7.21	<=0.05	0.13	0.91	0.036	0.012	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	0.058	-	3.5
B12	Feb-92	51.56	-	-	-	-	-	-	-	16.2	2.5	38.8	75.6	45.4	50.0	241	<=0.1	9.75	0.11	0.04	0.98	0.049	0.012	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	0.040	-	6.3
B12	Sep-92	51.24	693	7.6	-	-	<=0.01	<=0.01	-	16.2	2.6	38.0	75.0	41.6	40.4	247	<=0.1	7.80	<=0.10	<=0.01	0.71	0.045	0.020	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	0.042	-	8.2
B12	May-94	82.05	645	7.4	-	10.1	5.8	-	217	14.7	2.6	37.1	67.9	41.4	42.0	218	<=0.50	9.13	<=0.10	<=0.03	0.48	0.025	0.011	-	-	-	-	-	-	-	7.0
B12	Feb-95	51.88	422	7.3	-	10.1	4.2	-	179	14.3	2.3	34.9	59.0	40.2	44.2	210	0.426	7.12	<=0.10	0.036	1.09	0.18	0.052	-	-	-	-	-	-	0.06	2.0
B12	Feb-95 D	51.88	-	-	-	-	-	-	-	14.2	2.2	34.9	59.2	40.2	43.8	209	0.458	7.08	<=0.10	0.028	2.28	0.191	0.052	-	-	-	-	-	-	0.05	9.7
B12	Sept-95(3)	-	594*	7.1*	-	-	5.7*	-	-	16.3	2.8	34.2	66.5	42.6	41	230	<=0.10	9.0**	-	-	0.54	3.15	<=0.100	<=0.10	<=0.005	<=0.10	<=0.10	<=0.10	<=0.10	-	5.1
B12	Oct-95	51.27	620	7.7	243	10.4	6.79	-	182	13.9	2.3	33.0	66.4	37.0	44.5	223	<=0.05	9.56	<=0.10	0.01	0.54	<=0.004	<=0.002	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	<=0.004	0.06	4
B12	Jan-96	53.42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B12	Jan 96(3)	52.65	392	8.3	-	8.5	2.7			18.6	3.97	33.8	17.7	41	45		2.21				2	3.24	0.32	<0.02	<0.0005	<0.02	0.03	0.011	0.04		47.1

F1 contd. BURNTSTUMP GROUNDWATER QUALITY:INORGANICS

BURNTSTUMP FIELD AND INORGANIC GROUNDWATER DETERMINATIONS

		RWL	<------ on-site measurements ----->													Lab.															Ion
		m	Cond	pH	Eh	Temp	DO	Diss	alkal	Na	K	Mg	Ca	SO$_4$	Cl	alkal	NH$_3$	NO$_3$	NO$_2$	TSP	TOC	Fe	Mn	Ni	Cd	Cr	Cu	Pb	Zn	B	Balance
Bore		AOD						CH$_4$	CaCO$_3$							CaCO$_3$	As N	As N	As N	As P											%(1)
hole	Date		µS cm^{-1}		mV	°C	mg l^{-1}	mg l^{-1}	mg l^{-1}					results in mg l^{-1} unless stated otherwise																	
B13	May-91	52.63	-	-	-	-	<=0.01	-	-	7.40	2.3	13.5	28.2	42.0	23.7	-	<=0.05	3.73	<=0.01	0.10	4.36	0.626	0.034	<=0.01	<=0.004	<=0.01	0.011	0.1	0.021	-	-
B13	Sep-91	52.83	1140	6.5	-	-	-	<=0.01	-	8.30	2.2	13.1	28.5	35.6	24.7	-	0.24	5.92	<=0.10	0.04	0.75	0.008	0.004	<=0.01	-	<=0.01	0.013	<=0.05	0.141	-	-
B13	Nov-91	52.21	-	5.8	-	9.2	<=0.01	<=0.01	-	8.71	2.7	14.0	32.2	34.6	27.7	81.1	<=0.1	4.38	<=0.05	0.10	1.43	0.018	0.005	<=0.01	<=0.004	<=0.01	0.009	<=0.5	0.062	-	4.8
B13	May-94	52.63	309	7.8	-	10.5	7.73	<=0.01	72.0	8.35	2.1	15.5	29.4	32.9	21.7	74.8	<=0.50	4.19	<=0.10	<=0.03	<=0.20	<=0.004	<=0.002	-	-	-	-	-	-	-	7.7
B13	May-94 D	52.63	-	-	-	-	-	-	74.0	8.53	2.1	15.5	-	33.4	21.7	-	<=0.5	4.29	<=0.1	<=0.3	<=0.2	-	-	-	-	-	-	-	-	-	-
B13	Oct-94	52.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B13	Feb-95	53.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B13	Oct-95	52.41	377	8	-	10.4	6.93	-	142.0	9.87	2..3	18.2	36	31.5	24.6	108	<=0.05	6.88	<=0.10	0.024	<=0.5	<=0.004	<=0.002	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	<=0.004	<=0.01	-
B13	Jan-96	53.61	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B13	Jan96(3)	52.91	315	8.0	-	9	6.8	-	-	9.15	2.9	16.9	38.3	30.0	25	-	<0.01	-	-	-	0.8	8.960	0.16	0.0	0.0008	0.0	0.03	0.21	0.08	-	-
Cockliff	May-94		477	7.0	-	-	9.5	-	-	9.52	2.4	22.9	45.6	-	-	-	<=0.5	16.5	<=0.1	<=0.3	67.5	<=0.004	<=0.002	-	-	-	-	-	-	-	-
Farm	May-94		477	7.9	-	10.2	9.5	-	72	9.52	2.4	22.9	45.6	61.6	30.4	67.5	-	16.5	-	-	0.3	-	-	-	-	-	-	-	-	-	7.0
	Feb-95		410	7.2	-	8.9	9.9	-	55	9.78	2.4	23.5	47.5	62.4	31.7	70.1	0.1	15.7	0	0.2	0.5	<=0.004	<=0.002	-	-	-	-	-	-	0.02	8.1
	Sept-95(3)		392*	7.5*			11.8*	-	-	9.85	2.56	21.2	43.1	62.1	26	72	0.11	14.9**			0.88	<=0.10	<=0.100	<=0.10	<=0.005	<=0.10	<=0.10	<=0.10	<=0.10	-	6.0
	Oct-95		470	7.6	238	10.0	10.3	-	47	9.8	2.2	22.6	47.2	59.0	32.5	73.9	<=0.05	18.6	0.11	0.043	<=0.5	<=0.004	<=0.002	<=0.01	<=0.004	<=0.01	<=0.004	<=0.05	<=0.004	<=0.01	5.1
UK MACs			1500	5.5- 9.5																				0.05	0.005	0.05	3	0.05	5	2	

Notes

-	not determined
(1)	*Negative ion balance indicates cation deficiency*
(2)	B11 Dec 91- sampled straight after drilling, demonstrates grout contamination, not purged as pump broke
(3)	sampling and analysis comissioned by Greenways
D	duplicate sample
*	Laboratory Analysis
**	Nitrogen =Tot al Oxidised Nitrogen
May-94	carboxylic acids (ethanoic to n-hexanoic acid) all <2 mg/l acid in samples from B12 and B13
Feb-95	solvents barely detectable
Eh	Eh values have been corrected for the potential of the reference elctrode at a water temp. of 10°C (i.e. raw mV plus +251 mV)

F2 BURNTSTUMP GROUNDWATER QUALITY: CARBOXYLIC ACIDS

BURNTSTUMP GROUNDWATER CARBOXYLIC ACID DETERMINATIONS (1991-1995)

Borehole	Date	ethanoic acid	propanoi acid	i-butanoic acid	n-butanoic acid	i-pentanoic acid	n-pentanoic acid	i-hexanoic acid	n-hexanoic acid	total VFAs	AOX
			<--------------------		mg l^{-1} acid (not as C)				--------------	mg l^{-1} C	mg l^{-1} C
BH14	Nov-91	-	-	-	-	-	-	-	-	-	15.2
BH14	Sep-92	-	-	-	-	-	-	-	-	<10	11.7
BH14	Oct-95	<2	<2	<4	<5	<5	<6	<8	<8	<2.2	-
B11	Nov-91	-	-	-	-	-	-	-	-	-	23.8
BH 12	Apr-91	<4	<5	<6	<6	<6	<6	<7	<7	<7	10.2
BH 12	Nov-91	-	-	-	-	-	-	-	-	-	9.7
BH 12	Sep-92	-	-	-	-	-	-	-	-	<10	19.8
BH 12	Apr-94	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-
BH 12	Oct-95	<2	<2	<4	<5	<5	<6	<8	<8	<2.2	-
BH 13	Apr-91	<4	<5	<6	<6	<6	<6	<7	<7	<7	70.6
BH 13	Sep-91	-	-	-	-	-	-	-	-	-	144
BH 13	Apr-94	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-
BH 13	apr 94 D	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-
BH 13	Oct-95	<2	<2	<4	<5	<5	<6	<8	<8	<2.2	-
Cockliffe	Apr-94	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-
Farm	Oct-95	<2	<2	<4	<5	<5	<6	<8	<8	<2.2	-
trip blank	Apr-94	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-
trip blank	Oct-95	<2	<2	<2	<2	<2	<2	<2	<2	<2.2	-

Note: Denmark MAC of 10 mg/l for AOX

F3 BURNTSTUMP GROUNDWATER QUALITY: SOLVENTS

BURNTSTUMP CHLORINATED AND BROMINATED SOLVENT GROUNDWATER DETERMINATIONS

Borehole	Date	$CHCl_3$ $\mu g\ l^{-1}$ trichloro methane (chloroform)	$1,1,1,C_2H_3Cl_3$ $\mu g\ l^{-1}$ 1,1,1, trichloro ethane (TCA)	CCl_4 $\mu g\ l^{-1}$ tetra chloro methane (C-tet)	C_2HCl_3 $\mu g\ l^{-1}$ trichloro ethene (TCE)	$CHCl_2Br$ $\mu g\ l^{-1}$ bromo dichloro methane	$1,1,2\text{-}C_2H_3Cl_3$ $\mu g\ l^{-1}$ 1,1,2 trichloro ethane	C_2Cl_4 $\mu g\ l^{-1}$ tetra chloro ethene (PCE)	$CHClBr_2$ $\mu g\ l^{-1}$ dibromo chloro methane	$CHBr_3$ $\mu g\ l^{-1}$ tri bromo methane (bromoform)
B12	Feb-95	<0.4	0.6	<0.01	0.4	<0.2		4.7	<0.5	<0.4
B12 dup	Feb-95	<0.4	0.7	<0.1	0.4	<0.2		4.9	<0.5	<0.4
Blank	Feb-95	<0.4	<0.3	<0.1	<0.3	0.5		<0.1	0.5	<0.4
Cockliff Farm	Feb-95	<0.4	<0.3	<0.1	<0.3	<0.2		<0.1	<0.5	<0.4
detection limit		<0.4	<0.3	<0.1	<0.3	<0.2	<2	<0.1	<0.5	<0.4

D = Duplicate

APPENDIX G LANDFILL GAS QUALITY - BURNTSTUMP (1985-1996)

G1 BURNTSTUMP GAS QUALITY: BOREHOLES B7 AND B8

G2 BURNTSTUMP GAS QUALITY: BOREHOLE B9

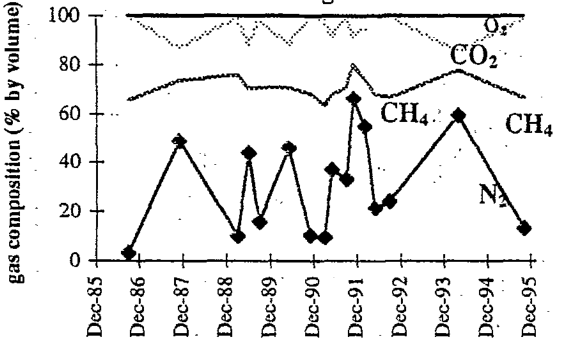
G3 BURNTSTUMP GAS QUALITY: BOREHOLE B15

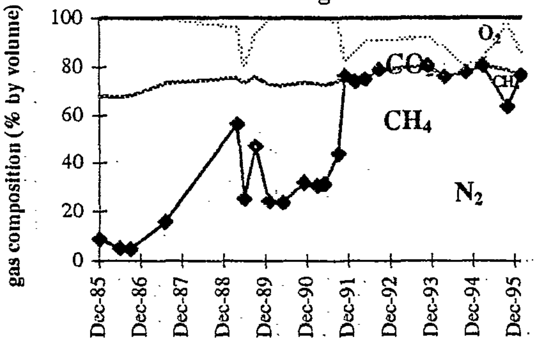
G4 BURNTSTUMP GAS QUALITY: BOREHOLE B13

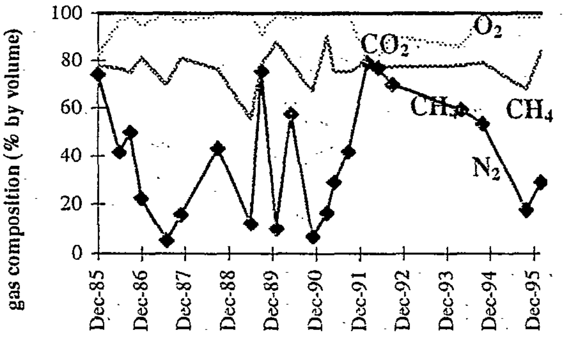
Note:

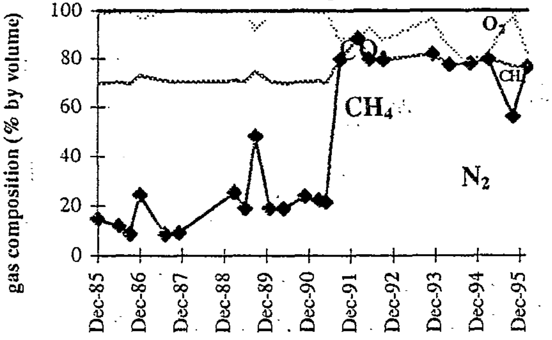
- Boreholes B7-B9 are in the old, shallow part of the site
- Borehole B15 is in the deeper phase completed in 1990
- Borehole B13 is off-site (just east of the eastern perimeter of the site)

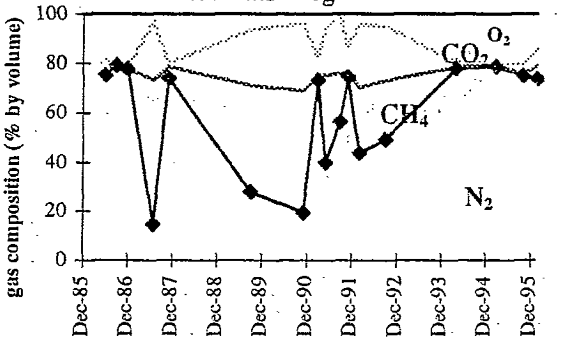
G1 BURNTSTUMP GAS QUALITY: BOREHOLES B7 AND B8

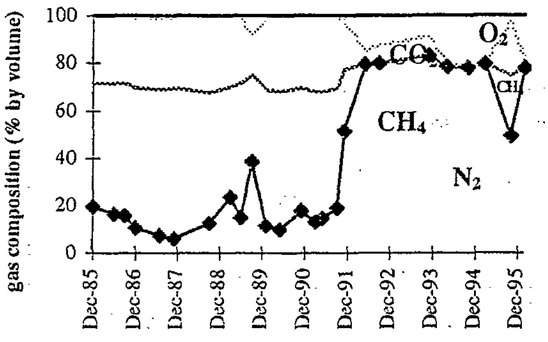

Borehole 8 probe 11
1.00-1.15m bgl

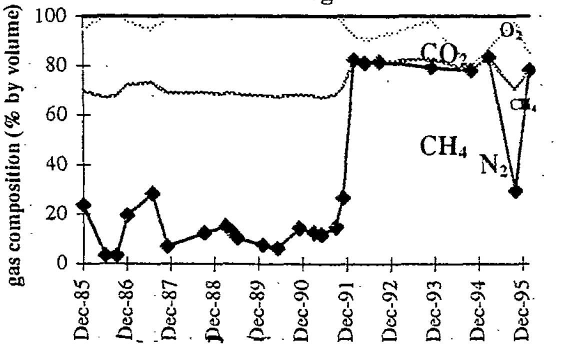

Borehole 7 probe 7
12.20-12.35m bgl

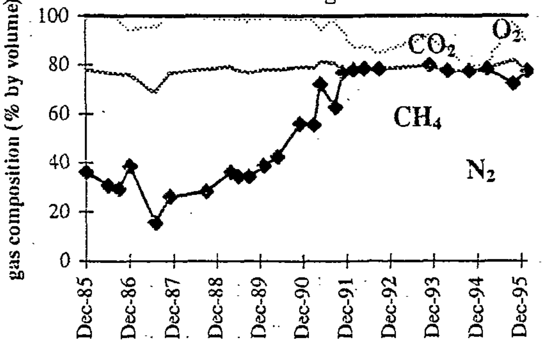

Borehole 8 probe 10
4.00-4.15m bgl


Borehole 7 probe 6
15.20-15.35m bgl

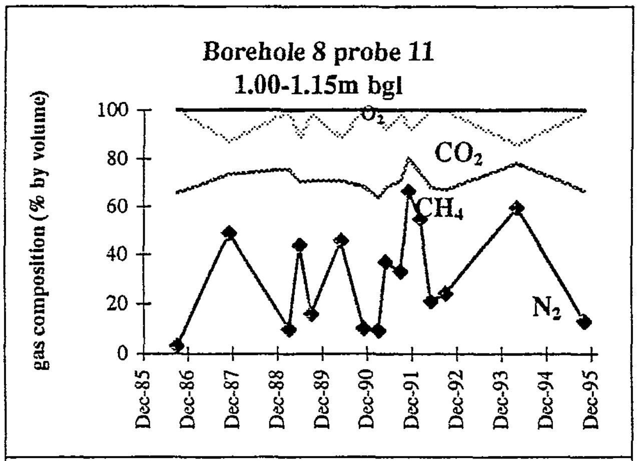

Borehole 8 probe 9
7.00-7.15m bgl

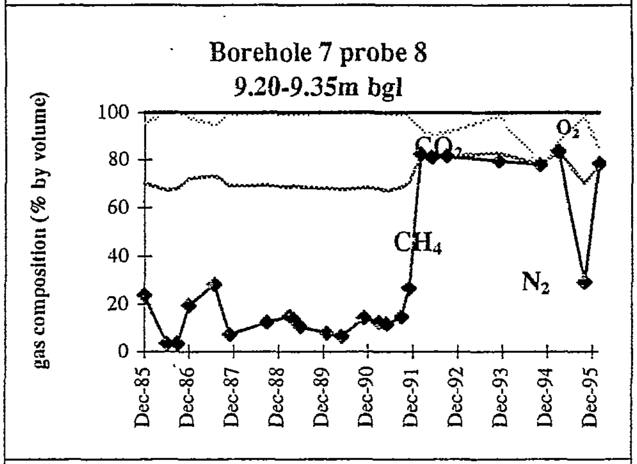

Borehole 7 probe 5
18.20-18.35m bgl

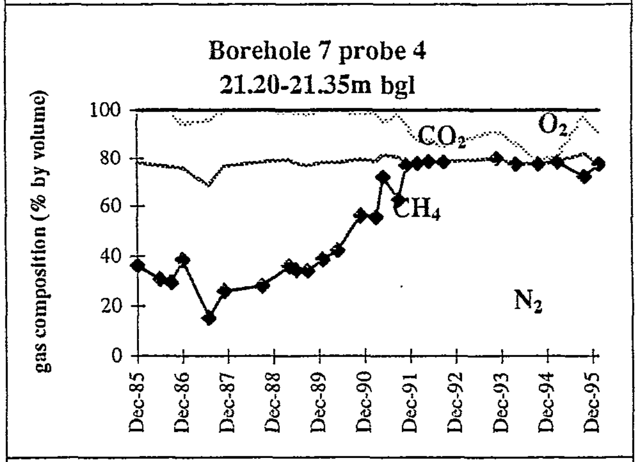

Borehole 7 probe 8
9.20-9.35m bgl

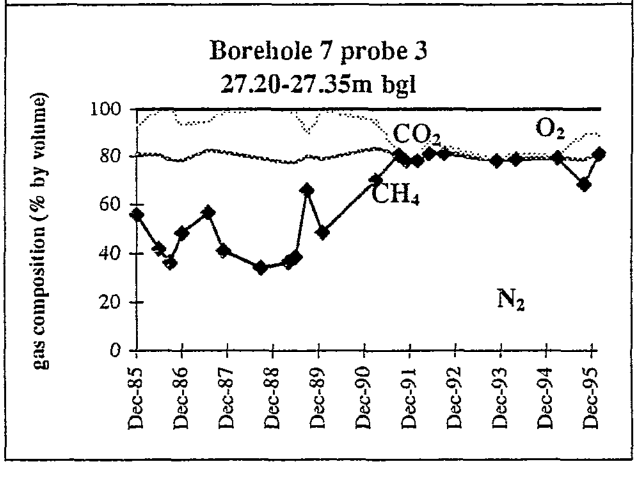

Borehole 7 probe 4
21.20-21.35m bgl

G1 BURNTSTUMP GAS QUALITY: BOREHOLES B7 AND B8



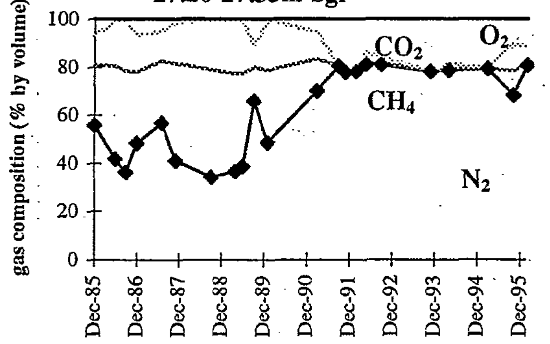




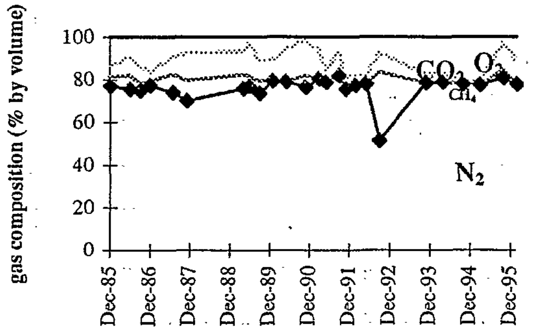


G1 BURNTSTUMP GAS QUALITY: BOREHOLES B7 AND B8

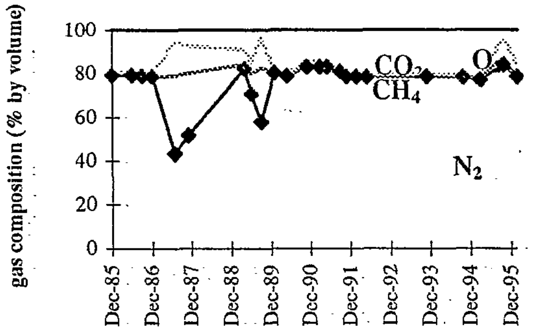
Borehole 7 probe 3
27.20-27.35m bgl



Borehole 7 probe 2
33.20-33.35m bgl



Borehole 7 probe 1
39.45-39.50m bgl



G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B7/1	(39.35-39.5m)				
Dec-85	79.0	0.3	0.3		
Jun-86	79.1	1.0	0.9		
Sep-86	78.7	0.1	0.3		
Dec-86	78.6	0.0	0.3		
Jul-87	43.5	35.3	16.0		
Nov-87	51.5	28.5	12.7		
Apr-89	82.1	1.9	7.0		
Jun-89	70.6	8.8	5.7		
Sep-89	57.7	25.0	13.3		
Jan-90	80.1	0.3	2.0		
May-90	78.8	0.0	0.9		
Nov-90	82.8	0.7	2.3		
Mar-91	82.9	0.5	1.8		
May-91	82.9	0.7	2.2		
Sep-91	80.8	0.2	1.7		
Nov-91	78.5	0.0	1.0		
Feb-92	78.4	0.1	2.3		
May-92	78.3	0.0	0.7		
Sep-92	#N/A	#N/A	#N/A		
Nov-93	78.6	0.0	0.7	0	20.6
Apr-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	78.3	0.0	0.9	0	20.9
Mar-95	77.1	1.2	1.1	0	20.6
Oct-95	83.7	3.3	8.9	0	4.1
Jan-96	78.4	0.1	5.6	0	15.9
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A
B7/2	(33.2-33.35m)				
Dec-85	77.1	4.3	4.7		
Jun-86	75.7	6.4	8.6		
Sep-86	74.9	3.4	8.2		
Dec-86	77.4	2.1	4.2		
Jul-87	74.0	8.7	8.1		
Nov-87	70.3	9.6	12.8		
Sep-88	#N/A	#N/A	#N/A		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	75.8	6.7	10.9		
Jun-89	77.0	4.8	15.7		
Sep-89	73.7	5.9	9.5		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	79.4	1.5	8.5		
May-90	79.3	0.0	14.9		
Nov-90	76.5	5.6	16.7		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	80.3	0.0	13.4		
May-91	78.8	0.0	6.1		
Sep-91	81.9	0.0	11.1		
Nov-91	75.6	0.0	5.3		
Feb-92	77.5	0.0	4.2		
May-92	78.0	0.0	3.7		
Sep-92	51.5	32.2	9.0		
Nov-93	78.7	0.0	3.6	0	17.6
Apr-94	79.0	0.3	3.9	0	16.8
Oct-94	77.9	0.0	2.2	0	19.9
Mar-95	77.7	0.1	1.4	0	20.8
Oct-95	81.0	3.8	12.6	0	2.6
Jan-96	78.0	0.1	10.9	0	11
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B7/3	(27.2-27.35m)				
Dec-85	56.0	24.9	12.4		
Jun-86	41.8	38.7	18.6		
Sep-86	36.4	42.0	21.0		
Dec-86	48.2	29.9	15.1		
Jul-87	56.7	25.7	12.6		
Nov-87	41.1	40.3	17.0		
Sep-88	34.3	44.5	20.6		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	36.5	40.9	21.9		
Jun-89	38.6	38.8	21.6		
Sep-89	65.8	14.0	9.3		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	48.5	30.0	20.7		
May-90	#N/A	#N/A	#N/A		
Nov-90	#N/A	#N/A	#N/A		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	69.9	13.3	11.5		
May-91	#N/A	#N/A	#N/A		
Sep-91	80.5	0.0	0.3		
Nov-91	77.9	0.1	0.2		
Feb-92	78.1	0.1	1.7		
May-92	81.0	0.5	4.3		
Sep-92	80.9	0.8	2.5		
Nov-93	78.1	0.0	0.3	0	21.6
Apr-94	78.7	0.3	2.2	0	18.8
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	79.2	0.0	0.5	0	20.3
Oct-95	68.1	10.2	10.9	0	10.8
Jan-96	80.6	0.7	7.5	0	11.2
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B7/4	(21.2-21.35m)				
Dec-85	36.2	41.9	21.0		
Jun-86	30.7	46.0	22.7		
Sep-86	29.4	46.9	23.3		
Dec-86	38.4	37.5	18.5		
Jul-87	15.5	52.8	27.6		
Nov-87	26.1	50.5	23.0		
Sep-88	28.3	50.1	20.9		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	36.0	43.3	19.6		
Jun-89	34.4	43.3	21.6		
Sep-89	34.2	42.5	21.1		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	38.7	39.4	21.2		
May-90	42.4	35.6	21.4		
Nov-90	56.1	23.3	18.9		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	55.6	23.1	20.4		
May-91	72.0	9.4	13.0		
Sep-91	62.6	17.9	18.2		
Nov-91	76.9	0.0	17.5		
Feb-92	77.9	0.0	9.1		
May-92	78.5	0.0	9.2		
Sep-92	78.4	0.0	6.5		
Nov-93	79.8	0.0	11.9	0	8.2
Apr-94	77.5	0.0	8.7	0	13.8
Oct-94	77.6	0.0	1.4	0	20.9
Mar-95	78.4	0.1	2.2	0	19.3
Oct-95	72.2	9.8	15.9	0	2.1
Jan-96	77.5	0.1	12.4	0	10.0
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B7/5	(18.2-18.35m)				
Dec-85	19.5	51.8	28.4		
Jun-86	16.7	54.6	28.2		
Sep-86	15.7	55.7	28.4		
Dec-86	10.8	58.7	29.2		
Jul-87	7.4	61.7	30.2		
Nov-87	6.2	63.4	29.8		
Sep-88	12.6	55.0	31.9		
Mar-89	23.4	46.6	29.5		
Apr-89	#N/A	#N/A	#N/A		
Jun-89	15.1	56.5	27.4		
Sep-89	38.8	36.0	16.5		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	11.4	57.2	31.1		
May-90	9.9	58.2	31.7		
Nov-90	17.9	51.5	30.0		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	13.0	54.8	32.0		
May-91	14.6	53.2	31.7		
Sep-91	18.9	50.7	29.7		
Nov-91	51.6	25.8	20.4		
Feb-92	#N/A	#N/A	#N/A		
May-92	79.4	0.1	5.5		
Sep-92	80.0	0.0	7.3		
Nov-93	82.8	0.0	8.6	0	8.6
Apr-94	78.3	0.0	1.3	0	20.4
Oct-94	77.9	0.0	1.1	0	21
Mar-95	79.3	0.0	0.4	0	20.3
Oct-95	49.5	25.1	23.0	0	2.4
Jan-96	77.8	0.1	3.6	0	18.5
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B7/6	(15.2-15.35m)				
Dec-85	14.8	55.2	29.3		
Jun-86	11.9	58.5	28.9		
Sep-86	8.5	61.2	30.0		
Dec-86	24.3	48.8	23.4		
Jul-87	8.6	62.3	28.8		
Nov-87	9.0	61.4	29.4		
Sep-88	#N/A	#N/A	#N/A		
Mar-89	25.5	45.5	28.6		
Apr-89	#N/A	#N/A	#N/A		
Jun-89	18.9	51.7	28.9		
Sep-89	48.2	26.6	16.5		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	18.8	51.9	28.8		
May-90	18.8	51.2	29.7		
Nov-90	23.8	47.0	28.7		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	22.4	48.5	28.3		
May-91	21.5	48.4	29.6		
Sep-91	79.7	0.4	7.5		
Nov-91	#N/A	#N/A	#N/A		
Feb-92	88.4	0.3	0.0		
May-92	79.9	0.1	12.2		
Sep-92	79.6	0.0	7.9		
Nov-93	81.8	0.0	14.5	0	3.7
Apr-94	77.5	0.0	6.8	0	15.7
Oct-94	77.9	0.0	0.8	0	21.3
Mar-95	79.9	0.1	1.7	0	18.3
Oct-95	56.3	20.4	21.8	0	1.5
Jan-96	76.7	0.1	5.5	0	17.7
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B7/7	(12.2-12.35m)				
Dec-85	8.7	59.2	31.9		
Jun-86	5.0	62.5	32.4		
Sep-86	4.8	63.4	31.7		
Dec-86	#N/A	#N/A	#N/A		
Jul-87	15.8	57.3	26.6		
Nov-87	#N/A	#N/A	#N/A		
Sep-88	#N/A	#N/A	#N/A		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	56.2	19.0	20.6		
Jun-89	25.3	47.9	6.0		
Sep-89	46.9	28.7	17.7		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	24.3	48.3	26.9		
May-90	23.8	48.1	27.8		
Nov-90	31.8	41.6	25.9		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	30.7	42.2	26.6		
May-91	31.3	40.9	27.3		
Sep-91	43.7	30.2	24.5		
Nov-91	76.3	0.2	5.7		
Feb-92	74.0	0.0	12.0		
May-92	75.0	0.0	15.8		
Sep-92	78.8	0.0	12.0		
Nov-93	80.6	0.0	11.6	0	7.8
Apr-94	75.6	0.0	12.0	0	12.3
Oct-94	77.5	0.0	3.1	0	19.4
Mar-95	80.4	0.0	2.2	0	17.4
Oct-95	63.3	15.2	19.8	0	1.7
Jan-96	76.2	0.0	9.1	0	14.7
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B7/8	(9.20-9.35m)				
Dec-85	23.6	46.3	25.0		
Jun-86	3.3	63.8	32.8		
Sep-86	3.4	64.5	32.0		
Dec-86	19.4	52.8	25.5		
Jul-87	28.2	45.0	21.6		
Nov-87	7.1	61.9	29.9		
Sep-88	12.4	56.8	30.5		
Mar-89	15.0	53.4	30.6		
Apr-89	13.6	55.7	29.5		
Jun-89	10.4	58.1	30.6		
Sep-89	#N/A	#N/A	#N/A		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	7.6	60.2	32.0		
May-90	6.2	61.2	32.5		
Nov-90	14.2	53.9	31.5		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	12.4	55.4	31.9		
May-91	11.6	55.2	32.8		
Sep-91	14.7	53.8	30.8		
Nov-91	26.6	44.3	27.8		
Feb-92	82.3	0.1	10.0		
May-92	81.1	0.0	9.2		
Sep-92	81.5	0.0	10.1		
Nov-93	79.4	3.6	15.4	0	1.6
Apr-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	78.0	0.0	0.4	0	21.6
Mar-95	83.5	0.0	3.2	0	13.3
Oct-95	29.2	40.7	28.9	0	1.2
Jan-96	78.3	0.0	6.2	0	15.5
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B8/9	(7.00-7.15m)				
Dec-85	#N/A	#N/A	#N/A		
Jun-86	75.2	1.0	5.0		
Sep-86	79.1	0.2	0.0		
Dec-86	77.5	0.3	0.2		
Jul-87	14.6	58.6	24.0		
Nov-87	73.9	4.6	1.5		
Sep-88	#N/A	#N/A	#N/A		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	#N/A	#N/A	#N/A		
Jun-89	#N/A	#N/A	#N/A		
Sep-89	27.8	43.2	22.8		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	#N/A	#N/A	#N/A		
May-90	#N/A	#N/A	#N/A		
Nov-90	19.3	49.6	27.3		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	73.3	2.1	7.0		
May-91	40.0	35.2	18.6		
Sep-91	56.5	19.4	23.3		
Nov-91	74.5	2.1	10.4		
Feb-92	43.7	26.4	25.9		
May-92	#N/A	#N/A	#N/A		
Sep-92	49.1	23.9	22.0		
Nov-93	#N/A	51.3	11.4	0	3.1
Apr-94	77.9	0.5	1.8	0	19.9
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	78.5	0.8	0.5	0	20.2
Oct-95	74.9	0.6	3.7	0	20.8
Jan-96	73.8	5.1	7.5	0	13.6
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

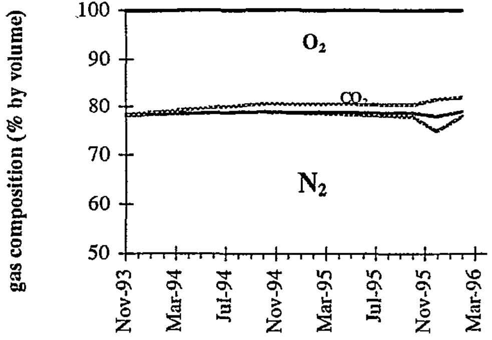
B8/10	(4.0-4.15m)				
Dec-85	74.0	3.8	4.0		
Jun-86	41.6	34.9	19.9		
Sep-86	49.8	25.0	24.5		
Dec-86	22.4	58.9	13.2		
Jul-87	5.3	64.5	29.9		
Nov-87	16.0	64.9	15.5		
Sep-88	43.0	33.1	22.8		
Mar-89	#N/A	#N/A	#N/A		
Apr-89	#N/A	#N/A	#N/A		
Jun-89	12.3	42.9	44.5		
Sep-89	75.3	3.3	12.1		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	10.0	77.5	12.2		
May-90	57.3	21.7	18.7		
Nov-90	6.8	60.2	32.8		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	16.7	73.4	8.6		
May-91	29.2	46.0	23.7		
Sep-91	41.8	33.4	24.2		
Nov-91	#N/A	#N/A	#N/A		
Feb-92	79.0	0.7	0.0		
May-92	76.8	1.6	1.6		
Sep-92	69.9	7.3	12.9		
Nov-93	#N/A	#N/A	#N/A	#N/A	#N/A
Apr-94	59.3	18.6	7.6	0	14.4
Oct-94	53.4	25.7	20.0	0	1
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	17.7	49.9	30.9	0	1.5
Jan-96	29.0	54.6	14.8	0	1.6
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G1 BURNTSTUMP GAS QUALITY : BOREHOLES B7 AND B8

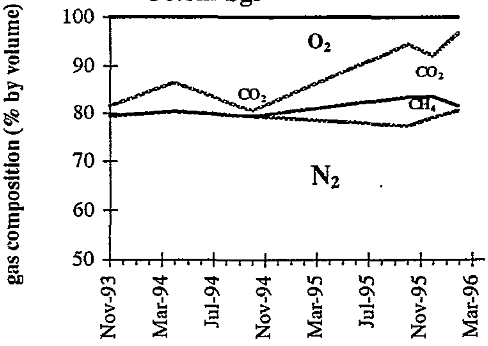
Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B8/11	(1.0-1.15m)				
Dec-85	#N/A	#N/A	#N/A		
Jun-86	#N/A	#N/A	#N/A		
Sep-86	3.1	62.6	34.2		
Dec-86	#N/A	#N/A	#N/A		
Jul-87	#N/A	#N/A	#N/A		
Nov-87	48.6	24.9	13.5		
Sep-88	#N/A	#N/A	#N/A		
Mar-89	10.0	65.9	23.4		
Apr-89	#N/A	#N/A	#N/A		
Jun-89	43.7	26.6	17.9		
Sep-89	15.8	54.8	27.7		
Dec-89	#N/A	#N/A	#N/A		
Jan-90	#N/A	#N/A	#N/A		
May-90	45.7	25.0	17.5		
Nov-90	10.1	58.2	31.4		
Dec-90	#N/A	#N/A	#N/A		
Mar-91	9.3	54.0	35.4		
May-91	36.9	31.1	23.7		
Sep-91	33.1	37.8	28.7		
Nov-91	66.3	13.9	11.7		
Feb-92	54.6	19.8	20.4		
May-92	21.2	46.8	31.6		
Sep-92	24.1	42.7	32.7		
Nov-93	#N/A	#N/A	#N/A	#N/A	#N/A
Apr-94	59.5	18.6	7.6	0	14.4
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	13.1	53.4	32.5	0	1
Jan-96	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G2 BURNTSTUMP GAS QUALITY: BOREHOLE B9

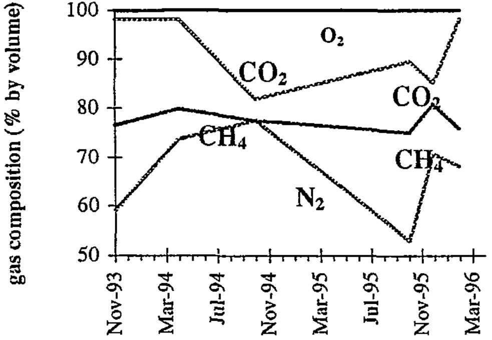
Borehole 9 probe black
9.6m bgl



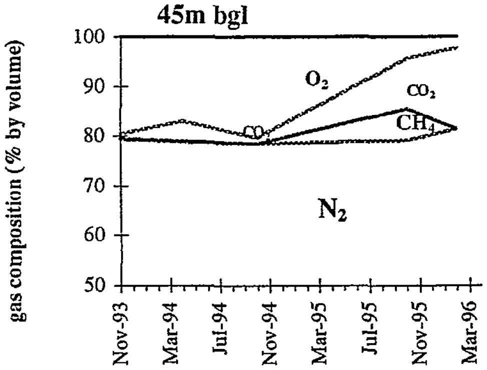
Borehole 9 probe red
36.6m bgl



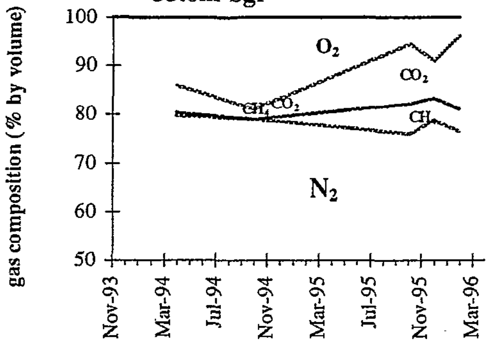
Borehole 9 probe green
21.6m bgl



Borehole 9 probe yellow
45m bgl



Borehole 9 probe blue
33.6m bgl



G2 BURNTSTUMP GAS QUALITY: BOREHOLE B9

Burntstump	**Gas composition (% by volume)**				
	N2	**CH4**	**CO2**	**H2**	**O2**
B9/yellow	**(45m)**				
Nov-93	79.4	0.1	0.9	0	19.6
Apr-94	78.9	0.1	4.0	0.0	17.0
Oct-94	78.5	0.0	1.1	0.0	20.4
Oct-95	79.1	6.3	10.2	0.0	4.4
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A
Jan-96	81.3	0.1	16.3	0.0	2.3
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B9/red	**(36.6m)**				
Nov-93	79.4	0.1	2.1	0	18.4
Apr-94	80.2	0.2	6.0	0	13.6
Oct-94	79.3	0.0	1.2	0	19.5
Oct-95	77.4	6.0	11.1	0	5.5
Dec-95	79.1	4.4	8.6	0	7.9
Jan-96	80.5	1.1	15.1	0	3.3
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

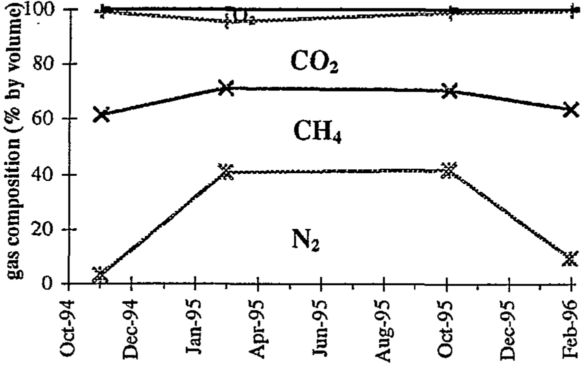
B9/blue	**(33.6m)**				
Nov-93	#N/A	#N/A	#N/A	#N/A	#N/A
Apr-94	79.7	0.6	5.5	0.0	14.1
Oct-94	79.0	0.0	2.1	0.0	18.9
Oct-95	76.0	6.1	12.3	1.1	4.5
Dec-95	78.7	4.6	7.6	0.0	9.1
Jan-96	76.5	4.6	15.0	0.0	3.9
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B9/green	**(21.6m)**				
Nov-93	59.2	17.3	21.5	0	1.9
Apr-94	73.7	6.2	18.1	0	2
Oct-94	77.6	0.0	4.3	0	18.1
Oct-95	52.9	22.2	14.4	3.2	7.3
Dec-95	70.7	10.3	4.2	0	14.8
Jan-96	68.1	7.7	22.3	0	1.9
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

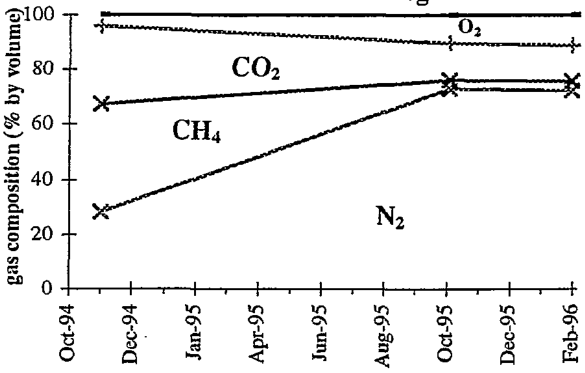
B9/black	**(9.6m)**				
Nov-93	78.2	0.0	0.1	0	21.6
Apr-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	78.9	0.0	1.8	0	19.4
Oct-95	77.9	0.8	1.7	0	19.6
Dec-95	74.9	3.1	3.6	0	18.4
Jan-96	78.0	1.0	3.0	0	18
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

G3 BURNTSTUMP GAS QUALITY: BOREHOLE B15

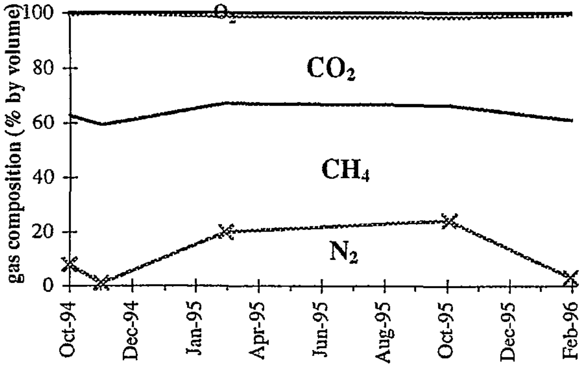
Borehole 15/9 - 5m bgl



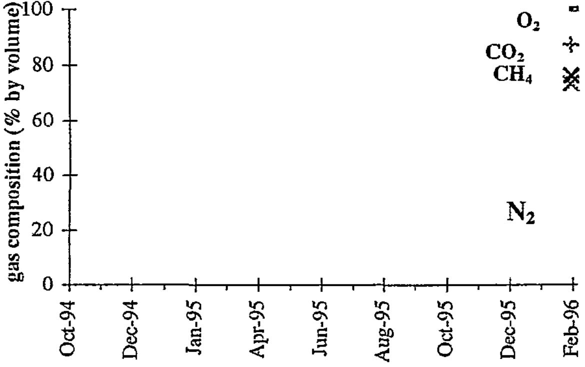
Borehole 15/32 - 32m bgl



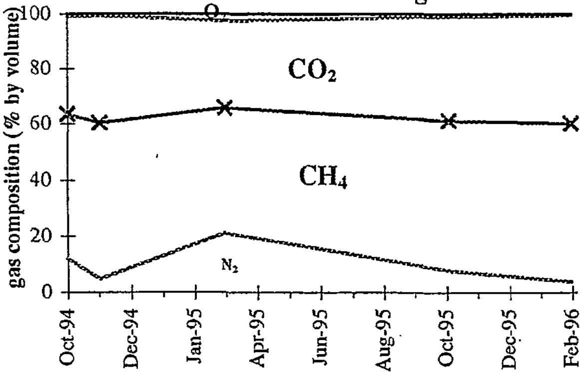
Borehole 15/8 - 8m bgl



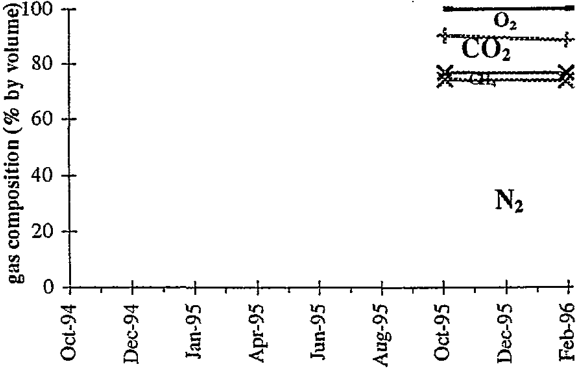
Borehole 15/37 - 37m bgl



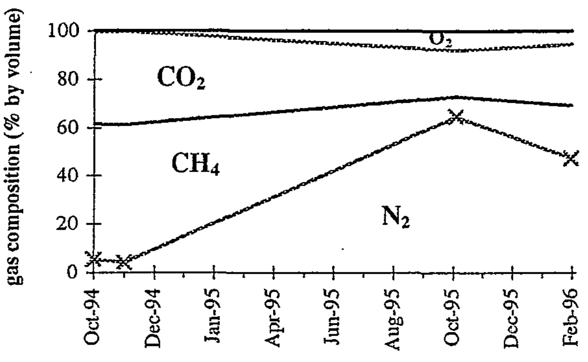
Borehole 15/14 - 14m bgl



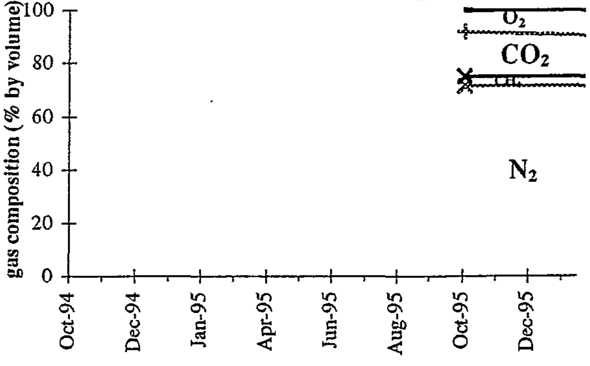
Borehole 15/41 - 41m bgl



Borehole 15/23 - 23m bgl



Borehole 15/47 - 47m bgl



G3 BURNTSTUMP GAS QUALITY: BOREHOLE B15

Burntstump	**Gas composition (% by volume)**				
	N2	**CH4**	**CO2**	**H2**	**O2**
B15/5	**(5m)**				
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-94	3.3	58.2	37.5	0.0	0.9
Mar-95	40.9	30.1	24.3	0.0	4.7
Oct-95	41.7	28.6	28.5	0.0	1.2
Jan-96	9.5	54.0	36.0	0.0	0.5
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B15/8	**(8m)**				
Oct-94	7.9	54.9	36.6	0	0.7
Nov-94	1.0	58.4	40.3	0	0.2
Mar-95	20.1	47.0	31.4	0	1.5
Oct-95	24.2	42.3	31.8	0	1.7
Jan-96	3.0	58.1	38.3	0	0.6
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B15/14	**(14m)**				
Oct-94	11.9	51.7	35.4	0.0	1.0
Nov-94	4.8	55.6	38.9	0.0	0.6
Mar-95	21.0	44.8	31.7	0.0	2.5
Oct-95	7.8	53.4	37.9	0.0	0.9
Jan-96	4.0	56.4	39.1	0.0	0.5
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

B15/23	**(23m)**				
Oct-94	5.4	56.1	38.1	0	0.4
Nov-94	4.1	57.1	38.5	0	0.3
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	64.6	8.3	19.0	0	8.1
Jan-96	47.3	22.1	25.1	0	5.5
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

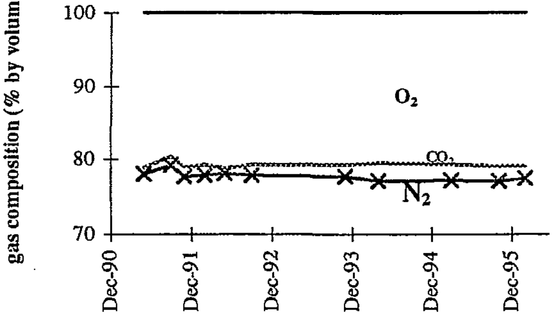
B15/32	**(32m)**				
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-94	28.2	38.9	28.8	0	4.1
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	72.9	3.2	13.5	0	10.4
Jan-96	72.3	3.4	13.0	0	11.3
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

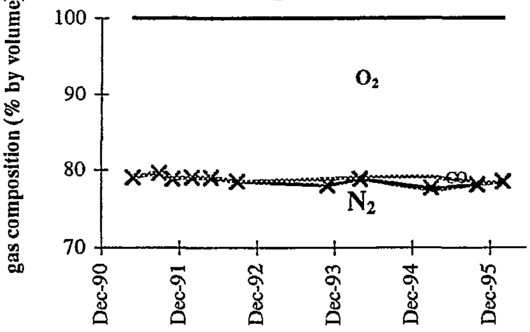
B15/35	**(35m)**				
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	#N/A	#N/A	#N/A	#N/A	#N/A
Jan-96	73.6	2.6	11.1	0	12.7
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

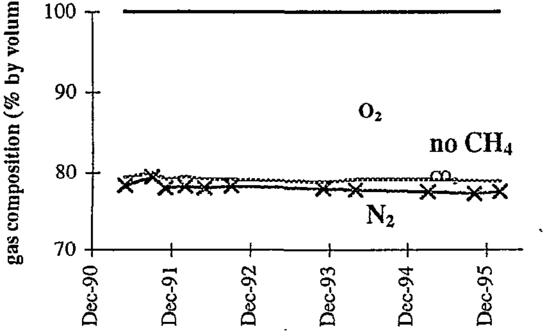
B15/41	**(41m)**				
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	74.2	2.6	13.6	0	9.6
Jan-96	73.8	2.7	12.1	0	11.4
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

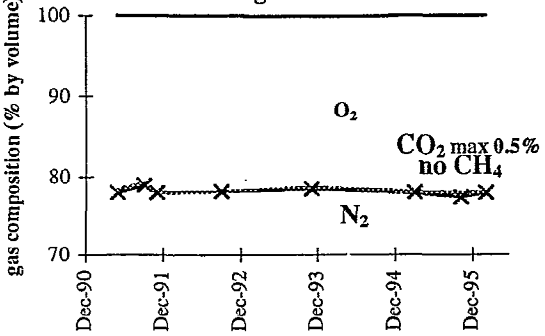
B15/47	**(47m)**				
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-95	71.5	3.7	16.7	0	8.1
Jan-96	71.6	3.6	15.4	0	9.4
Mar-96	#N/A	#N/A	#N/A	#N/A	#N/A

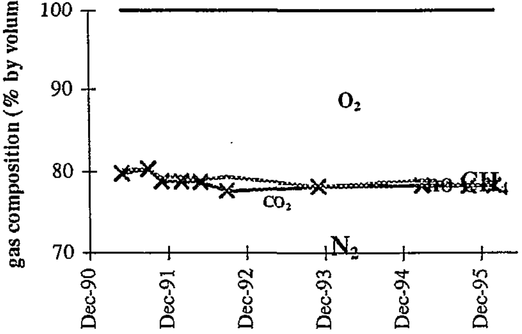
G4 BURNTSTUMP GAS QUALITY: BOREHOLE B13


Borehole 13 probe black & white
6m bgl


Borehole 13 probe yellow
24m bgl


Borehole 13 probe black
12m bgl


Borehole 13 probe white
30m bgl


Borehole 13 probe blue
18m bgl

G4 BURNTSTUMP GAS QUALITY: BOREHOLE B13

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B13/white	(30m)				
Dec-90	#N/A	#N/A	#N/A		
May-91	78.0	0.0	0.4		
Sep-91	79.0	0.0	0.4		
Nov-91	78.0	0.0	0.0		
Feb-92	#N/A	#N/A	#N/A		
May-92	#N/A	#N/A	#N/A		
Sep-92	78.2	0.0	0.0		
Nov-93	78.5	0.0	0.2	0	21.2
Apr-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	77.9	0.1	0.1	0.0	21.9
Oct-95	77.4	0.0	0.5	0.0	22.1
Jan-96	77.9	0.0	0.2	0.0	21.9
Jun-96	#N/A	#N/A	#N/A	#N/A	#N/A

B13/Yellow	(24m)				
Dec-90	#N/A	#N/A	#N/A		
May-91	79.0	0.0	0.0		
Sep-91	79.6	0.0	0.1		
Nov-91	78.8	0.0	0.1		
Feb-92	79.0	0.0	0.1		
May-92	78.9	0.1	0.1		
Sep-92	78.5	0.0	0.0		
Nov-93	78.0	0.0	0.8	0	21.2
Apr-94	78.8	0.0	0.3	0	20.9
Mar-95	77.3	0.4	1.4	0	20.9
Oct-95	78.1	0.0	0.3	0	21.6
Jan-96	78.5	0.0	0.0	0	21.5
Jun-96	#N/A	#N/A	#N/A	#N/A	#N/A

B13/blue	(18m)				
Dec-90	#N/A	#N/A	#N/A		
May-91	79.7	0.0	0.4		
Sep-91	80.3	0.0	0.0		
Nov-91	78.8	0.0	0.4		
Feb-92	78.7	0.1	0.6		
May-92	78.7	0.0	0.2		
Sep-92	77.6	0.0	1.7		
Nov-93	78.1	0.0	0.0	0	21.9
Apr-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	78.2	0.1	0.6	0.0	21.1
Oct-95	78.2	0.0	0.0	0.0	21.8
Jan-96	78.3	0.0	0.3	0.0	21.4
Apr-96	#N/A	#N/A	#N/A	#N/A	#N/A

G4 BURNTSTUMP GAS QUALITY: BOREHOLE B13

Burntstump	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
B13/black	(12m)				
Dec-90	#N/A	#N/A	#N/A		
May-91	78.3	0.0	1.1		
Sep-91	79.4	0.0	0.6		
Nov-91	78.0	0.0	1.2		
Feb-92	78.2	0.0	1.3		
May-92	78.0	0.0	1.2		
Sep-92	78.2	0.0	0.9		
Nov-93	77.9	0.0	0.9	0	21.2
Apr-94	77.8	0.0	1.3	0	20.9
Mar-95	77.5	0.0	1.6	0	20.9
Oct-95	77.3	0.0	1.7	0	21.0
Jan-96	77.5	0.0	1.4	0	21.1
Apr-96	#N/A	#N/A	#N/A	#N/A	#N/A

B13/black & white	(6m)				
Dec-90	#N/A	#N/A	#N/A		
May-91	78.0	0.0	0.9		
Sep-91	79.2	0.0	1.1		
Nov-91	77.7	0.0	1.3		
Feb-92	77.9	0.0	1.3		
May-92	78.1	0.0	0.7		
Sep-92	77.9	0.0	1.3		
Nov-93	77.7	0.0	1.5	0	20.8
Apr-94	77.1	0.0	2.4	0	20.5
Mar-95	77.2	0.0	2.1	0	20.7
Oct-95	77.1	0.0	2.0	0	20.9
Jan-96	77.4	0.0	1.7	0	20.9
Apr-96	#N/A	#N/A	#N/A	#N/A	#N/A

APPENDIX H GROUNDWATER QUALITY - GORSETHORPE (1986-1996)

H1 GORSETHORPE GROUNDWATER QUALITY (1994) - GENERAL AND INORGANIC PARAMETERS

H2 GORSETHORPE GROUNDWATER QUALITY (1994) - CARBOXYLIC ACIDS

H3 GORSETHORPE GROUNDWATER QUALITY (1994) - SOLVENTS

H4 GORSETHORPE GROUNDWATER QUALITY (1995)

H5 GORSETHORPE GROUNDWATER QUALITY- BULK SAMPLES (1986-1996)

H1 GORSETHORPE GROUNDWATER QUALITY (1994) - GENERAL AND INORGANIC PARAMETERS

FIELD AND INORGANIC DETERMINATIONS IN BULK AND DEPTH GROUNDWATERS AND SURFACE WATERS: FEB/OCT 1994

		<------ on-site measurements --->																					
		Cond	pH	Eh	Temp	DO	DO	Diss CH_4	Na	K	Mg	Ca	SO_4	Cl	Alkal $CaCO_3$	NH_3 As N	NO_3 As N	NO_2 As N	TSP As P	TOC	Fe	Mn	Ion Balance
Borehole/ m bgl	Date	µS cm^{-1}		mV	°C	%	mg l^{-1}	mg l^{-1}	<------------------							mg l^{-1}	------------------>						%
Depth groundwater samples																							
G17/23	Feb-94	1060	7.3	-	11.2	33.5	3.78	-	73.8	7.4	49.8	76.3	118	82.5	274	<0.05	26.6	<0.1	<0.01	1.4	0.026	0.005	-3.6
G17/26	Feb-94	1066	7.4	-	10.8	32	3.56	-	74.4	7.5	49.4	77	118	82.2	280	<0.05	26.3	<0.1	<0.01	1.2	<0.004	0.005	-3.9
G17/28	Feb-94	1085	7.4	-	10.7	30.5	3.38	-	76.8	7.3	50	77.4	117	85.2	287	<0.05	28.7	<0.1	0.03	1.9	<0.004	0.007	-4.7
G17/31	Feb-94	1076	7.4	-	10.7	30.6	3.41	-	74.8	7.4	50	76.9	117	83.1	269	<0.05	25.6	<0.1	<0.01	1.2	<0.004	0.009	-2.5
G17/34	Feb-94	1092	7.4	-	10.2	25.9	2.93	-	75.6	7.0	50.4	78.0	118	84.0	283	<0.05	28.2	<0.1	<0.01	1.0	0.007	0.003	-4.1
G17/37	Feb-94	1062	7.4	-	10.6	28.6	3.24	-	72.6	7.6	49.1	77.2	116	81.9	268	<0.05	27.6	<0.1	<0.01	0.9	0.008	0.004	-3.5
G17/37D	Feb-94	-	-	-	-	-	-	-	72.7	7.6	49.5	77.3	116	82.8	272	<0.05	26.1	<0.1	<0.01	1.2	0.013	0.004	-3.3
G18/24	Feb-94	1070	7.3	-	10.5	24.3	2.7	-	101	5.2	50.9	79.1	109	97.5	323	<0.05	15.8	<0.1	<0.01	2.6	0.034	0.048	0.3
G18/24D	Feb-94	-	-	-	-	-	-	-	101	5.2	50.7	78.7	109	97.8	323	<0.05	15.9	<0.1	<0.01	2.4	0.035	0.048	0.1
G18/27	Feb-94	1304	7.1	-	13.8	11.3	1.17	-	182	6.1	63.7	93.6	124	149	505	<0.05	13.0	<0.1	<0.01	8.6	0.05	0.339	0.6
G18/27D	Feb-94	-	-	-	-	-	-	-	182	6.1	63.7	93.6	137	158	499	<0.05	13.0	<0.1	<0.01	11.2	0.053	0.34	-0.6
G21/22	Feb-94	932	7.6	-	10.4	23.3	2.53	-	66.0	4.5	48	57.8	96.3	61.8	243	<0.05	15.0	<0.1	<0.03	3.46	0.006	0.124	0.8
G21/24	Feb-94	1016	7.6	-	10.9	7.5	0.82	-	66.5	4.9	51.6	68.7	110	77.1	249	<0.05	22.0	<0.1	<0.03	2.42	0.02	0.057	-1.4
G21/25	Feb-94	1086	7.5	-	10.8	32.1	3.58	-	75.8	5.4	52.6	73.5	116	83.1	254	<0.05	24.8	<0.1	<0.03	3.39	<0.004	0.044	-0.8
G21/26	Feb-94	1085	7.5	-	10.6	33.3	3.63	-	78.1	5.5	53.3	73.1	116	84.0	258	<0.05	24.9	<0.1	<0.03	2.18	0.013	0.039	-0.6
G21/28	Feb-94	1103	7.5	-	10.8	11.1	1.24	-	78.8	5.5	53	73.6	117	83.7	257	<0.05	25.1	<0.1	<0.03	2.54	0.017	0.035	-0.5
G22/22	Feb-94	2360	6.9	-	12	0	0	-	233	21.1	125	101	56.0	241	1120	34.3	1.1	<0.1	0.04	35.4	12.1	0.189	3.7
G22/24	Feb-94	2280	6.9	-	12	0	0	-	242	23	130	103	63.0	232	1050	32.6	3.5	<0.1	0.03	31.6	13.4	0.217	7.9
G22/25	Feb-94	2270	6.9	-	12	0	0	-	232	20.7	125	100	62.5	231	1050	32.1	3.7	<0.1	0.03	29.9	12.3	0.184	5.7
G22/27	Feb-94	2120	6.9	-	12.1	0	0	-	216	19.2	120	98.5	71.0	218	952	25.4	8.1	<0.1	0.03	44.5	11.2	0.156	5.6
G22/28	Feb-94	2090	6.9	-	12	0	0	-	205	18.4	112	95.0	77.5	209	899	24.8	8.0	<0.1	0.03	40.1	9.35	0.144	4.4
G22/29	Feb-94	1990	7	-	11.7	1	0.11	-	195	17.3	107	92.5	80.0	201	840	23.7	9.3	<0.1	0.04	23.4	9.19	0.144	4.9
G25/22	Feb-94	2440	7	-	11.1	2.7	0.27	-	262	12.6	144	97.3	55.5	239	1130	16.9	<0.10	<0.1	0.04	39.8	9.96	0.855	4.3
G25/23	Feb-94	2440	7	-	11.2	1.2	0.14	-	246	13.8	142	92.6	60.5	232	1080	22.6	3.2	<0.1	<0.03	37.3	12.6	0.612	6.1
G25/24	Feb-94	2250	7	-	11.3	1.2	0.13	-	226	12.4	127	92.7	58.5	185	971	16.7	6.7	<0.1	<0.03	30.6	10.8	0.48	7.0
G25/26	Feb-94	2060	7	-	11.3	13	1.47	-	193	11.3	112	88.5	68	170	835	13.3	10.8	<0.1	<0.03	25.2	7.56	0.351	4.6
G25/28	Feb-94	2030	7.1	-	11.1	7.5	0.83	-	186	10.7	106	86.1	82.5	185	819	11.4	10.9	<0.1	<0.03	24.8	5.39	0.335	0.1
G25/29	Feb-94	1900	7.1	-	11.3	6	0.62	-	169	10.3	97.4	84.6	89.5	166	695	9.0	14.6	<0.1	<0.03	20.1	5.32	0.275	2.1
G25/30	Feb-94	1835	7.1	-	11.3	7.9	0.89	-	169	10.2	96.4	84.9	91.5	164	685	8.4	15.7	<0.1	<0.03	18.6	5.6	0.267	2.4
G25/24D	Feb-94	-	-	-	-	-	-	-	225	12.4	127	92.5	71.5	213	946	16.7	6.8	<0.1	0.04	31.8	10.9	0.483	5.9

BULK GROUNDWATER SAMPLES AND RIVER SAMPLES .... OVERLEAF

H1 contd. GORSETHORPE GROUNDWATER QUALITY (1994) - GENERAL AND INORGANIC PARAMETERS

FIELD AND INORGANIC DETERMINATIONS IN BULK AND DEPTH GROUNDWATERS AND SURFACE WATERS: FEB/OCT 1994

				<----- on-site measurements --->																			
		Cond	pH	Eh	Temp	DO	DO	Diss	Na	K	Mg	Ca	SO_4	Cl	Alkal	NH_3	NO_3	NO_2	TSP	TOC	Fe	Mn	Ion
								CH_4							$CaCO_3$	As N	As N	As N	As P				Balance
Borehole/ m bgl	Date	µS cm^{-1}		mV	°C	%	mg l^{-1}	mg l^{-1}			<------					mg l^{-1}					------>		%
Bulk groundwaters																							
MM1B	Feb-94	827	7.3	355	9.6	15	1.7	-	44.1	4.1	40.7	73.6	121	47.8	197	<0.50	14.5	<0.10	<0.03	2.34	<0.004	<0.002	1.1
G2B	Feb-94	1169	7.1	328	10.3	13.9	1.56	-	93.9	6.1	49.9	78.5	113	87.6	289	<0.50	27.3	<0.10	<0.03	2.31	0.218	0.068	-0.8
G3B	Feb-94	1124	7.3	382	9.6	3.9	0.46	-	67.1	7	46.9	85.8	115	144	197	<0.50	13.6	<0.10	<0.03	2.05	<0.004	0.014	-0.6
G18B	Feb-94	2110	6.6	123	14.6	12.9	1.26	-	280	7.1	77.2	110	144	223	737	<0.50	8.7	<0.10	0.04	17.7	0.017	0.852	-0.8
G21B	Feb-94	1061	7.4	224	10.3	12.8	1.44	-	75.4	5.7	52.9	73.6	114	79.8	263	<0.50	24.1	<0.10	<0.03	1.75	0.005	0.048	-0.7
G22B	Feb-94	2060	7.0	148	10.8	11.2	1.2	-	198	19	107	90.3	68	215	944	26.5	9.7	<0.10	0.04	38.2	8.86	0.141	0.8
G23B	Feb-94	2420	6.8	107	11.4	4.9	0.51	-	226	14.3	131	107	56	240	1040	22.8	4.9	<0.10	0.07	28.3	18.40	0.329	8.6
River samples																							
RUS1	Feb-94	751	7.7	-	5.9	100.7	12.52	-	25.2	5.8	34.3	68.1	102	58	118	<0.50	22.9	<0.10	0.08	2.57	0.049	0.046	-1.8
RUS1 bridge	Feb-94	1152	7.7	-	7.1	77.6	9.34	-	105	10.4	39	77.9	133	143	193	<0.50	19.1	<0.10	2.0	12.0	0.147	0.049	-1.0
RMS2	Feb-94	1152	7.7	355	7	77.6	9.34	-	122	8.7	36.3	74	130	163	186	<0.50	17.6	<0.10	1.5	8.17	0.057	0.035	-0.8
RDS3	Feb-94	1157	7.8	334	7	78.9	-	-	128	8.9	36	74	143	172	184	<0.50	17.8	<0.10	1.6	8.58	0.054	0.036	-1.8
G21	Oct-94	776	7.4	276	10.0	-	-	-	61.4	5.1	50.5	64.6	104	80	315	0.5	21.9	0.1	0.04	1.8	0.004	0.032	-2.9
G22	Oct-94	1500	7.0	165	10.6	-	-	-	161	11.6	106	97.8	70	207	761	18.3	12.5	0.1	0.05	23.6	7.92	0.095	5.1
G18	Oct-94	1942	6.9	309	14.1	-	-	-	251	6.7	80	97.8	138	221	782	1.4	8.4	0.1	0.12	19.4	0.009	0.945	-4.6
G3	Oct-94	907	7.5	318	9.4	-	-	-	54.3	5.5	41.4	67.2	100	111	187	0.5	16.5	0.1	0.06	2.1	0.04	0.009	1.3

Eh Eh values have been corrected for the potential of the reference electrode at a water temperature of 10°C (i.e. raw mV plus 251 mV)

H2 GORSETHORPE GROUNDWATER QUALITY (1994) - CARBOXYLIC ACIDS

Gorsethorpe carboxylic acid determinations in bulk and depth samples - Feb 1994 (mg l^{-1} acid)

Borehole/ depth m bgl	ethanoic acid	propanoic acid	i-butanoic acid	n-butanoic acid	i-pentanoic acid	n-pentanoic acid	i-hexanoic acid	n-hexanoic acid
G17/23	<1	<1	<1	<1	<1	<1	<1	<1
G17/26	<1	<1	<1	<1	<1	<1	<1	<1
G17/28	<1	<1	<1	<1	<1	<1	<1	<1
G17/31	<1	<1	<1	<1	<1	<1	<1	<1
G17/34	<1	<1	<1	<1	<1	<1	<1	<1
G17/37	<1	<1	<1	<1	<1	<1	<1	<1
G17/37DUP	<1	<1	<1	<1	<1	<1	<1	<1
G18/24	<1	<1	<1	<1	<1	<1	<1	<1
G18/24D	<1	<1	<1	<1	<1	<1	<1	<1
G18/27	<1	<1	<1	<1	<1	<1	<1	<1
G18/27DUP	<1	<1	<1	<1	<1	<1	<1	<1
G21/22	<1	<1	<1	<1	<1	<1	<1	<1
G21/24	<1	<1	<1	<1	<1	<1	<1	<1
G21/25	<1	<1	<1	<1	<1	<1	<1	<1
G21/26	<1	<1	<1	<1	<1	<1	<1	<1
G21/28	<1	<1	<1	<1	<1	<1	<1	<1
G22/24	1	<1	<1	<1	<1	<1	<1	<1
G22/25	2	<1	<1	<1	<1	<1	<1	<1
G22/27	1	<1	<1	<1	<1	<1	<1	<1
G22/28	2	<1	<1	<1	<1	<1	<1	<1
G22/29	3	2	<1	1	2	2	3	4
G25/22	1	<1	<1	<1	<1	<1	<1	<1
G25/23	3	2	1	2	3	4	5	7
G25/24	2	<1	<1	<1	<1	1	2	3
G25/26	2	<1	<1	<1	<1	<1	<1	1
G25/28	2	<1	<1	<1	<1	<1	<1	<1
G25/29	1	<1	<1	<1	<1	<1	<1	<1
G25/30	1	<1	<1	<1	<1	<1	<1	<1
G25/24DUP	1	<1	<1	<1	<1	<1	<1	<1
MM1B	4	3	3	3	4	6	8	10
G2B	8	3	1	6	<1	3	<1	9
G3B	3	<1	<1	<1	<1	<1	<1	2
G18B	4	<1	<1	2	<1	1	<1	4
G21B	2	<1	<1	<1	<1	<1	<1	<1
G22B	2	<1	<1	<1	<1	<1	<1	<1
G23B	3	<1	<1	<1	<1	<1	<1	<1
River samples (River maun)								
R1 - upstreamUS1	1	<1	<1	<1	<1	<1	<1	<1
R1 at bridge	2	<1	<1	<1	<1	<1	<1	<1
R2 - midpoint	2	<1	<1	<1	<1	<1	<1	<1
R3 - downstream	2	<1	<1	<1	<1	<1	1	2

H3 GORSETHORPE GROUNDWATER QUALITY (1994) - SOLVENTS

CHLORINATED/BROMINATED SOLVENT GROUNDWATER DETERMINATIONS FEBRUARY AND OCTOBER 1994

Borehole	Date	$CHCl_3$ trichloro methane (chloroform) µg l^{-1}	1,1,1,$C_2H_3Cl_3$ 1,1,1, trichloro ethane (TCA) µg l^{-1}	CCl_4 tetra chloro methane (C tet) µg l^{-1}	C_2HCl_3 trichloro ethene (TCE) µg l^{-1}	1,1,2-$C_2H_3Cl_3$ 1,1,2 trichloro ethane µg l^{-1}	C_2Cl_4 tetra chloro ethene (PCE) µg l^{-1}	$CHCl_2Br$ bromo dichloro methane µg l^{-1}	$CHClBr_2$ dibromo chloro methane µg l^{-1}	$CHBr_3$ tri bromo methane (bromoform) µg l^{-1}
G21B	21.2.94	<0.4	<0.3	<0.1	<0.3	-	0.4	<0.2	<0.5	<0.4
G22	21.2.94	<0.4	<0.3	<0.1	<0.3	-	0.1	<0.2	<0.5	<0.4
G18B	21.2.94	<0.4	<0.3	<0.1	<0.3	-	0.2	<0.2	<0.5	<0.4
G3	21.2.94	<0.4	<0.3	<0.1	<0.3	-	0.2	<0.2	<0.5	<0.4
G21	12.10.94	<0.4	<0.3	<0.1	<0.3	<2	<0.1	<0.2	<0.5	<0.4
G22	12.10.94	<0.4	<0.3	<0.1	<0.3	<2	<0.1	<0.2	<0.5	<0.4
G18	12.10.94	<0.4	<0.3	<0.1	<0.3	<2	<0.1	<0.2	<0.5	<0.4
G3	12.10.94	<0.4	<0.3	<0.1	<0.3	<2	<0.1	<0.2	<0.5	<0.4
DETECTION LIMIT		<0.4	<0.3	<0.1	<0.3	<2	<0.1	<0.2	<0.5	<0.4

H4 GORSETHORPE GROUNDWATER QUALITY (1995)

GORSETHORPE FIELD AND INORGANIC GROUNDWATER DETERMINATIONS JULY 1995

		<------ on-site measurements					------>																
		Cond	pH	Eh	Temp	DO	Alkal	TOC	Na	K	Mg	Ca	SO_4	Cl	Alkal	NH_3	NO_3	NO_2	TSP	B	Fe	Mn	Ion
Borehole/							$CaCO_3$								$CaCO_3$	As N	As N	As N	As P				Balance
depth m bgl	Date	µS cm-1		(mV)	°C			<------						mg l^{-1}	------				------>				%
G18 25.5	25-Jul-95	1136	7.2	239	16.3	2.92	300	4.2	109	4.7	46.3	71.3	101	93.4	359	0.13	13.7	<0.01	<0.05	0.643	0.061	0.050	2.8
G18 28.5	25-Jul-95	1166	7.2	239	15.7	2.72	344	3.6	116	5.0	48.7	73	102	99.5	363	0.32	13.5	0.013	<0.05	0.763	0.06	0.095	1.4
G22 22.80	26-Jul-95	2230	7.0	188	12.6	0.10	840	31.7	200	17.9	107	77.7	54.0	232	894	30.3	2.17	0.013	0.08	1.45	1.68	0.393	6.2
G22 24.28	26-Jul-95	1720	7.0	162	12.7	0.35	590	18.2	148	12.6	83.4	73.2	82.5	160	614	17.0	13.0	0.02	0.06	0.978	2.80	0.268	4.3
G22 25.68	26-Jul-95	1760	6.9	151	12.5	0.55	602	17.7	155	12.6	85.7	73.5	81.0	172	625	17.6	13.2	0.023	0.11	1.010	4.29	0.191	4.0
G22 27.08	26-Jul-95	1610	7.0	156	12.4	0.9	538	15.6	143	11.3	79.3	76.4	89.0	159	559	14.5	14.3	0.029	0.08	0.888	3.53	0.122	3.2
G22 28.48	26-Jul-95	1490	7.0	174	12.1	0.87	460	10.3	121	10.9	71.7	73.6	96.0	139	491	10.8	15.8	0.071	<0.05	0.723	1.91	0.142	4.4
G22 29.88	26-Jul-95	1479	7.1	194	12.3	0.79	468	12.4	123	10.8	71.4	73.6	95.0	143	497	11.0	15.8	0.145	<0.05	0.72	1.93	0.12	4.7
G21 22.07	27-Jul-95	933	7.5	229	11.9	0.72	236	<1.0	51.3	4.7	49.4	70.1	108	72.7	269	<0.05	15.5	0.027	<0.05	0.265	0.010	0.063	4.2
G21 24.13	27-Jul-95	969	7.4	222	11.6	2.10	220	<1.0	55.4	4.8	49.8	71.7	111	74.5	277	<0.05	18.2	0.011	<0.05	0.282	<0.004	0.039	4.9
G21 25.56	27-Jul-95	1000	7.3	232	11.5	3.28	250	<1.0	59.0	5.0	50.2	73.2	112	76.8	265	<0.05	21.4	0.011	<0.05	0.289	<0.004	0.021	3.9
G21 26.96	27-Jul-95	1014	7.4	232	11.5	3.43	236	<1.0	61.1	5.1	50.6	73.8	113	78.1	264	<0.05	21.4	0.012	<0.05	0.303	<0.004	0.024	3.3
G21 28.36	27-Jul-95	1019	7.4	236	11.5	3.97	241	<1.0	62.6	5.3	50.9	74.4	114	79.9	268	<0.05	21.5	0.017	<0.05	0.31	<0.004	0.029	3.4
Bulk samplesw																							
G18 BULK	25-Jul-95	1737	7.0	305	14.9	1.29	572	9.7	207	6.7	65.7	90.0	116	171	598	1.79	10.5	0.05	0.06	1.67	<0.004	0.708	2.3
G21 BULK	27-Jul-95	1060	7.6	338	11.1	3.52	253	<1.0	69.5	5.5	52.6	73.2	112	86.1	284	0.22	20.7	<0.01	<0.05	0.334	0.017	0.054	3.3
G22 BULK	26-Jul-95	1743	7.0	133	11.6	3.10	582	18.3	161	11.1	86.4	74.3	79.5	187	616	14.5	12.5	0.015	0.1	0.987	5.81	0.109	3.8
G23 BULK	26-Jul-95	1724	7.1	66	11.7	0.71	516	12.7	144	8.1	91.9	82.2	108	213	523	7.84	5.9	0.73	0.1		7.33	0.167	7.5

Eh Eh values have been corrected for the potential of the reference electrode at a water temperature of 10°C (i.e. raw mV plus 251 mV)

H5 GORSETHORPE GROUNDWATER QUALITY - BULK SAMPLES (1986-1996)

GORSETHORPE FIELD AND INORGANIC GROUNDWATER DETERMINATIONS - BULK SAMPLES

		<------ on-site measurements					------>																			
		Conductivity	pH	Eh	Temp	DO	Alkal CaCO$_3$	TOC	Na	K	Mg	Ca	SO$_4$	Cl	Alkal CaCO$_3$	NH$_3$ As N	NO$_3$ As N	NO$_2$ As N	TSP As P	Fe	Mn	B	Br	Si	Sr	Ion balance
Borehole	Date	µS cm^{-1}		mV	°C	mg l^{-1}		<------									mg l-1								------>	%
PHASE 1 - EXTREME NW CORNER OF SITE																										
G2	Mar-89	-	6.9	-	-	-	-	5.6	82.5	6.3	56.6	88	111	103	286	<0.1	22.9	-	-	-	-	-	-	-	-	0.9
G2	Mar-90	1228	7.5	223	-	-	-	2.6	84.1	6.3	57.2	89.4	113	99	324	<0.04	19.3	-	-	-	-	-	<0.2	-	0.147	-0.1
G2	Mar-92	1665	7.2	-	-	-	-	8.6	101	7.2	59.2	95	112	120	338	<0.1	23.0	-	-	-	-	*0.58*	-	-	-	0.2
G2	Feb-94	1169	7.1	328.0	10.3	1.56	277	2.3	93.9	6.1	49.9	78.5	113	88	289	<0.50	27.3	<0.10	<0.03	0.218	0.068	-	-	-	-	-0.8
PHASE 1 WELL FIELD																										
G21	Jul-86	847	7.2	-	-	-	-	3.5	57.5	4.9	47	68	96	75	252	0.02	8.5	-	-	-	-	-	-	-	-	0.6
G21	Mar-89	-	7.2	-	-	-	-	2.8	66.8	4.7	48.9	66	103	87	249	<0.1	10.9	-	-	-	-	-	-	-	-	-0.1
G21	Mar-90	1067	7.7	213	-	-	-	2.6	74.4	5.4	53.4	72.1	112	96	272	<0.04	12	-	-	-	-	<0.2	-	-	0.081	0.1
G21	Feb-94	1061	7.4	224	10.3	1.44	264	1.8	75.4	5.7	52.9	73.6	114	80	263	<0.50	24.1	<0.10	<0.03	0.005	0.048	-	-	-	-	-0.7
G21	Oct-94	776	7.4	276	10.0	-	320	1.8	61.4	5.1	50.5	64.6	104	80	315	0.5	21.9	0.1	0.04	0.004	0.032	-	-	-	-	-9.2
G21	Jul-95	1060	7.6	338	11.1	3.52	253	<1.0	69.5	5.5	52.6	73.2	112	86.1	284	0.22	20.7	<0.01	<0.05	0.017	0.054	0.334	-	-	-	-3.2
G24	Jul-86	1118	6.9	-	-	-	-	6.8	103	5.5	52	79	86.7	134	360	0.08	4.1	-	-	-	-	-	-	-	-	-0.9
G24	Mar-89	-	7.1	-	-	-	-	5.5	106	5.7	59.1	79.3	103	·132	314	0.13	13.4	-	-	-	-	-	-	-	-	1.8
G24	Mar-90	1213	7.6	218	-	-	-	4.3	4.28	5.8	55	98.1	78.2	114	117	<0.04	13.6	-	-	-	-	-	<0.2	-	0.101	8.9
G25 PHASE 1/PHASE 2 boundary																										
G25	Jul-86	1048	6.9	-	-	-	-	6.4	80	4.77	53	87	79.4	109	358	<0.01	3.2	-	-	-	-	-	-	-	-	0.8
G25	Mar-89	-	7.0	-	-	-	-	5.5	104	6.74	60	81	103	137	315	0.62	14.7	-	-	-	-	-	-	-	-	1.3
G25	Mar-90	1300	7.5	221	-	-	-	10.8	113	7.2	61.6	80.1	113	130	342	0.9	14.6	-	-	-	-	-	<0.2	-	0.091	1.2
PHASE 2 WELL FIELD																										
G22	Jul-86	1489	7.0	-	-	-	-	16.6	190	6.0	59	93	34.6	242	500	<0.01	0.1	-	-	-	-	-	-	-	-	1.0
G22	Mar-89	-	7.1	-	-	-	-	14.1	149	5.5	68.1	85.3	92.3	195	384	<0.04	12.2	-	-	-	-	-	-	-	-	1.6
G22	Mar-90	1650	6.6	264	-	-	-	16.6	169	5.7	71.8	83.5	101	131	437	0.08	9.4	-	-	-	-	-	<0.2	-	0.115	7.3
G22	Feb-94	2060	7.0	148	10.8	1.2	742	38.2	198	19	107	90.3	68	215	944	26.5	9.7	<0.10	0.04	8.86	0.141	-	-	-	-	0.8
G22	Oct-94	1500	7.0	165	10.6	n.d.	753	23.6	161	11.6	106	97.8	70	207	761	18.3	12.5	0.1	0.05	7.92	0.095	-	-	-	-	3.4
G22	Jul-95	1743	7.0	133	11.6		582	18.3	161	11.1	86.4	74.3	79.5	187	616	14.5	12.5	0.015	0.1	5.81	0.109	-	-	-	-	2.6
G23	Jul-86	1446	7.3	-	-	-	-	14.6	200	6.4	45	70	41.1	234	452	0.05	1.2	-	-	-	-	-	-	-	-	-1.6
G23	Mar-89	-	7.0	-	-	-	-	28.0	223	5.2	59.5	82.6	54.6	308	425	0.14	4.4	-	-	-	-	-	-	-	-	0.6
G23	Mar-90	2150	7.3	227	-	-	-	30.9	258	5.2	75.7	89.6	74.3	367	505	0.15	5.9	-	-	-	-	-	4.0	-	-	-0.8
G23	Feb-94	2420	6.8	107	11.4	0.51	964	28.3	226	14.3	131	107	56	240	1040	22.8	4.9	<0.10	0.07	18.4	0.329	-	-	-	-	8.6
G23	May-95	2650	7.2	43	10.5	0.06	944	36.0	267	12.9	162	117	41	409	951	16.3	3.7	0.1	-	18.3	0.223	-	-	-	-	10.1
G23	Jun-95	1723	7.1	58	12.2	-0.04	602	15.5	163	9.8	105	83.6	102	220	601	10.1	7.3	0.1	-	9.14	0.166	-	-	-	-	7.3
G23	Jul-95	1724	7.1	66	11.7	0.71	516	12.7	144	8.1	91.9	82.2	108	213	523	7.84	5.9	0.73	0.10	7.33	0.167	-	-	6.98	-	7.5
G23	Oct-95	1825	7.0	-	11.6	1.72	489	13.9	153	7.9	91.8	90.5	102	207	522	5.66	8.5	0.181	0.008	0.037	0.235	-	-	6.13	-	3.1
G23	Feb-96	1586	7.0	71	11.1	12.6	491	13.6	162	9.1	97.6	115	103	235	543	<0.05	7	<0.01	0.009	6.49	0.64			6.99		9.6
G17	Mar-90	1171	6.9	-	-	-	-	2.0	86	6.3	51.2	78.8	116	104	279	<0.07	19.6	-	-	-	-	-	-	-	-	-1.1
G17	Mar-92	1178	7.3	257	-	-	-	1.8	83	6.9	51.0	80.7	117	93	277	<0.1	17.8	<0.1	-	-	-	0.33	0.4	-	-	0.6

CONTD....

H5 contd. GORSETHORPE GROUNDWATER QUALITY - BULK SAMPLES (1986-1996)

GORSETHORPE FIELD AND INORGANIC GROUNDWATER DETERMINATIONS - BULK SAMPLES

		<------------ on-site measurements ------------>																								Ion
		Conductivity	pH	Eh	Temp	DO	Alkal $CaCO_3$	TOC	Na	K	Mg	Ca	SO_4	Cl	Alkal $CaCO_3$	NH_3 As N	NO_3 As N	NO_2 As N	TSP As P	Fe	Mn	B	Br	Si	Sr	balance %
Borehole	Date	$\mu S\,cm^{-1}$		mV	°C	$mg\,l^{-1}$		<------								------		mg l-1	------						------>	
PHASE 3																										
G18	Mar-90	3700	6.8	256	-	-	-	**20.6**	297	9.4	164	282	334	**614**	825	**0.19**	2.53	-	-	-	-	-	6.5	-	-	-0.3
G18	Mar-92	2760	6.9	-	-	-	-	**19.6**	279	7.8	104	172	150	**415**	762	**<0.1**	10.7	0.1	-	-	-	1.64	-	-	0.141	-2.2
G18	Feb-94	2110	6.6	123	14.6	1.26	703	**17.7**	280	7.1	77.2	110	144	**223**	737	**<0.50**	8.7	<0.10	0.04	0.017	0.852	-	-	-	-	-0.8
G18	Oct-94	1942	6.9	309	14.1	n.d.	766	**19.4**	251	6.7	80	97.8	138	**221**	782	**1.36**	8.4	0.1	0.12	0.009	0.945	-	-	-	-	-5.6
G18	May-95	n.d.	7.2	254	13.9	n.d.	585	**13.0**	223	7.1	70.9	96.3	121	**169**	614	**1.39**	9.4	0.1	-	0.004	0.811	-	-	-	-	1.0
G18	Jun-95	1738	7.0	342	15.2	0.07	600	**12.8**	212	7.1	67.7	90.4	120	**164**	602	**2.19**	10	0.1	<0.05	<0.004	0.7	-	-	-	-	-0.6
G18	Jul-95	1737	7.0	305	14.9	1.2	572	**11.4**	207	6.6	65.7	90.3	112	**169**	593	**1.88**	9.3	0.051	0.06	<0.004	0.71	-	-	7.56	-	1.7
G18	Oct-95	1585	7.0	-	14.6	3.21	512	**10.5**	203	6.1	59.8	86.9	110	**152**	574	**0.91**	11.3	<0.10	0.4	<0.004	0.618	-	-	6.78	-	1.0
G18	Feb-96	1768	6.9	305	14.3	2.1	509	**12.3**	232	7.7	75.6	112	131	**198**	626	**1.8**	6.84	0.26	0.07	0.043	0.878			8.57		4.8
OFF SITE (SE of site)																										
G3	Jul-86	927	7.2	-	-	-	-	**2.3**	43	7.7	50.0	97.0	111	**62**	266	**1.63**	19.0	-	-	-	-	-	-	-	-	1.8
G3	Mar-89	-	7.1	-	-	-	-	**11.0**	33	8.7	53.8	97.3	102	**94**	260	**2.77**	12.9	-	-	-	-	-	-	-	-	1.1
G3	Mar-90	1087	7.0	248	-	-	-	**3.0**	39	8.6	51.3	92.5	111	**110**	258	**3.06**	9.2	-	-	-	-	-	0.7	-	0.035	-1.2
G3	Feb-94	1124	7.3	382	9.6	0.46	193	**2.05**	67.1	7.0	46.9	85.8	115	**144**	197	**<0.50**	13.6	<0.10	<0.03	<0.004	0.014	-	-	-	-	-0.6
G3	Oct-94	907	7.5	318	9.4	-	200	**2.1**	54.3	5.5	41.4	67.2	100	**111**	187	**0.5**	16.5	0.1	0.06	0.04	0.009	-	-	-	-	-4.3
G3	May-95	999	7.6	258	10.2	1.58	212	**2.0**	54.0	6.4	46.2	83.8	87	**100**	225	**0.5**	13.2	0.1	-	0.004	0.004	-	-	-	-	2.2
G3	Jun-95	932	7.2	344	11.2	0.78	268	**2.3**	53.4	6.7	46.7	81.0	95	**102**	228	**0.65**	15.2	0.1	-	0.004	0.7	-	-	-	-	-0.3
G3	Jul-95	1009	7.4	343	10.3	2.84	202	**1.8**	56	6.4	43.2	78.5	101	**105**	229	**0.83**	14.6	<0.01	<0.05	<0.004	0.007	-	-	5.08	-	0.8
G3	Oct-95	835	7.3	-	10.4	3.99	172	**1.7**	50	5.3	39.6	75.0	97	**85**	187	**0.34**	16.5	0.194	0.02	<0.004	<0.002	-	-	4.53	-	3.3
G3	Feb-96	740	7.61	305	10	5.29	136	**1.0**	48.6	5.1	34.9	67.6	106	**66.5**	152	**0.21**	14.8	<0.01	0.018	0.035	<0.002			4.86		5.9
South of southern perimeter																										
MM1	Jul-86	938	7.2	-	-	-	-	**2.1**	55	5.61	53	89.0	119	**79**	300	**0.2**	6.3	-	-	-	-	-	-	-	-	0.9
MM1	Mar-89	-	7.1	-	-	-	-	**1.4**	56.7	4.6	46.6	75.5	123	**64**	261	**0.06**	10.2	-	-	-	-	-	-	-	-	-0.6
MM1	Mar-90	896	7.4	229	-	-	-	**6.6**	51.6	3.8	41.8	79.4	129	**51**	266	**<0.04**	7.9	-	-	-	-	-	<0.2	-	0.078	-1.3
MM1	Mar-92	980	7.2	-	-	-	-	**0.96**	53.6	4.7	39.7	66.9	115	**55**	194	**<0.1**	10.7	-	-	-	-	0.23	-	-	-	2.6
MM2	Jul-86	949	7.2	-	-	-	-	**0.8**	68.8	8.69	47	84	107	**79**	238	**0.5**	21.2	-	-	-	-	-	-	-	-	2.6
G4	Jul-86	619	7.5	-	-	-	-	**1.0**	15.5	2.34	31	66	101	**53**	68.0	**0.2**	19	-	-	-	-	-	-	-	-	2.2
G4	Mar-89	-	7.6	-	-	-	-	**1.44**	15.1	2.94	30.9	61.7	106	**57**	65.9	**<0.1**	16.9	-	-	-	-	-	-	-	-	0.1
G4	Mar-90	676	7.9	205	-	-	-	**0.51**	15.2	3.1	31.8	64.1	114	**59**	72.3	**<0.04**	15.6	-	-	-	-	-	<0.2	-	0.026	-0.4
G4	Mar-92	620	7.8	-	-	-	-	**0.86**	14.8	3	29.9	63	107	**60**	65.6	**<0.1**	14.1	<0.1	-	-	-	0.03	-	-	-	0.7

Eh Eh values have been corrected for the potential of the reference electrode at a water temperature of 10°C (i.e. raw mV plus 251 mV)

APPENDIX I LANDFILL GAS QUALITY - GORSETHORPE (1985-1996)

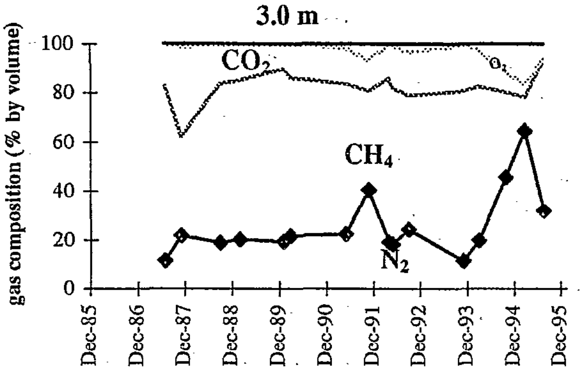
I1 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 1

I2 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 2

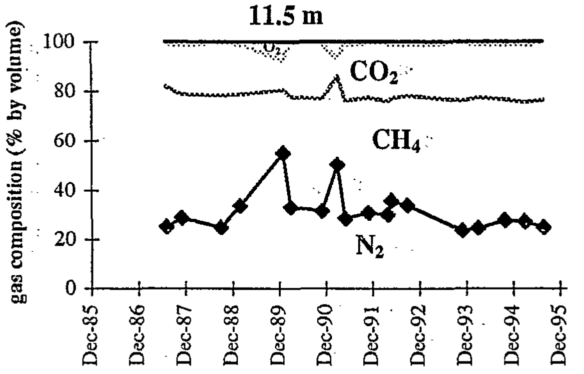
I3 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 3

I1 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 1

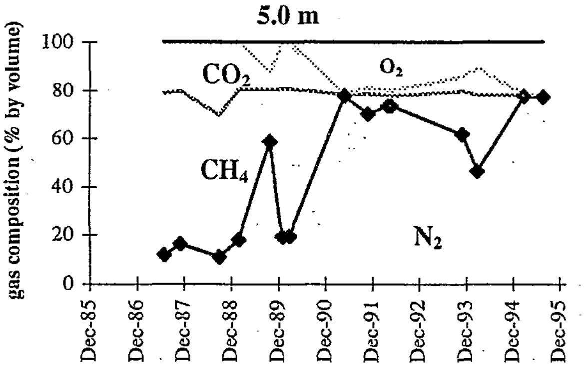
Borehole 14 probe 6
3.0 m



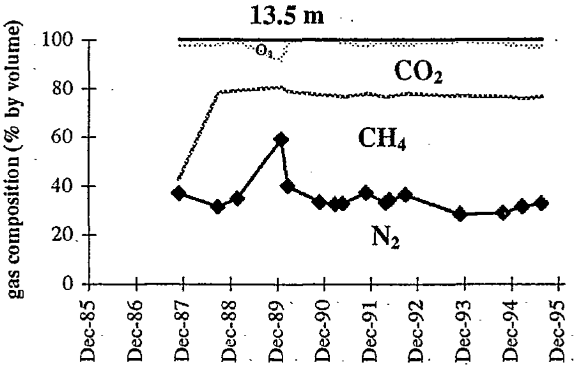
Borehole 14 probe 3
11.5 m



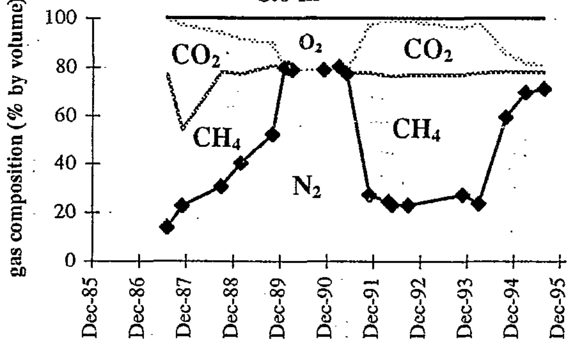
Borehole 14 probe 5
5.0 m



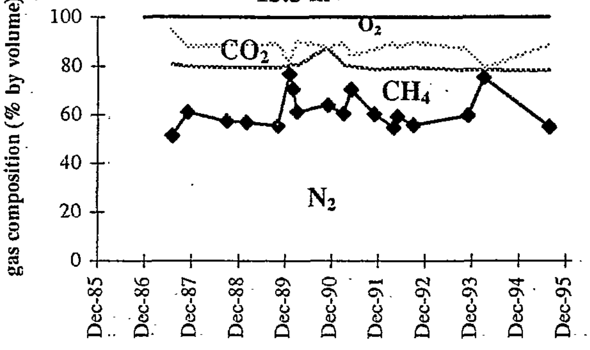
Borehole 14 probe 2
13.5 m



Borehole 14 probe 4
8.0 m



Borehole 14 probe 1
15.5 m



I1 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 1

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G14/1	**15.5m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	51.4	29.5	13.9	0	5.2
Nov-87	61.1	19.0	8.0	0	11.9
Sep-88	57.3	22.1	9.1	0	11.5
Feb-89	56.9	22.5	9.5	0	11.1
Oct-89	55.6	24.0	9.4	0	11.0
Jan-90	77.0	3.5	1.4	0	18.1
Feb-90	70.6	10.4	5.1	0	13.9
Mar-90	61.4	19.2	9.5	0	9.9
Nov-90	63.9	23.6	0.4	0	12.1
Mar-91	60.6	20.0	9.3	0	10.1
May-91	70.3	9.6	4.5	0	15.6
Nov-91	60.3	18.5	8.0	0	13.2
Apr-92	54.8	24.3	10.7	0	10.2
May-92	59.1	20.0	8.7	0	12.2
Sep-92	55.8	23.7	10.3	0	10.3
Nov-93	59.8	18.7	8.5	0	13.0
Mar-94	75.3	3.1	0.9	0	20.6
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-95	55.0	23.1	10.5	0	11.4
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

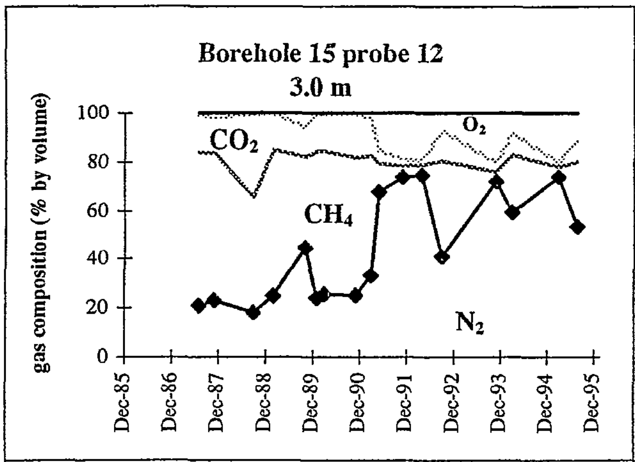
G14/2	**13.5m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-87	37.0	5.8	54.8	0	2.4
Sep-88	31.5	47.0	19.7	0	1.8
Feb-89	34.9	44.4	20.0	0	0.7
Oct-89	#N/A	#N/A	#N/A	#N/A	#N/A
Jan-90	59.4	21.3	11.0	0	8.3
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	40.2	38.7	20.5	0	0.6
Nov-90	33.5	44.0	22.0	0	0.5
Mar-91	32.7	44.5	22.4	0	0.4
May-91	32.8	44.0	22.0	0	1.3
Nov-91	37.2	40.7	19.7	0	2.4
Apr-92	33.1	43.7	22.3	0	0.9
May-92	34.4	42.5	21.3	0	1.4
Sep-92	36.4	41.5	20.3	0	1.9
Nov-93	28.5	48.4	22.5	0	0.5
Mar-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	28.9	47.8	21.8	0	1.6
Mar-95	31.7	44.1	21.7	0	2.5
Jul-95	32.9	43.8	20.5	0	2.8
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

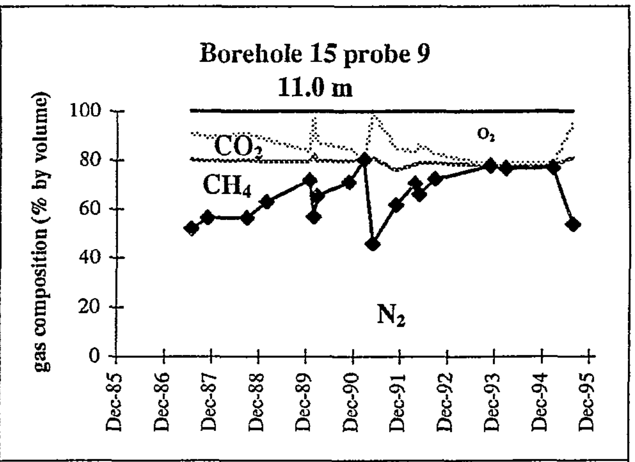
I1 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 1

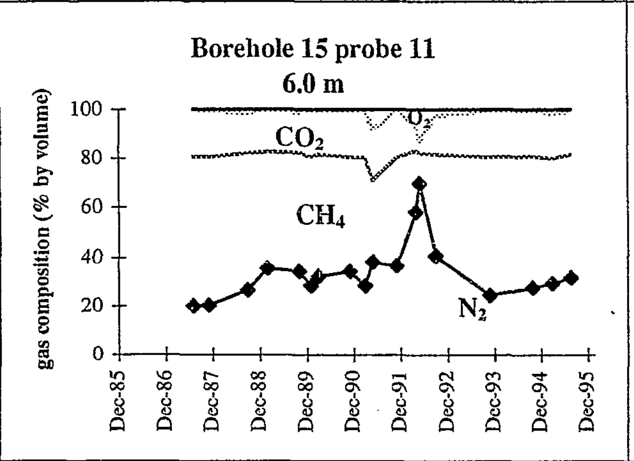
Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G14/3	**11.5m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	25.2	56.5	17.6	0	0.5
Nov-87	28.8	49.8	19.8	0	1.6
Sep-88	25.0	53.1	21.3	0	0.6
Feb-89	33.8	45.0	20.2	0	0.7
Oct-89	#N/A	#N/A	#N/A	#N/A	#N/A
Jan-90	55.0	25.4	12.1	0	7.5
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	33.3	44.4	21.9	0	0.5
Nov-90	31.7	45.1	22.8	0	0.4
Mar-91	50.5	35.4	7.6	0	6.5
May-91	28.5	47.7	22.5	0	1.3
Nov-91	30.8	46.6	21.9	0	0.8
Apr-92	30.2	45.7	23.3	0	0.8
May-92	35.9	41.3	21.0	0	1.8
Sep-92	34.1	44.1	19.9	0	1.9
Nov-93	23.6	52.6	23.4	0	0.4
Mar-94	24.6	52.8	21.4	0	1.1
Oct-94	27.8	48.9	22.1	0	1.3
Mar-95	27.3	48.4	22.7	0	1.6
Jul-95	25.0	51.4	23.0	0	0.6
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

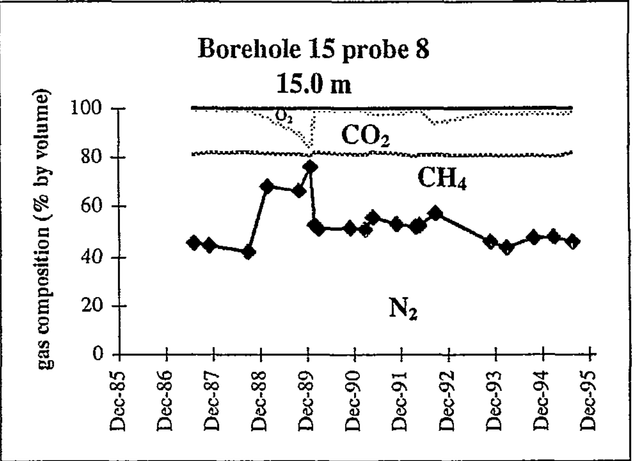
G14/4	**8.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	13.9	62.6	23.2	0	0.3
Nov-87	22.7	31.5	42.9	0	2.9
Sep-88	30.7	47.5	15.7	0	6.1
Feb-89	40.3	36.8	14.3	0	8.6
Oct-89	52.4	28.2	9.3	0	10.1
Jan-90	79.8	0.0	0.1	0	20.1
Feb-90	79.6	0.0	0.0	0	20.2
Mar-90	79.0	0.0	0.1	0	20.9
Nov-90	78.8	0.0	0.1	0	21.1
Mar-91	80.1	0.3	0.1	0	19.5
May-91	77.4	0.5	0.3	0	21.8
Nov-91	27.4	50.1	20.1	0	2.4
Apr-92	24.4	51.8	22.8	0	1.0
May-92	23.1	53.2	23.2	0	0.6
Sep-92	23.2	53.6	21.9	0	1.4
Nov-93	27.3	49.5	19.4	0	3.8
Mar-94	23.6	54.0	20.0	0	2.5
Oct-94	59.3	18.9	7.5	0	14.3
Mar-95	69.6	8.3	3.6	0	18.5
Jul-95	71.1	6.8	3.0	0	19.1
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

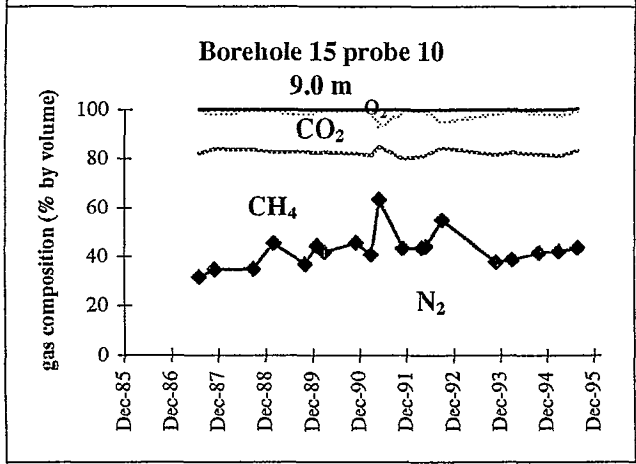
I2 LANDFILL GAS QUALITY - GORSETHORPE : PHASE 2

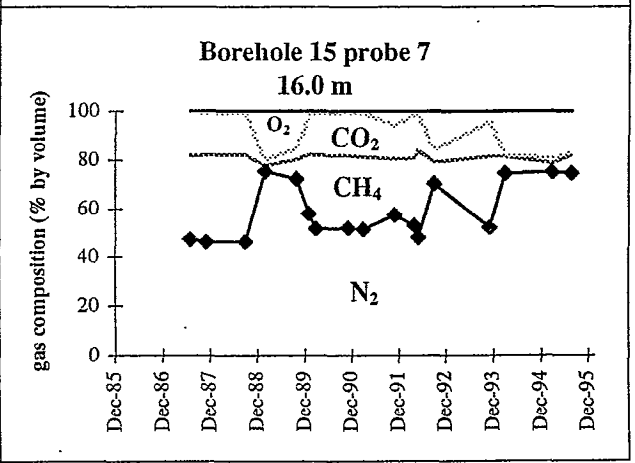












I2 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 2

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G15/7	**16.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	47.3	34.6	17.4	0	0.7
Nov-87	46.2	36.0	16.9	0	0.9
Sep-88	46.2	36.0	17.1	0	0.7
Feb-89	75.3	2.4	2.3	0	20.0
Oct-89	72.3	8.0	4.4	0	15.3
Jan-90	57.8	24.6	15.8	0	1.8
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	51.7	30.5	17.1	0	0.7
Nov-90	51.9	29.9	17.5	0	0.7
Mar-91	51.4	29.9	18.0	0	0.7
May-91	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-91	57.3	23.1	13.5	0	6.1
Apr-92	53.0	27.8	17.8	0	1.4
May-92	48.1	35.7	14.1	0	2.1
Sep-92	70.3	8.9	5.1	0	15.7
Nov-93	52.1	29.5	14.1	0	4.4
Mar-94	74.5	7.1	0.6	0	17.9
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	75.1	3.6	2.1	0	19.2
Jul-95	74.6	7.5	0.8	0	17.1
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

G15/8	**15.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	45.7	35.5	18.1	0	0.7
Nov-87	44.5	37.4	17.4	0	0.7
Sep-88	42.2	39.8	17.2	0	0.8
Feb-89	68.2	13.4	14.5	0	3.9
Oct-89	66.2	15.2	8.2	0	10.4
Jan-90	76.1	4.5	3.0	0	16.4
Feb-90	52.5	29.4	17.3	0	0.8
Mar-90	51.3	30.6	17.4	0	0.7
Nov-90	51.5	29.9	17.8	0	0.7
Mar-91	51.0	30.0	18.4	0	0.7
May-91	55.8	26.2	15.5	0	2.6
Nov-91	53.2	28.3	15.9	0	2.6
Apr-92	52.2	28.3	18.6	0	0.9
May-92	52.7	28.3	17.9	0	1.1
Sep-92	57.2	23.8	13.1	0	5.9
Nov-93	46.1	34.7	17.6	0	1.6
Mar-94	43.7	36.9	17.1	0	2.4
Oct-94	47.6	33.1	17.4	0	1.9
Mar-95	48.0	32.4	17.0	0	2.6
Jul-95	46.2	35.6	16.6	0	1.5
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

I2 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 2

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G15/9	**11.5m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	52.1	28.2	10.7	0	8.4
Nov-87	56.6	23.1	9.4	0	10.9
Sep-88	56.6	23.4	10.7	0	9.3
Feb-89	63.3	16.3	8.7	0	11.7
Oct-89	#N/A	#N/A	#N/A	#N/A	#N/A
Jan-90	71.9	7.6	4.1	0	16.4
Feb-90	57.0	25.5	14.1	0	3.4
Mar-90	65.5	14.3	7.3	0	12.9
Nov-90	71.3	8.6	4.7	0	15.4
Mar-91	80.3	0.2	0.0	0	19.6
May-91	45.8	35.2	18.0	0	1.1
Nov-91	62.0	14.2	8.7	0	15.2
Apr-92	70.6	8.0	4.7	0	16.7
May-92	66.4	12.7	7.1	0	13.8
Sep-92	72.6	6.4	3.7	0	17.3
Nov-93	77.9	0.0	0.0	0	22.1
Mar-94	76.9	1.3	0.5	0	21.2
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	77.1	1.0	0.6	0	21.3
Jul-95	54.0	27.1	13.1	0	5.8
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

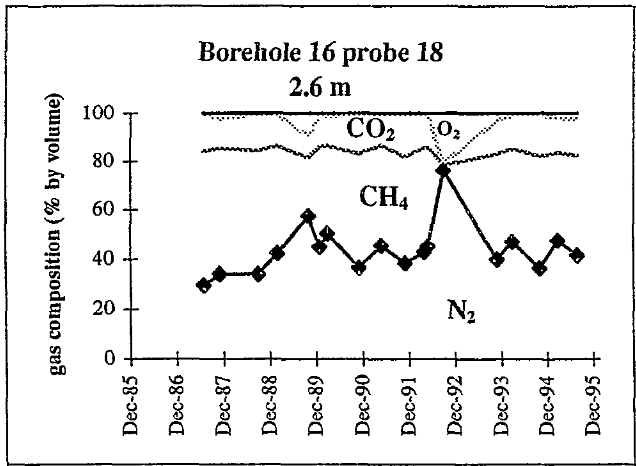
G15/10	**9.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	31.3	50.9	17.3	0	0.5
Nov-87	34.5	49.5	13.8	0	2.2
Sep-88	34.8	49.0	15.6	0	0.6
Feb-89	45.4	37.3	16.5	0	0.8
Oct-89	36.8	46.2	15.0	0	2.0
Jan-90	44.4	38.1	16.9	0	0.6
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	41.6	41.0	16.8	0	0.6
Nov-90	45.5	36.7	17.2	0	0.6
Mar-91	40.6	40.7	18.1	0	0.6
May-91	63.6	21.5	8.0	0	6.9
Nov-91	43.3	36.8	18.9	0	0.9
Apr-92	43.6	37.4	18.3	0	0.7
May-92	44.0	37.5	17.8	0	0.7
Sep-92	55.0	29.5	10.2	0	5.3
Nov-93	37.5	44.1	16.8	0	1.6
Mar-94	38.5	44.1	16.5	0	0.9
Oct-94	41.4	40.4	16.9	0	1.3
Mar-95	41.9	39.2	16.5	0	2.4
Jul-95	43.4	40.0	16.0	0	1.0
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

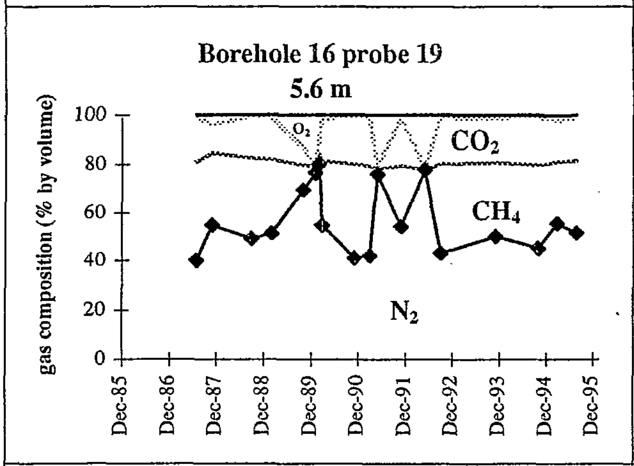
I2 LANDFILL GAS QUALITY - GORSETHORPE: PHASE 2

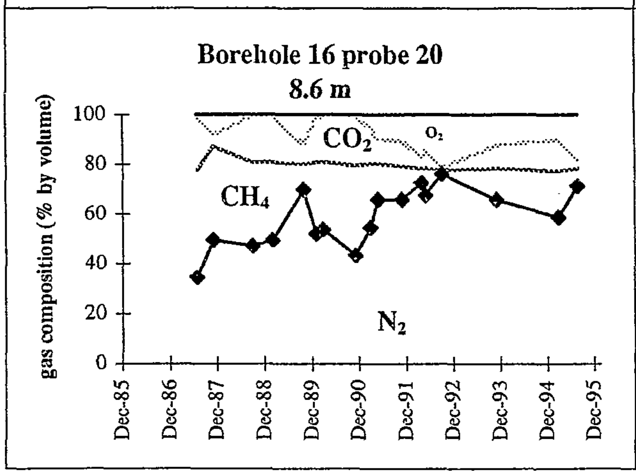
Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G15/11	**6.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	20.0	60.4	19.3	0	0.3
Nov-87	20.3	60.3	18.7	0	0.7
Sep-88	26.4	55.6	16.4	0	1.6
Feb-89	35.7	47.0	16.7	0	0.6
Oct-89	34.3	48.0	16.5	0	1.2
Jan-90	28.4	52.2	19.0	0	0.4
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	32.1	49.4	18.0	0	0.5
Nov-90	34.3	46.3	18.9	0	0.5
Mar-91	28.4	51.8	19.5	0	0.3
May-91	38.1	32.7	21.2	0	8.0
Nov-91	36.5	43.7	18.9	0	0.9
Apr-92	58.2	24.9	11.0	0	5.9
May-92	69.5	12.5	5.0	0	13.1
Sep-92	40.7	40.8	16.0	0	2.6
Nov-93	24.3	56.1	19.2	0	0.4
Mar-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	27.5	53.4	18.5	0.0	0.6
Mar-95	29.3	50.7	18.4	0.0	1.6
Jul-95	31.74	49.8	17.4	0.0	1.1
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

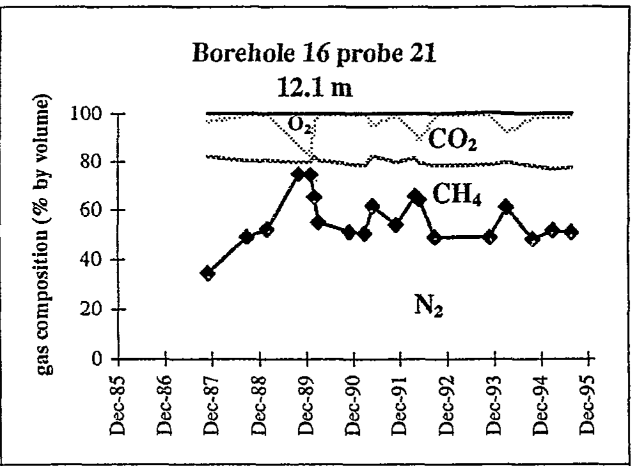
G15/12	**3.0m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	20.8	63.1	15.1	0	0.7
Nov-87	22.9	60.7	14.4	0	2.0
Sep-88	18.0	47.5	33.9	0	0.6
Feb-89	24.7	60.3	14.6	0	0.4
Oct-89	44.5	37.6	11.9	0	6.0
Jan-90	23.9	60.5	15.2	0	0.4
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	25.4	59.0	15.2	0	0.4
Nov-90	25.0	56.8	17.8	0	0.4
Mar-91	33.0	49.6	14.6	0	2.8
May-91	67.6	11.9	4.9	0	15.6
Nov-91	74.0	4.5	2.6	0	19.0
Apr-92	74.7	4.1	2.0	0	19.2
May-92	#N/A	#N/A	#N/A	#N/A	#N/A
Sep-92	41.0	39.4	12.3	0	7.4
Nov-93	72.2	3.9	3.7	0	20.2
Mar-94	59.5	23.2	9.0	0	8.3
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	74.0	4.2	1.5	0	20.3
Jul-95	53.5	26.5	9.2	0	10.8
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

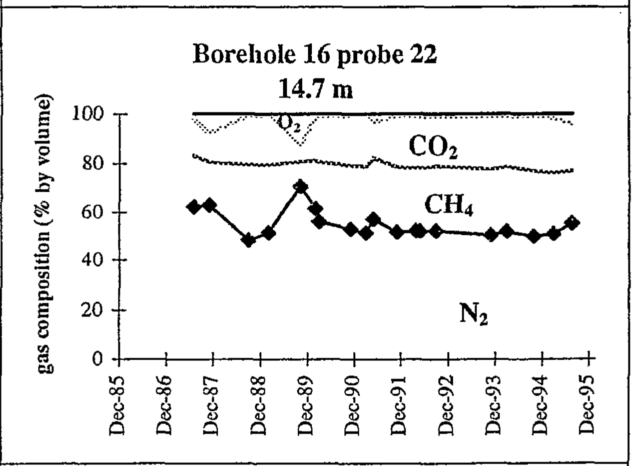
I3 LANDFILL GAS QUALITY - GORSETHORPE : PHASE 3

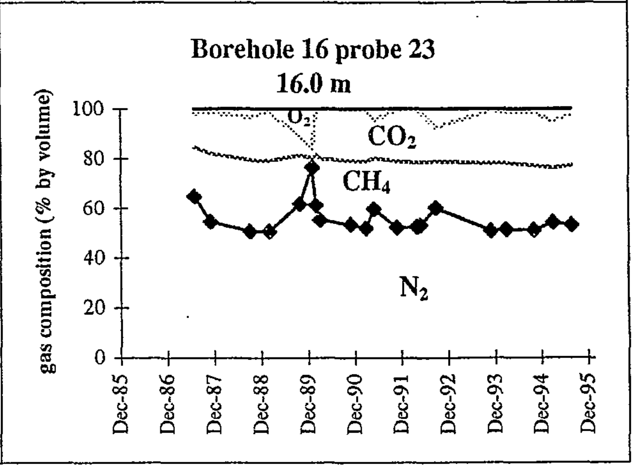

Borehole 16 probe 18
2.6 m


Borehole 16 probe 19
5.6 m


Borehole 16 probe 20
8.6 m


Borehole 16 probe 21
12.1 m


Borehole 16 probe 22
14.7 m


Borehole 16 probe 23
16.0 m

I3 LANDFILL GAS QUALITY - GORSETHORPE : PHASE 3

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G16/18	**2.6m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	29.6	54.5	15.7	0	0.5
Nov-87	34.0	51.4	12.2	0	2.4
Sep-88	34.0	50.3	15.2	0	0.5
Feb-89	42.2	44.3	12.8	0	0.7
Oct-89	57.4	24.1	8.9	0	9.6
Jan-90	45.0	41.1	13.0	0	0.9
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	50.4	35.9	12.5	0	1.2
Nov-90	36.6	46.4	16.5	0	0.5
Mar-91	#N/A	#N/A	#N/A	#N/A	#N/A
May-91	45.4	41.2	12.7	0	0.7
Nov-91	38.4	43.3	17.6	0	0.8
Apr-92	42.8	42.9	13.5	0	0.8
May-92	45.2	40.8	13.3	0	0.8
Sep-92	76.1	2.1	0.7	0	21.1
Nov-93	40.0	43.1	14.1	0	2.8
Mar-94	47.1	38.0	13.8	0	1.1
Oct-94	36.2	45.8	17.3	0	0.7
Mar-95	47.4	36.2	14.4	0	2.0
Jul-95	41.4	40.8	15.4	0	2.3
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

G16/19	**5.6m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	40.0	41.0	18.0	0	1.0
Nov-87	54.9	29.7	11.6	0	3.8
Sep-88	49.1	33.6	16.4	0	0.9
Feb-89	51.3	30.9	16.8	0	1.0
Oct-89	69.7	10.0	7.0	0	13.3
Jan-90	76.7	2.7	1.2	0	19.4
Feb-90	80.2	4.0	5.2	0	10.6
Mar-90	54.8	26.7	16.9	0	1.5
Nov-90	41.0	38.9	19.5	0	0.6
Mar-91	42.0	37.5	20.0	0	0.5
May-91	76.2	2.1	1.3	0	20.4
Nov-91	54.3	25.1	19.4	0	1.2
Apr-92	#N/A	#N/A	#N/A	#N/A	#N/A
May-92	77.8	0.1	0.5	0	21.6
Sep-92	43.1	37.1	18.7	0	1.1
Nov-93	50.1	30.7	18.0	0	1.3
Mar-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	45.3	34.5	19.4	0	0.8
Mar-95	55.5	25.5	16.7	0	2.0
Jul-95	51.7	29.9	16.6	0	1.9
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

I3 LANDFILL GAS QUALITY - GORSETHORPE : PHASE 3

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G16/20	**8.6m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	34.1	43.6	21.8	0	0.5
Nov-87	49.4	37.6	4.8	0	8.2
Sep-88	47.2	33.7	18.5	0	0.6
Feb-89	49.4	31.5	18.3	0	0.8
Oct-89	70.0	10.1	7.6	0	12.3
Jan-90	52.0	28.7	17.8	0	1.5
Feb-90	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-90	53.8	27.3	18.0	0	0.9
Nov-90	43.2	36.3	19.9	0	0.6
Mar-91	54.6	25.7	14.2	0	5.5
May-91	66.1	14.1	9.7	0	10.1
Nov-91	66.1	13.1	10.1	0	10.7
Apr-92	72.7	5.8	3.9	0	17.6
May-92	68.0	10.6	7.3	0	14.1
Sep-92	76.5	1.4	1.1	0	21.0
Nov-93	66.1	12.3	9.2	0	12.4
Mar-94	#N/A	#N/A	#N/A	#N/A	#N/A
Oct-94	#N/A	#N/A	#N/A	#N/A	#N/A
Mar-95	58.9	18.6	12.3	0	10.2
Jul-95	71.5	7.1	3.0	0	18.4
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

G16/21	**12.1m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	#N/A	#N/A	#N/A	#N/A	#N/A
Nov-87	34.5	47.5	14.6	0	3.4
Sep-88	49.0	31.2	19.1	0	0.7
Feb-89	52.1	28.2	18.8	0	0.9
Oct-89	74.8	4.9	7.6	0	12.7
Jan-90	74.3	5.3	3.1	0	17.3
Feb-90	65.2	16.8	14.0	0	4.0
Mar-90	55.2	25.2	18.7	0	0.9
Nov-90	51.2	27.6	20.5	0	0.7
Mar-91	50.7	27.5	21.2	0	0.7
May-91	61.7	20.5	12.9	0	4.9
Nov-91	54.0	25.7	19.5	0	0.8
Apr-92	65.5	16.0	9.9	0	8.6
May-92	64.1	15.4	9.0	0	11.5
Sep-92	49.0	29.4	20.6	0	1.0
Nov-93	49.0	29.5	21.1	0	0.8
Mar-94	61.1	18.6	11.9	0	8.3
Oct-94	48.4	29.6	20.5	0	1.4
Mar-95	51.8	24.9	21.6	0	1.7
Jul-95	50.8	26.5	21.5	0	1.2
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

I3 LANDFILL GAS QUALITY - GORSETHORPE : PHASE 3

Gorsethorpe	Gas composition (% by volume)				
	N2	CH4	CO2	H2	O2
G16/22	**14.7m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	62.2	20.9	14.9	0	2.0
Nov-87	63.0	17.7	11.3	0	8.0
Sep-88	48.2	31.5	19.6	0	0.7
Feb-89	51.3	28.2	19.6	0	0.9
Oct-89	70.8	10.1	6.5	0	12.6
Jan-90	#N/A	#N/A	#N/A	#N/A	#N/A
Feb-90	61.6	19.8	16.8	0	1.8
Mar-90	56.0	24.7	18.5	0	0.8
Nov-90	52.9	26.3	20.1	0	0.7
Mar-91	51.4	27.3	20.7	0	0.6
May-91	57.1	25.2	14.4	0	3.3
Nov-91	51.6	27.0	20.5	0	0.9
Apr-92	52.3	25.9	20.9	0	0.8
May-92	52.1	26.2	20.7	0	1.0
Sep-92	52.3	26.7	19.4	0	1.6
Nov-93	50.3	27.4	21.3	0	1.0
Mar-94	51.9	27.0	19.9	0	1.2
Oct-94	49.9	27.0	22.3	0	0.9
Mar-95	51.0	25.3	21.9	0	1.8
Jul-95	55.3	21.7	18.8	0	4.3
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A

G16/23	**16.6m**				
Dec-86	#N/A	#N/A	#N/A	#N/A	#N/A
Jul-87	65.1	19.5	13.2	0	2.2
Nov-87	54.7	27.4	16.6	0	1.3
Sep-88	50.8	28.8	17.1	0	3.3
Feb-89	50.9	28.5	19.8	0	0.8
Oct-89	62.0	19.4	7.8	0	10.8
Jan-90	76.6	3.7	2.9	0	16.8
Feb-90	61.4	20.2	16.5	0	1.9
Mar-90	55.4	24.7	19.1	0	0.8
Nov-90	53.5	25.8	20.0	0	0.7
Mar-91	52.1	26.9	20.3	0	0.7
May-91	59.9	20.4	15.3	0	4.4
Nov-91	52.4	26.7	20.0	0	0.9
Apr-92	52.5	26.0	20.8	0	0.7
May-92	53.4	25.4	20.2	0	1.0
Sep-92	60.3	18.8	13.6	0	7.3
Nov-93	51.1	27.1	20.9	0	0.9
Mar-94	51.5	26.7	20.5	0	1.4
Oct-94	51.3	26.1	21.3	0	1.3
Mar-95	54.5	22.0	18.8	0	4.7
Jul-95	53.5	24.0	20.4	0	2.2
Dec-95	#N/A	#N/A	#N/A	#N/A	#N/A