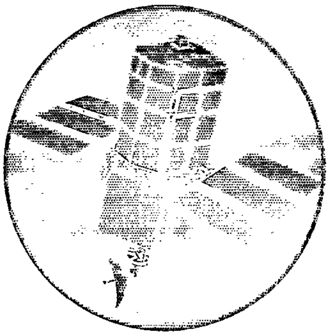
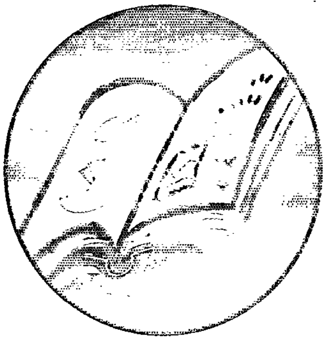
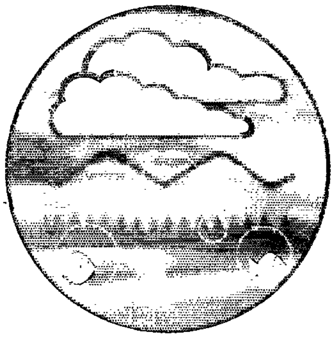
A Pilot Study of Landfill Leachate Denitrification







Research and Development

Technical Report
P230

ENVIRONMENT AGENCY

A Pilot Study of Landfill Leachate Denitrification

R&D Technical Report P230

K Knox

Research Contractor:
Knox Associates

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Statement of use
This R&D report presents results of an experimental study in which biologically nitrified landfill leachate from a full-scale treatment plant was passed through the beds of waste of different ages and the extent of denitrification examined. The report will be available to landfill operators and regulators, particularly those involved in considering different leachate treatment and management techniques.

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DISCLAIMER

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1. INTRODUCTION

This report presents the results of an experimental study in which biologically nitrified landfill leachate from a full-scale treatment plant was passed through beds of young and aged refuse and the extent of denitrification examined. The study was funded by the UK Department of the Environment as part of its programme of research into controlled waste management, and was undertaken by Knox Associates, under contract no. PECD 7/10/304.

2. BACKGROUND

Denitrification will increasingly become a requirement of leachate treatment at many UK landfills. At the time of this study no leachate treatment plant in the UK had been designed and constructed to incorporate denitrification and there has been little UK research focused specifically on it. However, denitrification has been observed intermittently in some UK studies, and purpose-built leachate denitrification systems have been in operation for several years at landfills in Germany. They use both the soluble organic matter in leachate and added chemicals such as glucose or methanol as the carbon source needed for denitrification. Denitrification in leachates appears to be kinetically very favourable, with the anoxic reactors in German plants sized at roughly one third of the size of the corresponding aerobic, nitrification reactors. The provision of an external source of degradable carbon is often the biggest component of the operating costs at leachate denitrification plants. Any scheme which avoided these costs could be economically attractive.

Concurrently with the need to introduce denitrification into UK leachate treatment, there is concern over the long-term stabilization of landfills and the time needed for leaching out of soluble contaminants. Ammonia has been identified as the contaminant most likely to determine the timescale for meeting completion criteria. The leaching generated by natural percolation through clay-capped landfills is such that the timescale to reach final storage quality is likely to be on the order of several centuries. One possible way of accelerating the leaching of ammonia is the recirculation of leachate through the landfill at a much higher flow rate than the net rate of leachate production after landfill capping. If denitrification could be shown to occur during recirculation of partly treated (nitrified) leachate, there would be no need to design external treatment processes to denitrify the full recirculation flow, but only for the net flow discharged off site, and there would be a consequent cost saving. Leachate treatment and landfill stabilization would then become an integrated process, as shown schematically in Figure 1.

The main purpose of this study was therefore to investigate the removal of nitrate from leachate when passed through decomposing refuse. The scope of the study included examining refuse at three different stages of decomposition, viz.

Young:	Less than four years after emplacement, possibly still in the acetogenic phase; with relatively little decomposition having occurred yet.

Mature:	Young refuse batch, as above, after becoming fully methanogenic and having undergone a significant degree of decomposition, while still having a high level of biological activity and remaining degradable components.
Old:	More than 20 years old with no more than a low level of remaining biological activity and little readily degradable matter remaining.

In addition to the removal of nitrate, it was intended that the study would monitor the flushing of ammonia and any other major changes in leachate quality which occurred during prolonged passage of leachate through the three types of refuse. Few rigorous studies have been reported on these aspects of leachate recirculation, though anecdotal evidence has fostered a view that recirculation may lead to adverse increases in ammonia and non-degradable COD concentrations. Part of the purpose was therefore to see if such changes occurred and whether they were short-lived or were maintained after the passage of several bed volumes of leachate.

The study was not designed to assess changes in the composition of the solid wastes as a result of recirculation. While it was considered possible that some stimulation of decomposition rate might occur, particularly in older wastes, the proposed duration of the study was too short to expect to be able to measure any changes in a given batch of solid waste.

3. OBJECTIVES

3.1 To determine the suitability of young, mature and well-decomposed domestic refuse as carbon sources for denitrification in landfill leachate.

3.2 To determine the kinetics of denitrification when using domestic refuse as a carbon source.

3.3 To assess other major leachate quality changes which may occur during recirculation of nitrified leachate through domestic refuse of different ages.

4. EXPERIMENTAL PROGRAMME

4.1 LOCATION

The experiment was located adjacent to a rotating biological contactor (RBC) leachate treatment plant, operated by Cleanaway Limited at their landfill at Pitsea, Essex. At the time of the study this was the only leachate treatment plant in the UK designed and operated specifically to nitrify ammonia. It was therefore the only location where a source of fully nitrified leachate was readily available to use as influent for this study.

4.2 GENERAL DESCRIPTION OF PLANT

The general arrangement of the plant is shown in Figure 2 and Plates 1 and 2. Detailed specification of plant equipment is given in Table 1 and a cross-section through the reactor is also shown in Figure 2. The refuse bed reactor consisted of a purpose-built cylindrical steel container, 1m in diameter and 3m high, raised approximately 1m off the ground on a scaffolding support. The scaffolding support was placed on a 2m x 2m Stelcon reinforced concreted slab which was emplaced on made ground, adjacent to the Pitsea RBC plant. Scaffolding was also erected to the full height of the reactor, to allow easy access while carrying out maintenance or experimental work.

Influent and effluent holding tanks (capacity ~1m^3 each) were placed at ground level, such that effluent could flow by gravity from an outlet at the base of the reactor, into either holding tank. Leachate was pumped from the influent tank through tubing which passed through the lid of the refuse reactor and was then introduced to the top of the refuse column via a perforated pipe distributor device. The leachate distributor in place in its operating position, is shown in Plate 3.

Gas flow from the reactor was collected via a valve in the reactor lid and routed via tubing to a gas flowmeter. The measures taken to attempt to seal any other escape routes for gas are described in the next section, section 4.3.

Two temperature probes, connected to a temperature logger, were placed inside the reactor in knock-in piezometer tubes. In the old refuse these were at depths of approximately 1m and 2m into the waste column. In the young/mature refuse one probe was placed in a piezometer tube at ~1m depth and the other just into the top of the refuse, beneath the covering sand layer.

An electrical control cabinet provided housing for the leachate pump, pump timer, temperature recorder and gas flowmeter. The equipment in place in the control cabinet is shown in Plate 4.

Trace heating of the steel refuse reactor and thermal insulation, were added for the young/mature refuse, to maintain temperatures in the range 15-20 C in the winter.

Filling and emptying of the reactor with different refuse sources was undertaken in a separate area of the site. The reactor was then lifted in and out of position by a mobile crane.

Operation of the leachate dosing pump was controlled by an electrical timer switch which allowed adjustment over a wide range of on and off periods, from 0.2 minutes to 10 hours.

Table 1. Equipment Specification for Refuse Bed Leachate Denitrification Plant

STEEL REACTOR TANK

dimensions:	1000mm i.d. x 3000mm high end flanges 1250mm o.d.
materials:	walls: 8mm mild steel base plate and flanges: 10mm mild steel top plate: 10mm polypropylene
inlets, outlets and fittings:	4 no. lifting lugs beneath top flange 2 no. lifting lugs at 1.5m height 3 no. " brass BSP sockets 15cm below top rim 2 no. 1" brass BSP sockets above base flange 2 no. 100mm raised, flanged polypropylene sockets in lid
weight of empty reactor, minus lid:	700 kg

INFLUENT AND EFFLUENT TANKS

2 no. dosing tanks in black, medium density polypropylene.

dimensions: 1050 mm i.d.
working capacity: ~1100 litres

LEACHATE DOSING EQUIPMENT

- Electronic diaphragm pump, rated 0.48 - 95 litre/hour
- Timer switch capable of setting on and off periods independently at any value from 1 minute to 10 hours.
- Distributor consisting of branched 14 mm i.d., 17 mm o.d. grey UPVC pipe arrangement, 4.2 m total pipe length fed from dosing pump via a central vertical riser pipe, and containing 28 no. 1.5 mm holes on upper pipe surface. Dead volume of distributor: 500-600 ml.

INSTRUMENTATION

- 1 no. knock-in piezometer probe with 2m steel tubing.
- 1 no. knock-in piezometer probe with 1m steel tubing.
- 1 no. Skye Instruments temperature logger with two thermocouple probes on 10m cable length.
- 1 no. Triton Electronics Gasflow meter, model P181

HEATING AND INSULATION

- 40m of Jimi-Heat self-limiting 33 W/m heating tape, wound around lower 2m of reactor, at ~150mm spacing.
- 1 no. Jimi-Heat thermostat controller, with thermocouple taped to side wall of steel reactor.
- 50mm foil-coated fibreglass insulation jacket fitted around vertical sides of reactor.
- chicken wire guard fitted around insulation jacket.

4.3 REFUSE SOURCES USED

Two sources of refuse were used for the study.

YOUNG/MATURE REFUSE

Young refuse was obtained on 24th November 1992 from the Mucking landfill, Essex, operated by Cory Waste Management Limited. It was obtained from a recently completed area of the site which had received only domestic refuse, a high proportion of which was known to be pulverized. An excavator was used to expose the refuse to examine suitable sources. The waste which was used was found in the second lift down and appeared to be predominantly pulverized, little-decomposed, and smelled strongly of acetogenic landfill leachate. Approximately $10m^3$ (loose) was transported by skip to Pitsea and was used the following day (25th November) to fill the reactor. Newspaper pieces found in the waste had dates of June 1990 and September 1990, so it was roughly 2-2.5 years old when used in this study.

Despite being pulverized, some fairly large pieces of plastic, from bags and refuse sacks, were encountered during filling. These were removed by hand, as far as possible, as were items such as tins, rags and lengths of wire. In total, some 10-20% of the <u>volume</u> of the loose waste was removed by hand. In spite of this, significant amounts of plastic remained in the waste during emplacement. Some large pieces of cardboard were broken up by hand, during placement, to a size of roughly 100mm. However, it is entirely possible that the waste, as emplaced, still contained a significant proportion of materials which could interfere with the downward vertical flow of leachate during operation of the reactor, and some short-circuiting or wall-effects might have been expected. The appearance of the young refuse after loading into the reactor is shown in Plate 5.

MATURE REFUSE

Difficulty was encountered in identifying a landfill from which to obtain an appropriate source of mature refuse. To be suitable for this study it had to have been pulverized, of known deposition date, known to have been actively methanogenic for 10-15 years, and to be readily reached by a hydraulic excavator. Few UK landfills receive pulverized waste and it was concluded that in most such sites the appropriate refuse would now be too deeply buried to be conveniently accessible.

Instead, measures were taken to accelerate the decomposition of the young refuse batch after sufficient information had been obtained from it. This was achieved by increasing the temperature to 40 C, and recirculating leachate through it for 63 days. The study then attempted to establish whether there had been any loss of denitrification capacity. This modification to the original objective had the benefit of eliminating uncertainty which might arise when comparing denitrification rates in wastes from completely different sources.

The appearance of the 'matured' refuse emptied from the reactor at the end of the experiment, is shown in Plate 6.

OLD REFUSE

Very well decomposed refuse was obtained from Pitsea site. The decomposed refuse was reported to be between 40-70 years old (MOFFATT AND HOUSTON, 1991) and was landfilled on an area which did not receive hazardous wastes, known as Fobbing Horse Island. Subsequently, in the early 1980s it was excavated and used as cover in 1.5m layers on another part of the site for an experimental study into tree growth on landfills, run by the Forestry Commission (MOFFATT AND HOUSTON, 1991). It must be assumed that when originally landfilled, the refuse had a significant proportion of ash and much less plastic than today's refuse. At the time of this study, it had a soil-like consistency but contained some fragments of pottery and glass, shoe soles and a small amount of plastic. In addition, the batch excavated for this study (see Plate 7) contained some plant roots, probably as a result of its 10 years spent as cover, and some clods of clay, which were presumed to have been taken up incidentally by the excavator. No metal cans were encountered. Hand sorting of the waste was undertaken, to remove as much of the extraneous material, as possible, as well as larger items of glass, pottery, plastics and shoe soles. The material removed in this way is visible in Plate 7 and was estimated to be ~5% of the initial weight of the waste.

Because of its soil-like consistency and the absence of plastics, it was anticipated that leachate flow through the old waste would be fairly even and would not be subject to significant short-circuiting or wall effects.

4.4 GAS SEALING ARRANGEMENTS

Different gas sealing techniques were used at various times for different refuse batches. They varied in their effectiveness. Measures taken at different times are described below. Throughout the study, any unused BSP outlet sockets were plugged, and PTFE tape wound around the plug threads before tightening.

1ST REFUSE BATCH (OLD WASTE)

Two tracks of silicone bathroom sealant were applied to the top flange, before placement of the lid. These tracks were placed inside and outside the line of the bolt holes in the flange. Non-hardening waterproofing tape was applied around the outside edge of the flange and lid, after tightening of all the bolts. This tape was also wound around the point where the influent leachate tubing entered the lid of the reactor.

Flexible gas-sealing compound was applied to the flanges of the two 100mm sockets in the lid, through which the temperature probe cables and gas sampling valves were fitted. The tubing which led from one of the gas valves to the gas flowmeter was 7.5mm i.d., thick-walled (3mm) polyethylene tubing and was simply push-fit on to the gas valve outlet of the reactor and gas inlet of the flowmeter. No additional sealing was applied at these points.

2ND REFUSE BATCH (YOUNG/MATURE)

Similar techniques to those described above were used. In addition, the piping connecting the reactor to the gas flowmeter was replaced by nylon tubing and a compression fitting was installed on the gas outlet manifold in the reactor lid. In spite of these measures, no gas flow through the Triton flowmeter was obtained at any time during the study. It is assumed that leakages were still sufficient to prevent establishment of the ~2cm water pressure necessary to operate the Triton flowmeter.

4.5 INFLUENT LEACHATE SOURCE

The influent used for the experimental reactor was final effluent taken from the settling tank of the full-scale nitrification plant at Pitsea. This leachate was pumped, as required, in batches of approximately 1m^3, from the settling tank, into the black polypropylene influent tank of the pilot-scale reactor. As a result, some variation in the quality of the influent to the reactor was inevitable during the course of the experiment, reflecting the variability of the leachate entering the full-scale plant. The most significant variations were in the chloride and TOC concentrations, which tend to vary seasonally in the Pitsea leachate. The extent of this variation is typically ~20% of the annual mean value and is not regarded as having any significant impact on the results of this study.

During the operation of the reactor with young refuse, the nitrified leachate used as influent was supplemented, for a limited period, with potassium nitrate. Influent NO_3-N concentrations were increased from typical values in the range 300-500mg/l, to as high as 2500mg/l. This was done in order to increase the NO_3-N loading without having to raise the irrigation rate above the range that had already been used, which would have taken it further away from the rates that might realistically be applied at landfills. The addition of KNO_3 led to a large temporary increase in the potassium concentration in the influent and allowed potassium to be used as a convenient tracer to provide additional information on the hydraulic characteristics of the reactor.

4.6 OPERATIONAL DETAILS

4.6.1 REACTOR FILLING/CONSTRUCTION DETAILS

Filling of the reactor was carried out on a separate area and the reactor was removed and replaced in position using a mobile crane. Weighing of the reactor, empty and full, was undertaken using the weighing facility of the mobile crane. Filling was achieved using the bucket of a hydraulic excavator. First, a layer of washed flint gravel (~10-20mm particle size) was placed in the base of the empty reactor, to a depth of 80-100mm. This was levelled by a person climbing inside the cylinder via a ladder suspended from a beam straddling the top flange. Next a circular piece of terram fabric, ~1.1m in diameter, was placed on the gravel and the edges folded upwards to be flush with the tank walls. The first bucketful of waste was then put in and carefully levelled by hand to ensure that the terram fabric remained correctly in place. Light compaction of this layer was achieved by the weight of a person treading carefully up and down on the waste. The depth of waste was then built up in layers of approximately 100-200mm, usually the equivalent of 2-3 buckets of waste for each layer. After placement by the excavator bucket, each lift was levelled by spade and by foot and subjected to as much compaction as could be achieved by a person repeatedly jumping up and down on it (70kg individual, size 9 feet). Particular care was taken to try to ensure that the perimeter areas were compacted at least as much as the inner areas, to minimise the risk of wall-effects. In the case of the aged refuse, a layer of washed sand, 80-100mm thick, was then added before the reactor was put into position. With the young refuse, sand was added after an initial period of operation, so that any initial settlement upon wetting the refuse would have taken place. Details of the reactor dimensions and quantities of waste used are given in Table 2.

Table 2. Reactor dimensions and filling details

		young refuse	**old refuse**
date filled		25.11.92	7.8.92
date emptied		29.3.94	25.11.92
height/depth(mm)			
- empty reactor		3,000	3,000
- washed flint gravel, 10-15mm		100	80
- refuse		2,770	2,720
- sharp sand		50	80
- freeboard		70	120
diameter	(m)	1.0	1.0
cross-section area	(m^2)	0.785	0.785
initial volume of refuse	(m^3)	2.176	2.136
initial weight of refuse	(kg)	1,680	2,330
initial wet density of refuse	(kg/m^3)	772	1,091
moisture absorption during study	(l)	580	550
estimated bed volume	(l)	1,000	1,074
settlement during study	(mm)	620	120
settlement as % initial refuse depth	(%)	22	4.4
estimated final wet density	(kg/m^3)	1,339	1,411

4.6.2 TEMPERATURE PROBES

After filling the reactor, either one or two piezometer tubes were driven into the refuse, using a sledgehammer. Their depths and distance from the perimeter were as follows:

	depth (m)	distance (m)
Old Refuse		
piezometer 1	2	0.3
piezometer 2	1	0.15
Young Refuse		
Piezometer 1	1	0.5

Results from the old refuse, undertaken first, and without heating, are presented graphically in Appendix 1. They showed that there was relatively little difference in average daily temperature with depth, both probes responding to changes in ambient temperature. However, the outer, shallower piezometer showed more response to diurnal temperature fluctuations. In the young refuse, a single piezometer was therefore positioned near the centre of the reactor at a depth of 1m. The second temperature probe was located centrally, at the junction of the sand and refuse layers. Results for the first month of operation of the young refuse reactor are also shown graphically in Appendix 1.

The probe at the upper surface of the waste exhibited large diurnal fluctuations, responding directly to changes in ambient temperature during winter weather, and appeared unaffected by insulation and the initiation of trace heating. The deeper probe exhibited almost no diurnal fluctuation and a less marked response to longer term changes in ambient temperature. Initiation of the trace heating system led to a steady increase in temperature until a steady state was reached. Subsequent data confirmed that the temperature in the 1m probe matched the setting selected on the control thermostat of the heating system.

After installation of the piezometer tubes and temperature probes, the leachate distributor was positioned, the lid fitted, and leachate dosing was started. Gas sealing was undertaken after an initial period of flow, to allow removal of the lid for examination of any initial settlement, and possible adjustment of the distributor position.

4.6.3 FLOW REGIMES AND HYDRAULIC ASPECTS

Two flow regimes were used.

At the start of each refuse batch, a down-flow, recirculation mode was used, usually at a fairly high flow rate for a short period, to bring the waste to field capacity quickly, and to speed up any initial settlement caused by wetting. In this mode, effluent flowed directly back into the influent tank. This allowed the plant to be left unattended without any risk that the influent tank would run dry. It also allowed the easy measurement of the amount of water absorbed by the refuse. The flow was then switched to down-flow, single pass, which was the normal operating mode used during the study.

Recirculation mode was also used on two other occasions during the experiment with young refuse. In the first of these, it was used for six weeks (0.75BV) in order to help induce methanogenic conditions within the waste. Later in the study, leachate was again recirculated, at a high flow rate and elevated temperature (40 C), for nine weeks (~2.5BV), to accelerate decomposition of the waste and generate a simulated 'mature ' refuse.

Flow and hydraulic information is shown schematically in Figure 3 (young/mature waste) and Figure 4 (old waste), while raw flow data are included with the detailed results in Appendices 2 and 4 respectively.

Irrigation rates used in the study varied from ~20 to ~80mm/d during normal operation, and up to 140mm/d during initial wetting periods. No difficulty was experienced with the passage of these flows, which require refuse hydraulic conductivities of only 10^{-7} to 10^{-6}m/s. However, some ponding occurred in the young refuse, late in the study, which may have been a result of biofouling in the distributor and sand layer. Ponding is shown in Plate 8 and slime growth on the distributor is shown in Plate 9.

Hydraulic retention times varied from 8 to 54 days. During the study of young/mature refuse, ~16.4 bed volumes (BV) of nitrified leachate were passed through the waste in single pass mode, plus ~4BV during periods of recirculation. In the study of old waste ~3.3BV of nitrified leachate were passed through the reactor in single pass mode.

4.6.4 CHRONOLOGY OF OPERATION

A chronological summary of the operation of the plant is shown in Table 3 and in Figures 3 (young/mature refuse) and 4 (aged refuse)

Table 3. Chronology of plant operation

Refuse type	Date	Details
Old	7.8.92	reactor filled: initial weight of refuse 2,330 kg
	24.8.92	leachate flow started; DF/RC mode at ~55 l/day; 1st leachate batch
	3.9.92	flow increased: ~120 l/d; mode unchanged: DF/RC
	10.9.92	moisture absorption complete; 2nd leachate batch started; flow cut: ~50 l/d; mode switched: DF/SP
	1.10.92	3rd leachate batch started; flow cut: ~20 l/d; mode unchanged: DF/SP
	22.10.92	gas sealing applied to lid and fittings
	14.11.92	additional gas sealing applied to lid and fittings
	24.11.92	flow stopped; reactor allowed to drain End of old refuse study. NB no trace heating or insulation were used for the old refuse.
Young	25.11.92	Reactor emptied and refilled with young refuse: flow: 120 l/d; mode: DF/RC
	2.12.92	absorption nearly complete; flow cut: 23 l/d; mode switched: DF/SP
Young	15.12.92	trace heating fitted; *(Continued over)*

Refuse type	Date	Details
	16.12.92	Thermal insulation added. Temperature controller set at 20 C
	22.12.92	sand layer placed; gas sealing applied around reactor lid
	30.12.92	complete denitrification became established
	28.1.93	flow rate increased to give loading ~9gN/m^3.d
	9.3.93	flow rate increased to give loading ~12gN/m^3.d; bacterial growth observed around holes in leachate distributor when lid was removed
	14.4.93	flow stopped and temperature controller increased to 25 C to try to induce methanogenesis
	20.4.93	flow re-started in DF/RC mode to try to induce methanogenesis
	26.5.93	temperature controller increased to 30 C
	4.6.93	flow re-started in DF/SP mode following successful establishment of methanogenesis. Nitrified leachate feed enriched with KNO_3 to allow higher loadings at established flow rates; flow re-started at ~30gN/m^3.d
	9.8.93	loading cut to ~6gN/m^3.d following breakthrough of NO_3-N in effluent
	2.9.93	flow switched to recirculation mode and flow rate increased, to try to accelerate ageing of refuse; temperature controller increased to 40 C, to stimulate higher rates of decomposition
	3.11.93	flow switched back to single-pass mode, at loading of ~5gN/m^3.d
	6.12.93	temperature controller lowered to 30 C
	10.12.93	lid removed, sand layer re-levelled and distributor thoroughly cleaned of accumulated bacterial growth; loading rate increased to ~14gN/m^3.d
	21.2.94	temperature controller increased to 40 C to see if higher rate of denitrification achievable
	28.3.94	flow stopped and plant dismantled

DF = downflow; RC = recirculation; SP = single pass

Old waste was studied first, partly because of the immediate on-site availability of a suitable source of waste, and partly because more uniform hydraulic characteristics were expected. This was regarded as a potential advantage during the initial commissioning of the plant, in case any operational problems led to the need to empty and re-fill the reactor. In the event, no such problems occurred.

The aged refuse experiment lasted 4 months from 7th August to 24th November 1992. During this time the reactor was neither insulated nor heated. The young/mature refuse experiment lasted ~16 months, from 25th November 1992 to 28th March 1994. Trace heating and insulation were added approximately three weeks after filling the reactor, so for most of the duration of the young refuse experiment, temperature was a controlled variable.

4.7 CHEMICAL ANALYSIS AND MONITORING

4.7.1 INFLUENT AND EFFLUENT LEACHATE

Samples were taken daily or three times a week during most of the study, for a basic analysis consisting of:

total oxidised nitrogen, TON
total organic carbon, TOC
ammoniacal nitrogen, NH_3-N
pH

More detailed monitoring was undertaken, usually on a weekly basis, for the above parameters plus:

BOD
COD
major ions

All leachate analyses were carried out at the laboratory of Cleanaway Limited.

4.7.2 LEACHATE FLOW RATE

Leachate flow rate was controlled by changing the timer settings on the leachate pump. The actual flow rate was monitored by measuring levels in both the influent and effluent holding tanks, typically 2-3 times per week. By monitoring both tanks it was possible to assess initial losses due to uptake of absorptive capacity.

4.7.3 GAS MONITORING

Bomb samples of the headspace gas in the reactor were taken for analysis by gas chromatography at intervals of, typically, 2-4 weeks. The analysis was undertaken by Cleanaway Limited. Occasional spot checks of methane and oxygen concentrations were made on site using a Gascoseeker.

During the later stages of the young refuse study, after simultaneous denitrification and methanogenesis has been satisfactorily demonstrated, the gas monitoring results were affected by ingress of air into the top of the reactor. This is thought to have occurred via the two small access holes provided for the temperature probes. It proved impossible to obtain any gas flow data during the study. This was attributed to the inability to produce good enough sealing around the reactor lid and inlet manifolds to allow the necessary ~2.5cm water gauge pressure to build up.

4.7.4 TEMPERATURE MONITORING

Continuous logging of internal reactor temperature was undertaken throughout the old refuse study and during the first part of the young refuse study. Once it was established that the heating and insulation produced steady, controllable temperatures, continuous logging was discontinued.

4.7.5 REFUSE ANALYSIS

Analysis of the young and old refuse used in the study was undertaken for:

moisture content
loss on ignition
acid-digestible fibre
total nitrogen

Two samples of matured young refuse, taken from top and bottom of the reactor at the end of the study, were also analysed.

The old refuse had been analysed previously by Cleanaway for several parameters. Additional analysis, for cellulose and loss on ignition, was carried out at the University of East London. Because of its soil-like consistency, no particular sample preparation was undertaken. Acid-digestible fibre was determined gravimetrically, which was found to be unsatisfactory because the determination includes non-fibrous material such as carbonates.
The young refuse was prepared for analysis by NETCEN laboratories, Culham, using a size-reduction and sub-sampling protocol developed at Warren Spring Laboratory.

Samples weighing 10-20kg were weighed and then dried at 105 C for 48 hours. They were then re-weighed and split into two fractions, one fraction being put into storage. The other was then ground in three stages using a combination of knife and ball mills to produce a sample with a particle size of <2mm. At each stage half of the sample was removed and discarded.

Analysis was undertaken by AEA laboratories at Harwell. Cellulose was determined gravimetrically after digestion in 72% H_2SO_4, following a mild acid reflux stage to remove proteins and other components (e.g. carbonates) which could interfere with the cellulose determination. The residue, after cellulose determination, was ashed at 550 C to provide an estimate of lignin content. The method for determination of nitrogen content has not been reported.

5. RESULTS

5.1 YOUNG REFUSE

Detailed chronological results for flow rate and concentrations of major leachate parameters are shown in Appendix 2 More detailed laboratory analyses, undertaken less frequently, are given in Appendix 3. Headspace gas analyses are shown in Table 4.

Table 4. Headspace gas composition in young refuse experiment.

date	duration		method	headspace gas concentration (%)			
	days	BV		CH_4	CO_2	N_2	O_2
30.12.92	35	1.44	GS	3%LEL	-	-	3
11.1.93	47	1.72	bomb	26	45	19	1.6
8.2.93	75	2.54	bomb	45	27	15	0
9.3.93	104	3.75	GS	44	-	-	1
23.3.93	118	4.73	GS	39	-	-	3
20.4.93	146	6.3	GS	35	-	-	0
6.5.93	162	6.3	GS	50	-	-	1
12.5.93	168	6.3	GS	50	-	-	1.5
4.6.93	191	6.3	GS	50	-	-	0
2.7.93	219	7.18	bomb	23	17	9	0.2
29.7.93	246	7.86	bomb	39	28	10	0.5
2.9.93	281	8.79	GS	50	-	-	1.5
8.9.93	287	8.79	bomb	47	33	5.9	0.5
15.9.93	294	8.79	bomb	50	34	5.1	0.4
27.9.93	306	8.79	bomb	44	30	5.2	0.4
30.9.93	309	8.79	bomb	53	35	2.2	0.2
6.10.93	315	8.79	bomb	53	32	3.3	0.5
21.10.93	330	8.79	bomb	50	31	1.9	0.4
28.10.93	337	8.79	bomb	59	34	3.0	0.6
18.11.93	358	9.25	bomb	57	33	6.4	0
1.12.93	371	9.63	bomb	66	35	1.7	0
17.12.93	387	10.24	bomb	0.9	0.5	81	19
29.12.93	399	11.01	bomb	2.8	1.4	80	18
9.2.94	441	13.61	bomb	2.6	3.3	78	23
23.2.94	455	14.47	bomb	4.6	1.5	76	18
11.3.94	471	15.43	bomb	2.3	1.2	79	18
26.3.94	486	16.30	bomb	0.9	0.4	80	20

GS = gascoseeker measurement on site; bomb samples analysed by g.c. in laboratory

5.1.1 COMPATIBILITY OF DENITRIFICATION AND METHANOGENESIS

Denitrification became established soon after the initial rapid addition of the first bed volume of leachate. Figure 5 shows the influent and effluent total oxidised nitrogen (TON) results, in which the rapid early decline of effluent TON, to almost zero, is clearly apparent. Once established, the flow rate was increased in stages as shown in Figure 3, to increase the TON loading. Complete removal was maintained up to loadings of ~15gN/m^3.d, reached after the passage of ~6BV. At this stage the reactor effluent was still acetogenic with a low pH and a high BOD/COD ratio, even though much diluted by flushing. It was felt unlikely that methanogenic conditions would become established as long as the reactor continued to receive leachate high in TON. The operational mode was therefore changed to recirculation of denitrified reactor effluent for a 6-week period and the temperature increased to 25 C. This proved completely successful. The TOC concentration, shown in Figure 6, fell from its diluted acetogenic value of ~1200mg/l to ~350mg/l. Similarly, the BOD (Figure 7) fell from ~1500mg/l to ~200mg/l and subsequently to <50mg/l. The pH value (Figure 8) rose from ~6.5 to 7.5, the characteristic smell of fatty acids disappeared and the CH_4 concentration in the headspace gas increased to ~50% (Table 4). After re-starting the single pass dosing of nitrified leachate, no reversion to acetogenic conditions occurred during the remainder of the study. This was despite large increases in the loading of TON that led to its appearance at concentrations up to 500mg/l in the reactor effluent. Thus methanogenesis and denitrification were able not only to continue simultaneously in the same reactor, but the methanogens appeared able to tolerate, at least on a macro scale, high ambient TON concentrations throughout the reactor. This is a phenomenon that would not normally be expected in a more conventional type of anaerobic digester.

5.1.2 DENITRIFICATION KINETICS

TON concentrations are shown in Figure 5 and removal rates are shown in Figure 9.

The highest removal rates were achieved following the establishment of methanogenesis, when the influent was supplemented with potassium nitrate, to produce influent TON concentrations of ~2000 to 2400mg/l. Removal rates reached ~30gN/m^3.d during this period at a temperature of 30 C. The loading was then increased further and eventually led to breakthrough of TON in the effluent, reaching ~500mg/l or ~25% of the influent concentration. As a consequence, the removal rate fell to ~20gN/m^3.d, and it fell further, to ~5gN/m^3.d when the potassium nitrate supplement was stopped and the applied loading reduced. Having obtained these initial data on the achievable loadings and limitations of the process, a second period of recirculation was begun after ~8.8BV, to try to accelerate the decomposition of the waste in order to assess whether any loss of denitrification capacity could be detected. During a 2 month period the equivalent of ~2.5BV of denitrified reactor effluent was recirculated through the wastes and at the same time the temperature was increased to 40 C. Following this accelerated ageing period, a single pass operation was re-started at a low loading of ~5gN/m^3.d and complete removal was achieved. This can be seen in Figures 5 and 9 at ~10BV or 350 days. The flow rate was then increased at approximately day 380 and the temperature lowered to 30 C, to reproduce the conditions that had been applied previously up to ~day 250. Breakthrough of TON occurred and the removal rate was ~9gN/m^3.d compared with ~21gN/m^3.d previously. This provided some evidence that the achievable removal rates may have fallen as a result of removal of readily degradable compounds. The final variation tested, from ~15BV or ~450 days onwards was to maintain the same loading while raising the temperature back to 40 C. Figures 5 and 9 show that following this, the effluent TON concentration fell to zero and the removal rate rose slightly to ~10gN/m^3.d.

5.1.3 CONTAMINANT FLUSHING AND WASTE DEGRADATION

The flushing of TOC is shown in Figure 6 and NH_3-N in Figure 10. In Figure 11, both parameters are normalised with respect to their initial concentrations and compared with the theoretical expectation for a completely mixed reactor, which has the form:

$$C_o = C_t \exp[-t/HRT] = C_t \exp[-BV]$$

where: C_t is the concentration of a conservative parameter at time t;
C_0 is the initial concentration;
t is the elapsed time;
HRT is the hydraulic retention time, or the time for one Bed Volume to pass through the reactor, and
BV is the number of Bed Volumes that have passed.

The initial concentrations C_0, derived for this exercise by back extrapolation, were 16,000mg/l (TOC) and 1200mg/l (NH_3-N). Both parameters exhibited a similar shape to the theoretical washout curve but are shifted to the right along the time axis. This can certainly be attributed to the effects of continuing degradation within the reactor. In the case of TOC, this effect ceased to be observed after methanogenesis had been established -any degradable organics were presumably converted to gas and did not appear in the leachate. Thereafter, effluent TOC concentrations were very similar to those in the influent (shown in Figure 6). The BOD results (Figure 7) exhibited a similar washout curve to those for TOC and NH_3-N.

The NH_3-N results provide an opportunity to make some tentative estimates of the rates of waste degradation that may have been occurring at various times during the study. During the two recirculation periods, at ~6BV and ~8.8BV, the NH_3-N concentration increased, even though no TON was present. This means that reduction of nitrate can not be postulated as the source of the ammonia, which must therefore have come from continuing degradation of the solid wastes. During single pass operation, at some combinations of flow rate and temperature, the NH_3-N concentration increased steadily (e.g. from 9 to 10BV in Figure 10), at others it remained relatively constant, and at others still (e.g. from 10 to 12BV in Figure 10), it decreased due to the rate of flushing exceeding the rate of generation. The concentrations and associated leachate flow rates can be used to estimate daily NH_3-N production at various times, and by implication the rates of carbon metabolism. These are shown in Table 5.

Several observations can usefully be made from the results in Table 5:

- Lowering the temperature from 40 to 30 C at ~10BV had a dramatic effect on the rate of waste degradation, which fell by at least 75% from 60gC/m^3.d. This is consistent with the inability of the reactor to denitrify all of the applied TON at this time.

- Estimated carbon metabolism rates were, overall, high compared with typical values for landfills. In landfills, rates of approximately 10 - 15gC/m^3.d (equivalent to ~7 - 10m^3LFG/t.a) would be fairly typical.

Table 5. Estimates of waste degradation rates based on accumulation/flushing of NH_3-N

Period:	**dates:** **days:** **BV:**	**3/93** **98-120** **3.5-5.0**	**6-8/93** **190-280** **6.3-8.8**	**11/93** **343-385** **8.8-10.1**	**12/93-2/94** **386-446** **10.1-14.0**	**3/94** **446-483** **14.0-16.0**
temperature	C	20	30	40	30	40
leachate flow	(l/d)	70	25-30	30	71	64
NH_3-N trend		steady	steady	increasing	falling	increasing
NH_3-N	(mg/l)	~10	50	200	25	~60
daily NH_3-N production	(g/d)	0.7	1.5	6	1.78	3.8
daily C turnover	(g/d)	14	30	120	35.5	77
daily C turnover	(g/m^3.d)	7	15	60	18	39

Note: carbon turnover estimates are based on an assumed C:N ratio of 20:1

The carbon metabolism rates as calculated in Table 5 were, at times, insufficient to support the observed denitrification rates if the efficiency of carbon use by the denitrifiers is assumed to be similar to that typically experienced in denitrifying wastewater treatment plants (a C:N ratio of ~3:1 would be typical). It is possible that in a fixed bed reactor such as this, the efficiency of carbon use by denitrifiers is much greater. It is also possible that the C:N ratio of 20:1 used in the calculation was too low.

Table 5 provides some evidence that at a given temperature the rate of activity was declining slightly during the study. Because of the absence of gas flow data, it was not possible to monitor the extent of waste degradation.

The cumulative leaching of NH_3-N during the whole study was ~1.2 - 1.3kgN/tonne MSW, based on recorded flow rates and effluent NH_3-N concentrations. This is similar to a figure of 1.6kgN/t reported by Ehrig (1993) from laboratory-scale refuse columns subjected to accelerated leaching. Both values are considerably lower than the measured nitrogen content of MSW, for which a range of 4 - 10kgN/t is typical. The question of how much of the total N-content of MSW would ultimately be leachable thus remains an important topic for future research. At a C:N ratio of 20:1, the extent of degradation of organic matter would have been 24 - 26kgC/tonne MSW. This is a significant, but still minor, proportion of the total reservoir of degradable matter present in the refuse.

5.1.4 HYDRAULIC CHARACTERISTICS OF THE REACTOR

The washout of TOC and NH_3-N depicted in Figure 6, 10 and 11 showed that there is some similarity in the hydraulic behaviour of the refuse-bed reactor and a completely mixed reactor. Similar behaviour was evident in results from laboratory-scale lysimeters reported by Ehrig (1993) and in a limited amount of data from old landfills (Knox, 1990; Robinson, 1995). Because landfills and lysimeters are clearly not completely mixed reactors it is assumed that this similarity of behaviour is due to dispersion and, particularly, diffusion effects being rapid in comparison with the net downward rates of liquid movement. The analyses for potassium following the addition of KNO_3 to the influent are shown in Figure 12 and provide further evidence of this behaviour. The first increase in influent potassium was made at 6.3BV and breakthrough up to ~30% of the increased level had already occurred by 6.75BV. By 7.66BV the effluent concentration was as high as the influent concentration. Unmodified influent was used again from 8.2BV onwards and an exponential fall in effluent K concentration is apparent from that point onwards in Figure 12, reaching background levels by 11-12BV.

5.1.5 OTHER INORGANIC IONS

An important concern regarding high-rate leachate recirculation is the extent to which a build-up of soluble inorganic salts and poorly-degradable TOC might occur. This study was not designed to examine this factor because it used predominantly a single-pass mode of operation rather than recirculation. There was little evidence of a build-up or significant release of soluble salts even during recirculation periods.

Chloride

The chloride concentrations in the influent and effluent are shown in Figure 13. Fluctuations in the influent chloride concentration were a result of seasonal cycles in the quality of the leachate being treated in the full-scale nitrification plant. The reactor effluent concentration largely followed these same fluctuations and there was no evidence of any general increase. At around 8.8 - 10BV, when a large increase in effluent NH_3-N was occurring (see Figure 10) due to waste degradation, the effluent chloride concentration was falling.

Alkalinity

Alkalinity results for the influent and effluent are shown in Figure 14. High initial concentrations in the acetogenic leachate were lowered by flushing, similar to those of TOC, NH_3-N and BOD. However, the flushing was much less rapid than for those other components. This suggests that on-going waste degradation generated a disproportionate amount of bicarbonate compared with, say, ammoniacal nitrogen. A large increase in alkalinity occurred at 6-8BV. This suggests that there must have been a very high rate of carbon metabolism at this time, and it was coincident with the highest rates of denitrification. Conversely, no accumulation of alkalinity occurred during either of the two periods of recirculation, when no denitrification was occurring, even though it is clear that carbon metabolism continued at high rates at these times (this is confirmed by the accumulation of NH_3-N). The pattern of alkalinity production thus appears to be very strongly correlated with the rate of denitrification. This is consistent with the expectation that the denitrification process results in a net removal of dissolved CO_2 and generation of bicarbonate, according to the empirical equation given by the US EPA:

$$NO_3^- + 1.08\ CH_3OH + 0.24\ H_2CO_3 \quad 0.056\ C_5H_7NO_2 + 0.47\ N_2 + 1.68\ H_2O + HCO_3^-$$

This equation predicts an alkalinity production of ~3.5g (as $CaCO_3$) per g of NO_3-N. During the last ~5 Bed Volumes of the study, effluent alkalinity was fairly consistent, at ~1500mg/l, while the influent NO_3-N concentration was typically ~3-400mg/l. The effluent alkalinity at this stage can therefore be almost entirely attributed to its generation during the denitrification reaction.

Sulphate

Sulphate results for the influent and effluent are shown in Figure 15. Reduction of influent sulphate concentrations of several hundred mg/l by ~80% occurred under both acetogenic and methanogenic conditions. It is presumed that this was due to the action of sulphate-reducing bacteria. The degree of reduction was high, up to ~7BV, with effluent concentrations typically less than 100mg/l. At ~7BV complete inhibition of sulphate reduction occurred, coinciding with the breakthrough of NO_3-N in the reactor effluent. It therefore appears that sulphate reduction was inhibited by the presence of nitrate, whereas methanogens were not inhibited. From 8BV onwards, the degree of sulphate reduction, and its inhibition, varied, roughly correlating with the concentration of NO_3-N in the reactor effluent (see Figures 5 and 15). No accumulation of sulphate occurred during either of the two periods of recirculation.

Further research, using a prolonged recirculation mode of operation would be needed to provide more definitive conclusions on this aspect of high rate recirculation.

5.1.6 EFFLUENT QUALITY

Effluent quality is dependent on several factors. Concentrations of the products of on-going degradation, such as TOC, ammoniacal nitrogen and alkalinity, are dependent on whether the flushing rate exceeds their rate of production. The TON concentration itself depends on the applied loading rate and the capability of the reactor to remove TON. Sulphate concentrations are affected by the activity of sulphate-reducing bacteria, which may be inhibited by excess TON concentrations. For other, more conservative, parameters quality is largely dependent on the influent concentrations. A typical effluent analysis obtained during this study is shown in Table 6, together with the influent analysis for a sample taken one bed volume earlier.

Table 6. Typical influent and effluent analyses from young refuse study (concentrations in mg/l)

	influent **14.2.94**	**effluent** **2.3.94**
BV passed	13.91	14.91
Duration of study (days)	446	462
HRT (days)	16	17
PH	7.93	7.43
Conductivity, S/cm	12,100	12,740
Chloride	4,518	4,281
NH_3-N	<0.1	43.5
total oxidised nitrogen, N	288	47.3
sulphate, as SO_4	443	208
TOC	306	302
COD	855	744
BOD	10	21
alkalinity, as $CaCO_3$	482	1,566
Ca	175	122
Mg	221	175
K	508	564
Na	3,114	2,931

5.2 OLD REFUSE

The duration and number of bed volumes passed in the study of fully-decomposed refuse are shown in Figure 4. Detailed chronological results for flow rate and major leachate parameters are shown in Appendix 4. More detailed analyses, undertaken less frequently, are shown in Appendix 5.

5.2.1 DENITRIFICATION

Results for TON and TOC in the influent and effluent are shown in Figure 16. Initially, no denitrification was apparent, and the flow rate was progressively reduced in an attempt to detect any difference between influent and effluent concentrations. After the passage of ~2BV, at an applied loading of ~4.9gTON/m^3.d, a consistent low rate of removal became evident, from a mean of ~505mg/l in the influent to ~470mg/l in the effluent, although analytical variability makes these numbers subject to considerable uncertainty. This removal was equivalent to 0.34gTON/m^3.d or ~7% of the applied loading. The headspace gas became nitrogen enriched, and oxygen depleted, consistent with some denitrification occurring. No methane was detected.

Throughout the experiment, consistent removal of ~150mg/l of TOC occurred, equivalent to ~42% of the influent TOC. This is shown in Figure 16. A large proportion of the colour was also removed. This is shown in Plate 10, where the considerable colour removal in old refuse is compared with the very small amount of colour removal in young refuse. No change in the extent of TOC removal was observed, even after nearly 3.5 Bed Volumes, leading to the conclusion that the removal may have been due to biodegradation rather than adsorption.

This was an unexpected observation since the TOC and colour in the leachate had always proved resistant to aerobic biological treatment, in bench, pilot and full-scale plants operated at Pitsea from the late 1970s to the present time, consistent with experiences elsewhere on residual TOC in leachate treatment. However, Imai et al. (1993) reported similar results in bench-scale activated carbon columns treating nitrified leachate. Sustainable removal of 49.4% of the residual TOC was obtained even after more than 350 Bed Volumes had passed through their columns and the authors concluded that the predominant removal mechanism was biodegradation. In the present study, the ratio of TOC removed to TON removed was ~4.4, which is enough to suggest that leachate TOC may have been the carbon source for the observed rate of denitrification. There was therefore no evidence that the old refuse itself provided any degradable carbon source. The absence of detectable methane in the headspace gas is consistent with the TOC removal being associated with denitrification.

5.2.2 OTHER PARAMETERS

Significant removal of NH_3-N occurred. The first two leachate batches used in the old refuse study contained ~20mg/l of ammoniacal nitrogen that had not been nitrified in the full-scale plant. Influent and effluent NH_3-N concentrations in the old refuse study are shown in Figure 17. A high proportion of the NH_3-N was removed initially but effluent concentrations were gradually increasing throughout the experiment. It is assumed that removal was due to adsorption or ion-exchange rather than to any biological mechanism. The gradually increasing effluent NH_3-N concentrations were presumed to be due to depletion of suitable adsorption sites.

Leaching of the inorganic ions bicarbonate and sulphate occurred throughout the old refuse study. Influent and effluent results for alkalinity and sulphate are shown in Figures 18 and 19.

The effluent alkalinity was very consistent, at ~600mg/l. The ratio of the increase in alkalinity concentration to the decrease in TON concentration was approximately 400:35, or 11:1. This exceeds the generation of alkalinity that is usually expected from denitrification (typically 3.5:1) and might suggest that leaching from a reservoir of bicarbonate or carbonate in the solid waste was the most likely source of bicarbonate, rather than biogeneration. However, the removal of 150mg/l of TOC, presumably by biological mineralisation of some sort, would have produced more than enough inorganic carbon to produce the observed increase in effluent alkalinity and this mechanism would account for its very consistent concentration.

The concentration of sulphate in the effluent (Figure 19) varied during the study but was high at all times, ranging from ~1500mg/l (as SO_4) to ~2600mg/l. It is presumed that at these levels the concentrations were solubility-controlled. The implication of the results is that the old waste contained a reservoir of sulphate. This may reflect the original composition of the waste (e.g. if it contained a high proportion of ash) or changes during its degradation and composting.

5.3 REFUSE ANALYSIS

The results of analysis of refuse used in the study are shown in Table 7.

Table 7. Results of analysis of solid wastes used in the study

	Young Refuse			**Old Refuse**
	Start of Study	**End of Study**		
		top of reactor	bottom of reactor	mean of five sub-samples
moisture content (% wet weight)	55.0	54.4	55.7	22.1
loss on ignition (LoI) (%)	90.6	94.6	93.1	28.3
soluble saccharide (%)	-	-	-	0.7
cellulose (%)	25.0	39.2	46.1	1.6
total monosaccharide (%)	-	-	-	2.3
total nitrogen (g/kg)	11.1	11.0	6.8	2.4
extractable nitrogen (g/kg)	-	-	-	0.2
CEC (meq/g)	-	-	-	56
lignin (% dry weight)	41.9	21.7	33.4	-
cellulose:lignin ratio	0.6	1.8	1.4	-
cellulose: loss on ignition ratio	0.28	0.41	0.50	0.06

NB All determinations refer to dry weight except for moisture content.

The results for the young waste are typical of partly-decomposed MSW, with high values for organic content (loss on ignition), cellulose and the ratio of cellulose to loss on ignition (LoI). Given the heterogeneity of young MSW, even when pulverized, and the consequent sampling errors, the results give no statistically significant indication of the changes that may have occurred during the study. Nor do they provide a reliable indication of any differences that might have developed between the top and bottom of the reactor by the end of the study. However, the differences between young and old waste are very clear. The old waste had much lower loss on ignition, cellulose, cellulose:LoI ratio and total nitrogen content than the young waste. The results in Table 7 and the behaviour of the old waste during the study can be compared with the completion criteria given in Waste Management Paper 26A. The old waste had a volatile solids content (= loss on ignition) of 28%, which exceeds the limit of 25% implied in WMP26A. Conversely, its ratio of cellulose:volatile solids (= cellulose:loss on ignition) was lower than the criterion of less than or equal to 0.1, given in WMP26A. The old refuse gave no indication of undergoing any biological decomposition, although the study was not specifically designed to detect this. No measurable leaching of nitrogen occurred, even though the waste still contained a significant concentration of total nitrogen. The figure of 2.4gN/kg may represent nitrogen present in the form of recalcitrant organic compounds, such that its rate of release to the environment would be negligible.

6. DISCUSSION AND CONCLUSIONS

6.1 DENITRIFICATION

The study showed that actively decomposing MSW was able to support denitrification at high rates. It also showed that there was some loss of capacity, as the refuse aged, and fully decomposed refuse provided no carbon source at all for denitrification, in spite of having a significant organic carbon content, measured as ~28%. The peak denitrification rates of up to 30gN/m^3.d achieved at 30 C in waste that was ~2 years old at the start of the study had fallen to ~9gN/m^3.d at the same temperature, near the end of the study. The solid waste analyses were too imprecise to gauge how much degradation had occurred in between these periods, but the leaching of NH_3-N can be used to provide crude estimates of waste decomposition. A total of ~1.3kgN/tonne MSW was leached during the whole study. At a C:N ratio of 20:1 this implies carbon degradation of ~26kgC/t. At a higher C:N ratio of 50:1, more commonly used when considering anaerobic processes, carbon degradation of ~65kg/t is implied. Even this larger estimate is still not more than half of the likely reservoir of 'available' carbon in fresh refuse and the visual appearance of the refuse at the end of the study (Plate 6) was consistent with it still containing a large amount of degradable material. The greater proportion of the NH_3-N leached during the study was already present in the moisture content of the refuse when the study began. Relatively little of it was released as a result of decomposition in the interval between the period of peak denitrification rates (at ~6.5BV) and the end of the study. The drop in denitrification rates therefore occurred during a relatively small increment in the state of degradation of the MSW. Considerable uncertainty therefore remains regarding the ability of waste in its later stages of decomposition to support denitrification. This information is needed in order to establish optimum strategies for bioreactor landfills.

There is probably more than enough degradable carbon in MSW to denitrify all of the nitrogen leached, without having any significant impact on total LFG yields. Using worst-case values, if

10kgN/t were leached from MSW as NH_3-N and if the C:N requirement for denitrification was assumed to be 3:1, then up to 30kgC/t might be diverted from LFG production to supporting denitrification. That would be a significant proportion of the gas potential of the MSW. In practice, the leachable nitrogen concentration is likely to be very much less than 10kg/t, perhaps not more than 2kgN/t and the C:N requirement may also be lower than 3:1. It is therefore probable that not more than 10-20kgC/t would be diverted from LFG production. This likely to be not more than 10% of total gas potential, but could be closer to 20% of the commercial gas potential. It would be of particular value to do further research to determine whether the bulk of the necessary denitrification could be achieved in the later stages of MSW decomposition, using that part of the degradable carbon that does not produce commercially attractive quantities of LFG.

It is also necessary to consider how the denitrification rates achieved in this study compare with those that would be needed to support accelerated landfill stabilization using an enhanced leaching régime that incorporates leachate recirculation and integral denitrification. Consider the following calculation:

Say, nitrogen leachable from MSW = 5kgN/t

Assume denitrification over period of x years at constant rate

For x = 10 years,

rate = 5000gN/t (365 x 10) days = 1.4gN/t.d

For x = 20 years,

rate = 5000gN/t (365 x 20) days = 0.7gN/t.d

For x = 30 years,

rate = 5000gN/t (365 x 30) days = 0.5gN/t.d

For 20 and 30 year stabilization periods, the required rates are at least an order of magnitude lower than those achieved during this study. If the leachable nitrogen content is lower than 5kgN/t, then the required denitrification rate will be correspondingly lower. The rates are therefore more than adequate to support a flushing bioreactor scheme.

6.2 METHANOGENESIS

There was no evidence of inhibition of methanogenesis during this study once it had been established, despite the presence of nitrate. Many studies in other media have observed the inhibitory effect of oxidised nitrogen upon methanogens. For example, Chen and Lin (1993) found that methanogens and denitrifiers could co-exist in acclimated sludges but that the activity of the methanogens was suppressed until all oxidised nitrogen was removed. The suppression was, somewhat surprisingly, not thought to be Eh-related but rather a result of inhibition by nitrogen oxides. In another study, Hendriksen and Ahring (1995) reported removal of nitrate and the formation of methane simultaneously in an up-flow anaerobic sludge blanket (UASB) reactor. In this case it appeared likely that there was physical separation, within the UASB, between denitrifying zones and methanogenic zones. A similar separation of activities could have occurred in the present study - no investigation was made of stratification of activity with the refuse-bed reactor. However, denitrifying bacteria were identified in the reactor effluent, when a sample was examined by Dr Steve Forsythe of Nottingham Trent University, and there were prolonged periods when excess nitrate (up to ~500mgN/l) was present in the reactor effluent. Presumably at such times nitrate was present throughout the refuse column and yet there was no evidence of any reversion to acetogenic conditions. The existence of micro environments within the reactor, provided by the heterogeneous nature of the refuse, may explain this phenomenon. It is therefore puzzling that sulphate reduction appeared to be inhibited when effluent TON concentrations were high, whereas it had evidently been completely unaffected by the acetogenic/methanogenic status of the reactor during the first 6 Bed Volumes. There is an evident need for a better understanding of the relationship between denitrifiers, sulphate reducers, methanogens, and the environmental conditions, in decomposing MSW.

6.3 EFFLUENT QUALITY

Effluent quality from the reactor varied during the course of the study. After the passage of 6 Bed Volumes, most of the NH_3-N and TOC initially present had been flushed out. Effluent quality from then on was largely determined y the balance between the rate of on-going degradation and the rate of flushing. Effluent BOD was consistently low and effluent TOC was virtually identical to influent TOC. The influent NH_3-N fluctuated directly in response to the flushing rate and the temperature (which affected the decomposition rate) and was typically in the range 20-200mg/l. This raises the possibility of using a refuse bed as a separate-stage denitrification reactor, as distinct from its potential rôle in enhanced bioreactor schemes. Because the rates of denitrification were so high, it would be possible to design a refuse bed sufficiently shallow that it achieved complete denitrification while contributing negligible additional concentrations of leachate components such as chloride, TOC and BOD, and relatively low concentrations of NH_3-N. There would be an inevitable increase in alkalinity, as a result of denitrification, but that would rarely be likely to affect the discharge of the effluent. Some post treatment of residual NH_3-N might still be necessary but overall there could be costs savings due to avoiding most of the costs of an external carbon-source.

6.4 CONTAMINANT FLUSHING

The ability to model how long, and how much moisture flux, it will take to flush contaminants from a landfill is important if the effects of particular leachate management régimes are to be predicted reliably.

In this study, the washout of soluble species clearly did not follow plug flow hydraulics, but instead was spread over ~6 Bed Volumes rather than a single bed volume. This type of exponential dilution pattern has also been observed in other small-scale studies and lysimeters. In three 200 litre lysimeters studying phenol co-disposal (Blakey and Barber, 1980), breakthrough of a tritium tracer, added once at the start of leaching, began at 0.25 -0.3BV. Peak concentrations occurred at ~1BV and dilution thereafter followed an exponential flushing pattern. This is consistent with a high degree of equilibration of the added tracer with the moisture content of the lysimeter and is analogous to the behaviour of a completely mixed reactor. In the present study, breakthrough of potassium tracer began within less than 0.45BV of its being added to the influent (see Figure 12). Its subsequent dilution in the effluent began within 0.2BV of stopping the potassium supplementation. This behaviour is also consistent with a rapid equilibration of incoming water with the whole of the moisture content of the reactor. The decline in concentrations of non-conservative components, such as TOC, NH_3-N, BOD and alkalinity was also exponential but was less rapid than for potassium because there was a continuing production of these components by the refuse decomposition processes. This phenomenon was also evident in the decline of TKN compared with that of chloride, in accelerated lysimeter studies reported by Ehrig and Scheelhaase (1993). In their study both declined exponentially. The halving of initial chloride concentrations of 2100mg/l, due to flushing, took 52 - 55 days (quoted as equivalent to 60 - 64 years at a modelled full-scale landfill). For TKN, however, a halving of the initial concentration of 1200mg/l took longer at 65 - 71 days (equivalent to 75 - 82 years). The longer time for TKN flushing may be attributed to its disproportionate release compared with that of chloride, at later stages of decomposition.

Limited data reported previously from old landfills in the UK (Knox, 1990) suggested that dilution at full-scale sites also follows an exponential pattern. Data from additional landfills have been reported more recently (Robinson, 1995) and the combined data set (Robinson, 1995) provides support for the use of some form of exponential function to describe the dilution behaviour. For dilution of a conservative parameter in a completely mixed reactor, the exponent is a simple function of the hydraulic retention time, as described earlier in section 5.1.3, namely,

$$C_t = C_o \exp [-t/HRT]$$

It is evident that over short time-scales such as those in the present study, this simple dilution equation is made inaccurate for non-conservative parameters by the effects of on-going decomposition. For landfills, where active management over several decades or longer is likely, the effects of on-going degradation may be much less, and the simple dilution equation may give a better fit.

Further development of flushing models, to provide more accurate predictions would be desirable, but the complete mixing model, based on HRT as the key variable, appears to offer the best means currently available.

The factors affecting the speed and extent of equilibration of added moisture with that already present in a landfill or lysimeter have received little research effort to date and are not well understood. It is reasonable to assume that diffusion across concentration gradients, and mixing due to thermal convection, could both be important parameters. Research to determine their relative importance, and the possible rôle of other factors, would be very beneficial in developing greater control over landfill processes.

6.5 ACCUMULATION OF DISSOLVED SALTS

Although the present study was not designed to examine this topic, it included two periods of recirculation, during which ~0.7 and ~2.5BV of leachate were cycled through the reactor. Neither of these periods produced any evidence of accumulation of dissolved species other than ammoniacal nitrogen. Unfortunately, the very high chloride and sodium concentrations in the leachate feed meant that release of up to a few hundred mg/l of those ions could have occurred (as it did for NH_3-N) but would not have been distinguishable from the natural variation in analytical results. To examine salt accumulation thoroughly, experiments designed for the purpose would be needed. They would need to incorporate more prolonged recirculation of leachate derived entirely from the solid waste being studied, rather than single passage of leachate derived elsewhere.

6.6 REMOVAL OF TOC BY OLD REFUSE

The failure of the old refuse to provide any source of degradable carbon was not particularly surprising in view of its known history and soil-like appearance. More surprising was the relatively high organic carbon content of such an unreactive material. The sample analysed contained 28% of organic matter. Visually there appeared to be very little plastic in the waste and the nature of the unreactive organic carbon content may therefore have been largely biological in origin. It would be useful to undertake further denitrification studies, at bench-scale, using a variety of partly and fully decomposed wastes. These could be taken from old landfill sites of known age and history, and also from modern refuse composting and digestion plants, or could be produced in lysimeters.

One of the most interesting aspects of the old waste study was its contrast with the young waste. Although providing no source of degradable carbon itself (which the young MSW did) it provided an environment that encouraged biodegradation of over 40% of the recalcitrant TOC in the leachate (which the young refuse did not). A high proportion of the colour of the leachate was removed in the process whereas only slight colour removal occurred in the young refuse. It would be useful to examine other sources of decomposed MSW for their ability to promote this removal of recalcitrant TOC. Similar phenomena have been reported in studies using activated carbon rather than MSW. Imai et al. (1993 and 1995) reported results from two different biological activated carbon fluidised bed processes operated at pilot-scale. They achieved 42 - 58% TOC removal at rates up to ~22.5gTOC/m^3.d, which were sustained for more than 350 Bed Volumes. The leachate they used was, as in this study, a highly stabilized low BOD leachate from a co-disposal landfill. Their results suggest that adsorption by the activated carbon may have played an important rôle in promoting the biodegradation of leachate organics. If adsorption was also an important factor in TOC removal in the present study, it would be useful to know whether the difference between young and old wastes was simply due to changes that result from decomposition, or to differences in the initial characteristics of the waste, such as the presence of ash in the old waste.

7. PRACTICAL IMPLICATIONS FOR SUSTAINABLE LANDFILL

7.1 The ability to achieve denitrification at zero marginal cost, during recirculation, without affecting LFG production, may become an important factor in the economic assessment of sustainable landfilling of bioreactive wastes. Without it, a recirculatory approach to enhanced flushing would be much less attractive. The study has produced several results of direct practical relevance to this condition:

(i) Denitrification kinetics are very favourable in young MSW and comfortably exceed the rates likely to be necessary for enhanced bioreactor landfills.

(ii) Denitrification and methanogenesis can continue simultaneously at high rates. The finding that it may be necessary to establish methanogenesis <u>before</u> establishing denitrification is unlikely to be a practical problem at landfills. Nitrification in leachate treatment plants is only likely <u>after</u> methanogenesis has already become established.

(iii) Landfill gas yields could be slightly reduced, as a result of competition for degradable organics by denitrifying bacteria. However, there may be scope for delaying most of the denitrification activity until the bulk of the economically viable gas has been recovered, as this is typically regarded as less than 50% of the total gas potential of the wastes.

7.2 The results of the study support the use of an exponential decay function to predict the dilution of leachate components by flushing. An exponent based on the number of bed volumes passed through the landfill gives satisfactory results, and is suitable for use in the absence of more refined models.

7.3 The study of old waste suggested that fully-stabilized refuse can have high organic and nitrogen contents and yet undergo no further significant biological activity nor leach significant concentrations of nitrogen.

8. SUGGESTIONS FOR FURTHER RESEARCH

The study answered many of the questions posed at the beginning of the project, but also identified several specific areas where more information is still needed and where additional research would be beneficial. These were as follows:

- Determine denitrification kinetics in MSW at more advanced stages of decomposition, specifically to assess whether that part of the degradable carbon content remaining after commercial LFG exploitation has ceased, would support sufficient denitrification. This study would define the relationship between cumulative carbon removed and denitrification kinetics.

- Study the microbial interactions between denitrifying bacteria, methanogens and sulphate-reducing bacteria in decomposing MSW and the effects of high ambient NO_3-N concentrations on each of these bacterial groups.

- Study the effects of early removal of nitrogen from MSW (by leaching) on the metabolism of the remaining organic compounds.

- Study the accumulation of dissolved salts during prolonged leachate recirculation.

- Study the relative importance of diffusion, thermal convection and other processes in the equilibration of moisture added to landfills.

- Compare the performance of the denitrification process at a full-scale landfill or large-scale test-cell with the results obtained in this study.

FIGURES

1. Schematic illustration of enhanced leaching by recirculation with partial treatment.
2. General arrangement and schematic cross-section of experimental plant.
3. Operational summary (young/mature refuse).
4. Operational summary (old refuse).
5. Influent and effluent total oxidised nitrogen, young refuse.
6. Influent and effluent TOC during young refuse study.
7. Influent and effluent BOD during young refuse study.
8. Effluent pH during young refuse study.
9. Oxidised nitrogen removal rate in young refuse.
10. Ammoniacal nitrogen results during young refuse study.
11. Normalised effluent TOC and NH_3-N concentrations, young refuse.
12. Leaching of potassium tracer, young refuse.
13. Influent and effluent chloride results, young refuse.
14. Influent and effluent alkalinity results, young refuse.
15. Influent and effluent sulphate results, young refuse.
16. Influent and effluent TOC and TON results during old refuse study.
17. Influent and effluent NH_3-N results during old refuse study.
18. Influent and effluent alkalinity results during old refuse study.
19. Influent and effluent sulphate results during old refuse study.

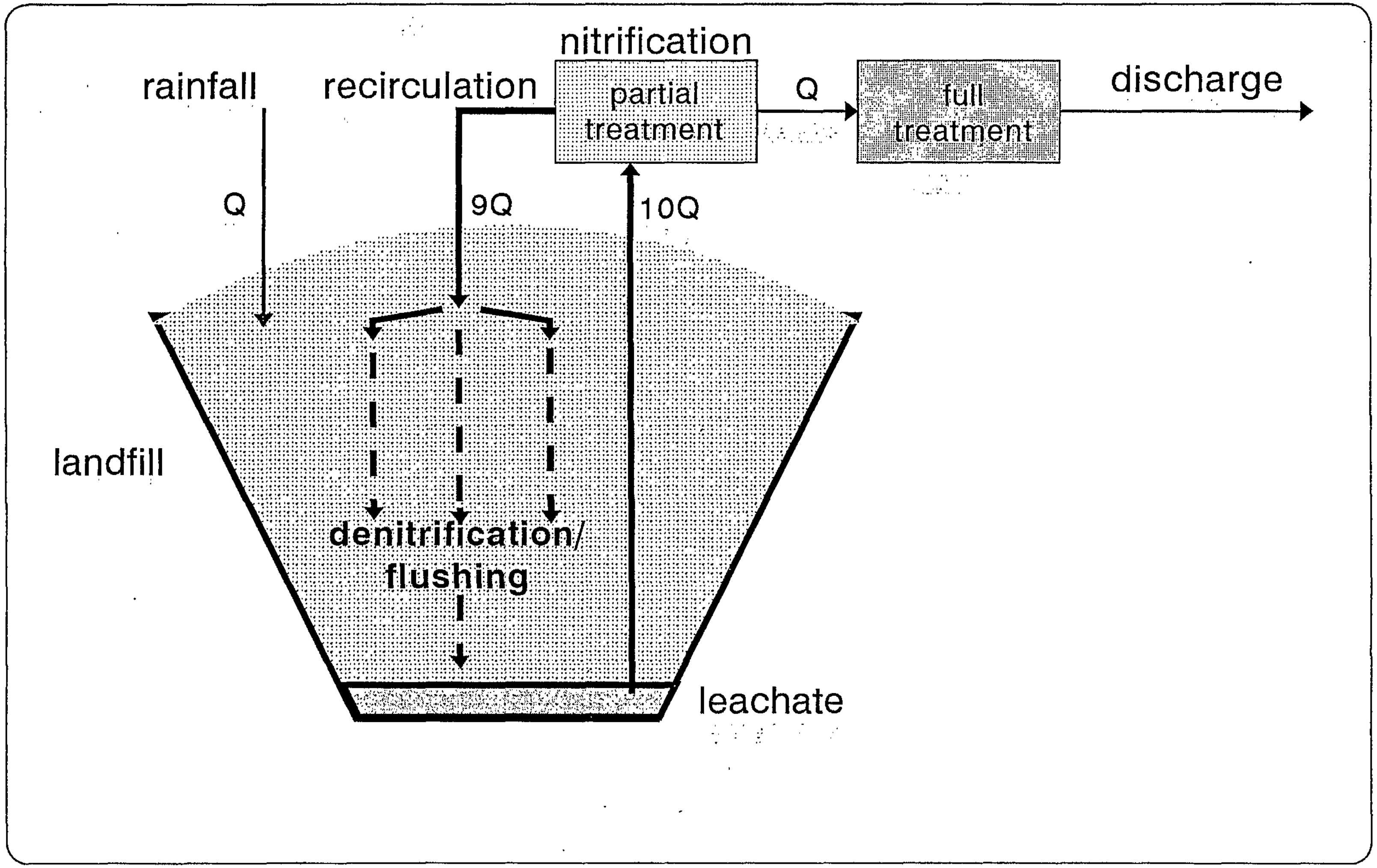


Figure 1. Schematic illustration of enhanced leaching with partial treatment

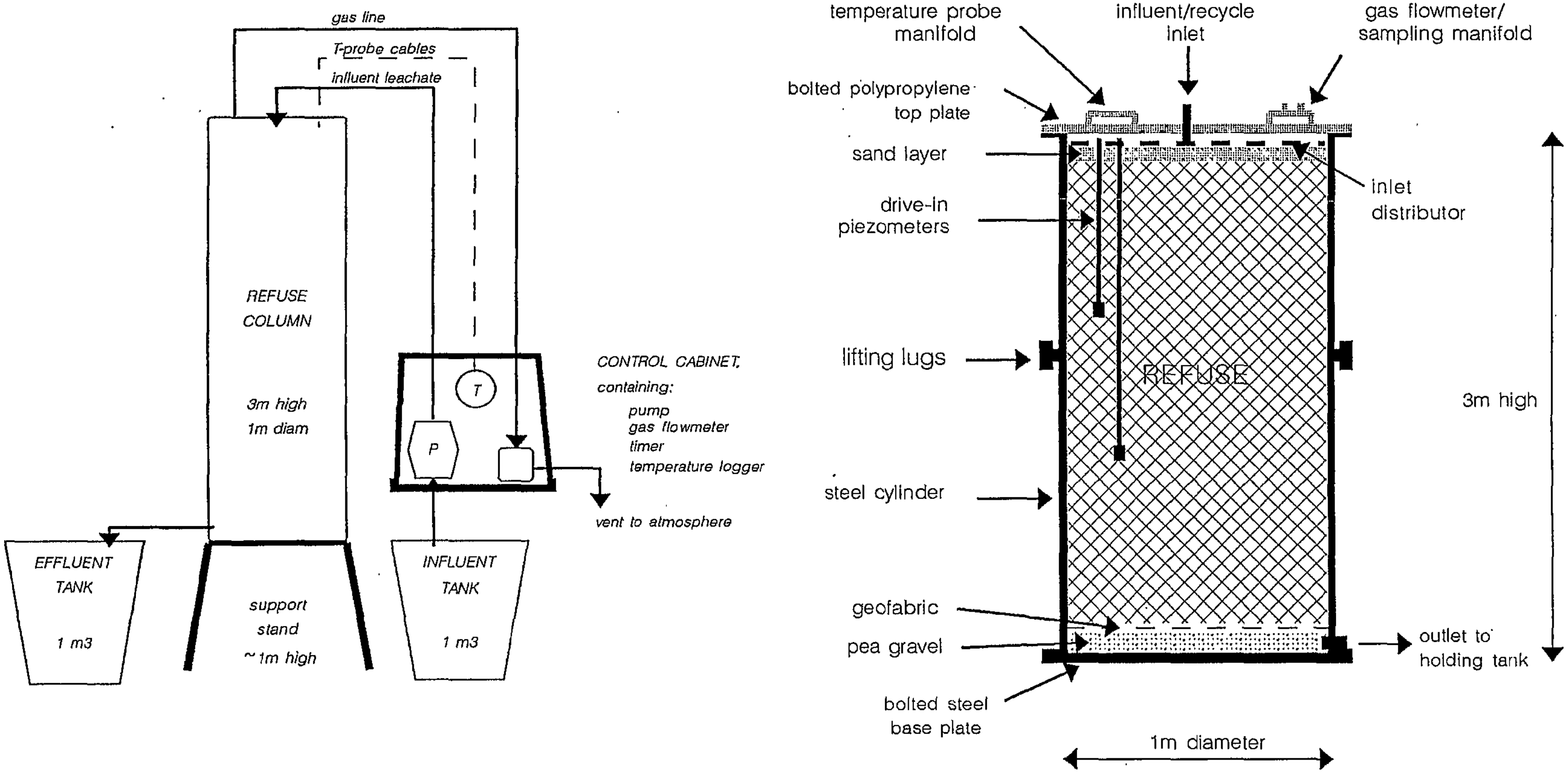


Figure 2. General arrangement and schematic cross-section of plant

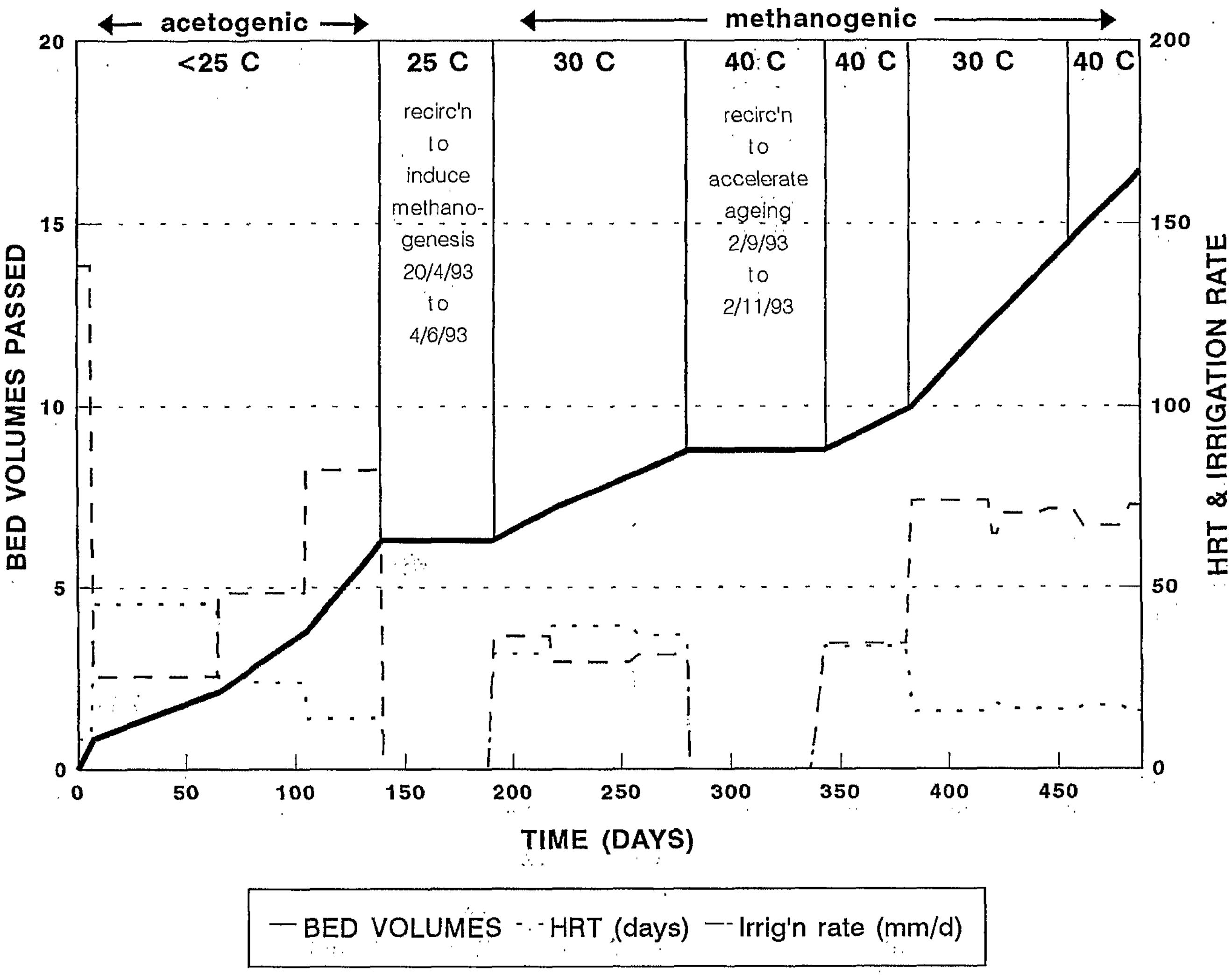


Figure 3. Summary of operating details for young refuse

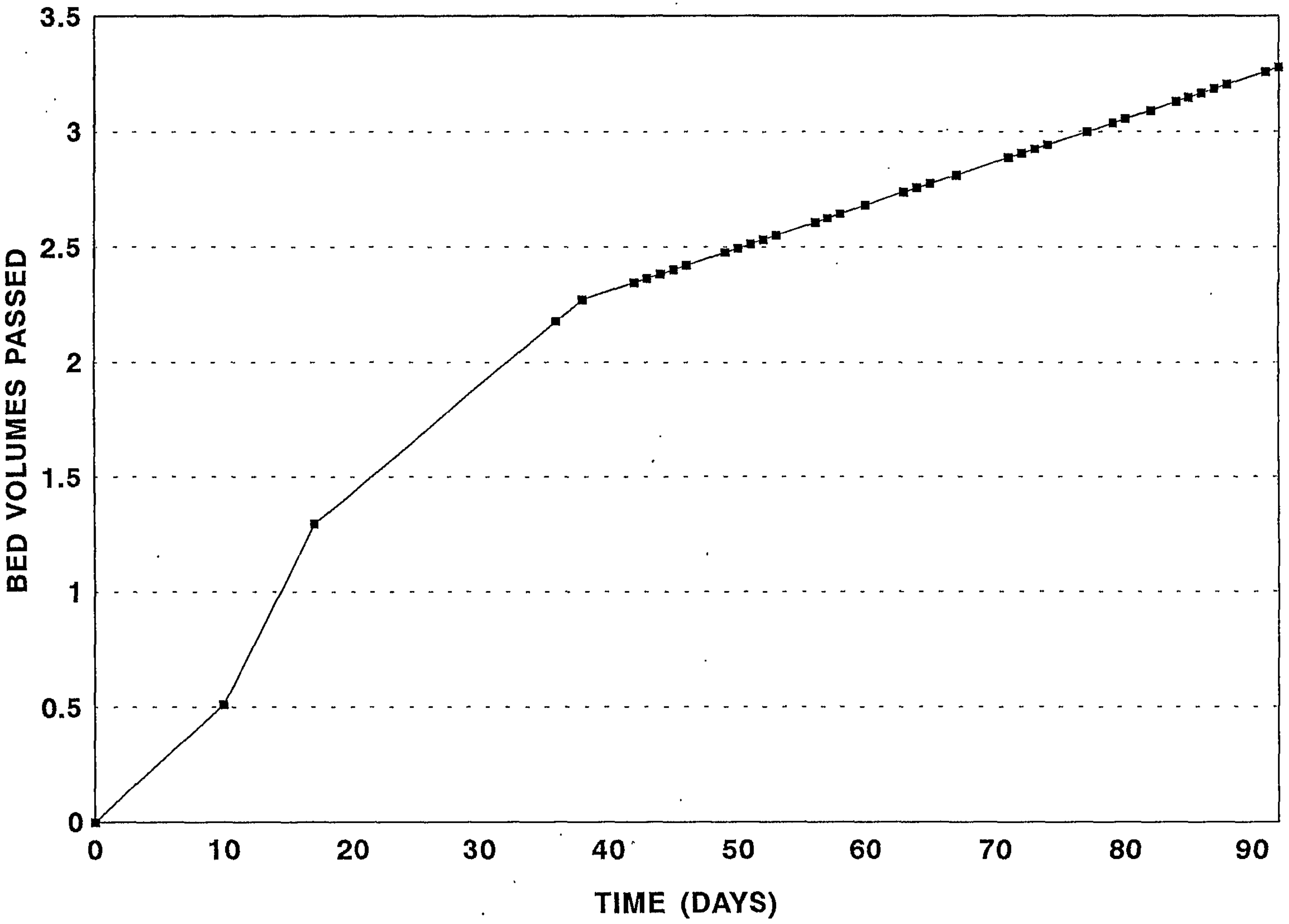


Figure 4. Operational summary, old refuse

Figure 5a. Influent and effluent total oxidised nitrogen, young refuse

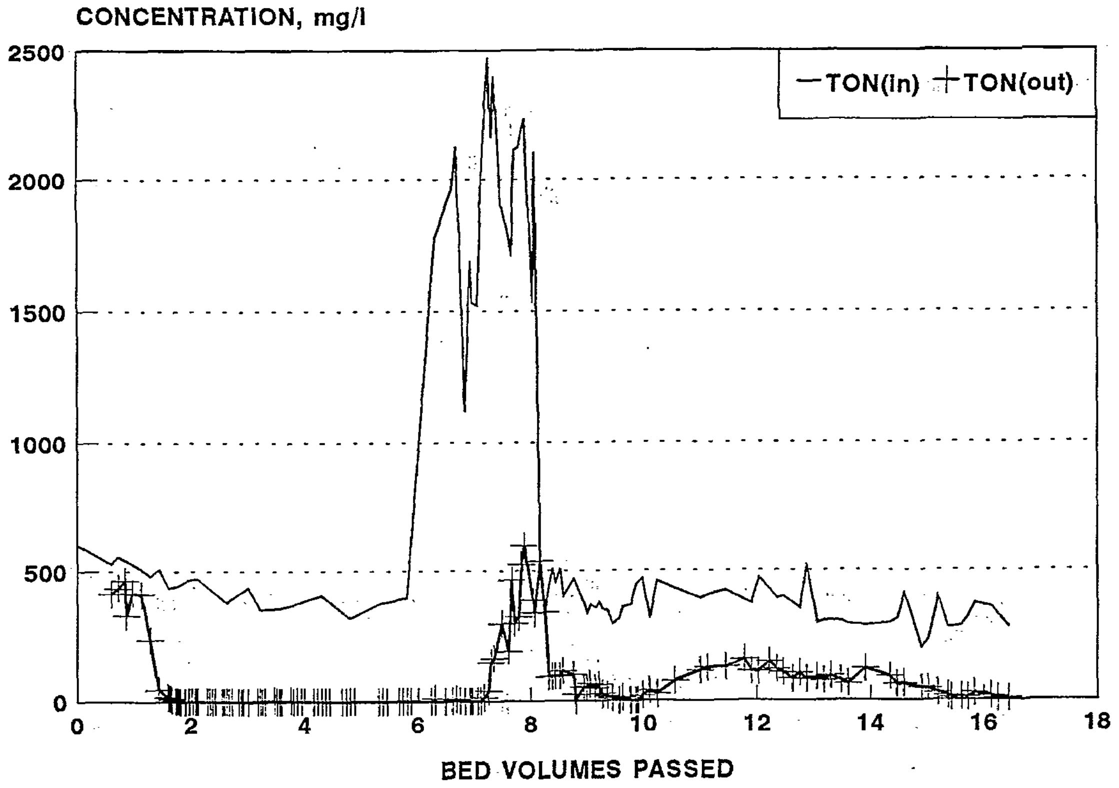


Figure 5b. Influent and effluent total oxidised nitrogen, young refuse

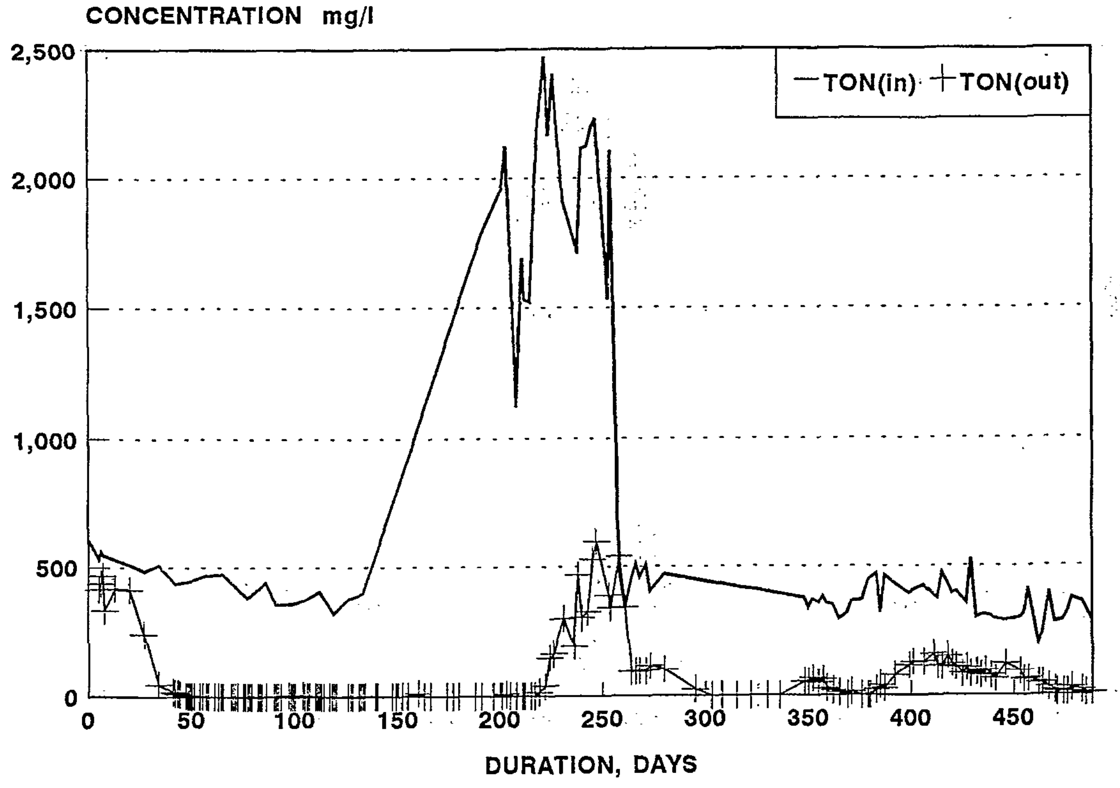


Figure 6a. Influent and effluent TOC during young refuse study

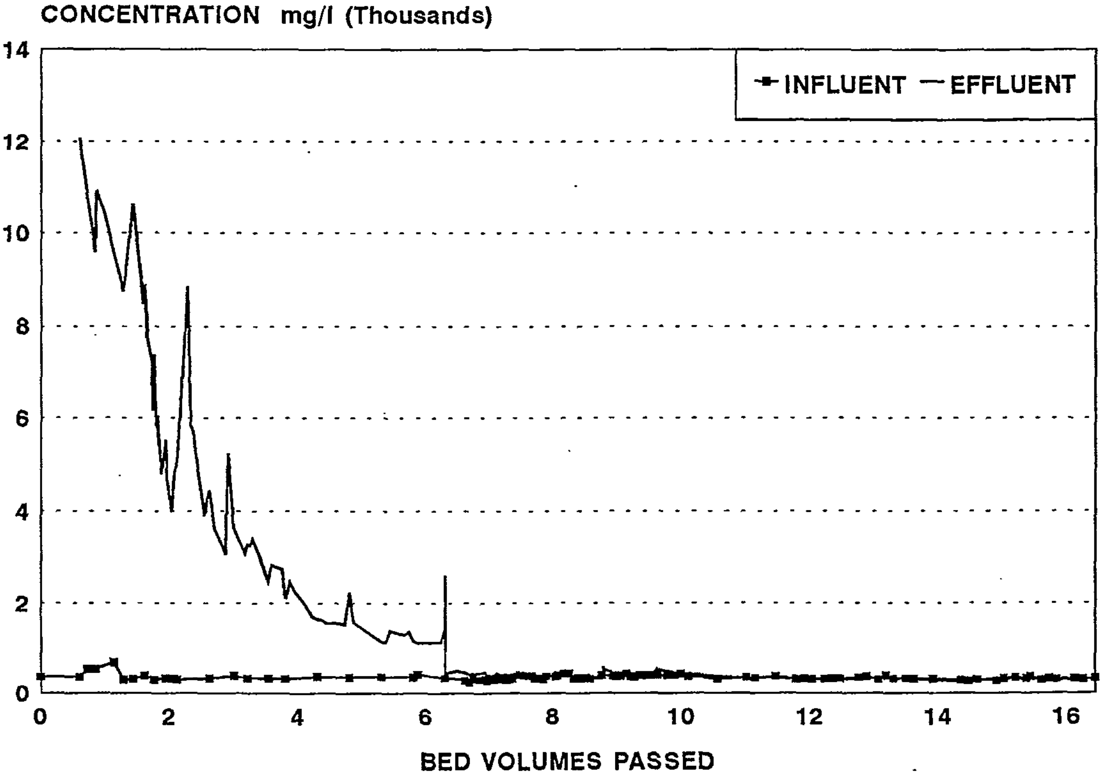


Figure 6b. Influent and effluent TOC during young refuse study

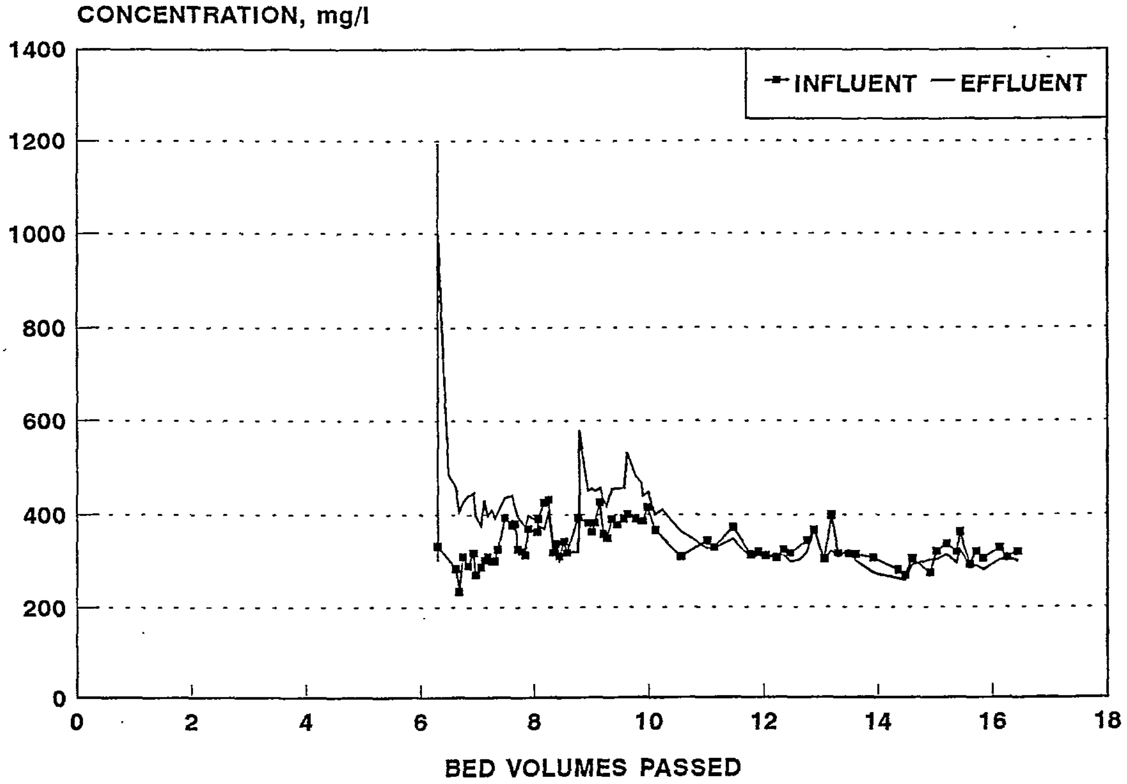


Figure 7a. Influent and effluent BOD during young refuse study

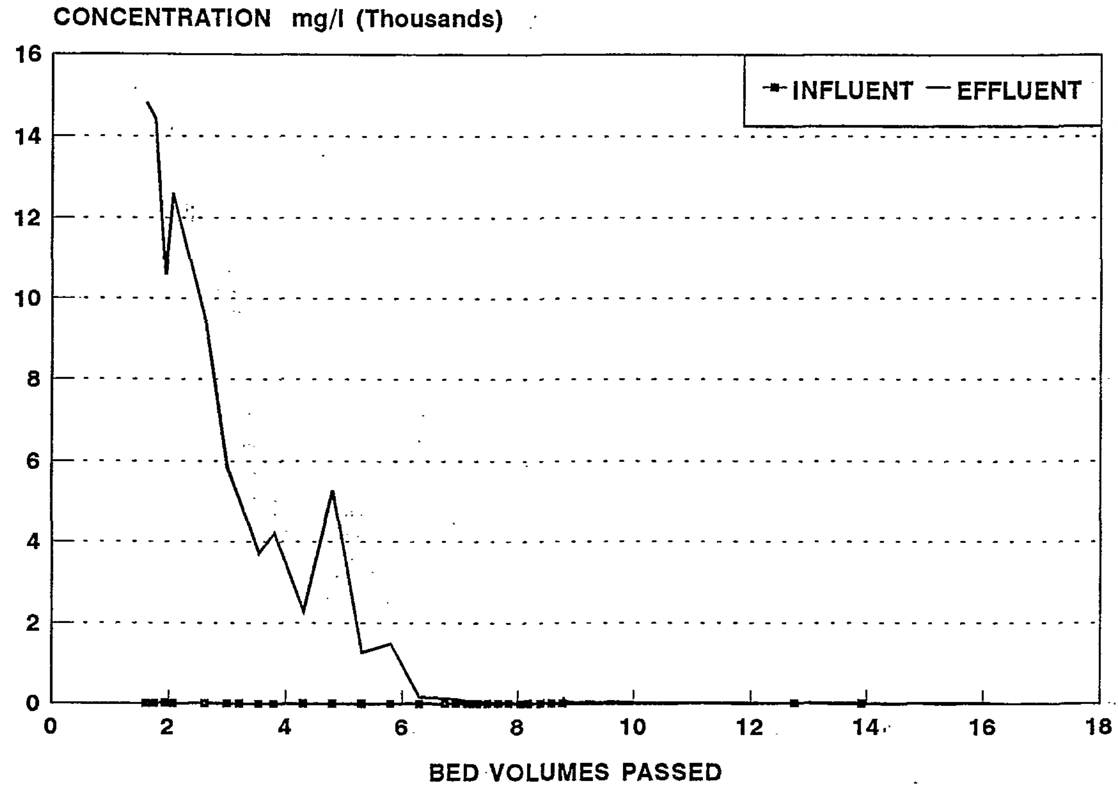


Figure 7b. Influent and effluent BOD during young refuse study (expanded scale)

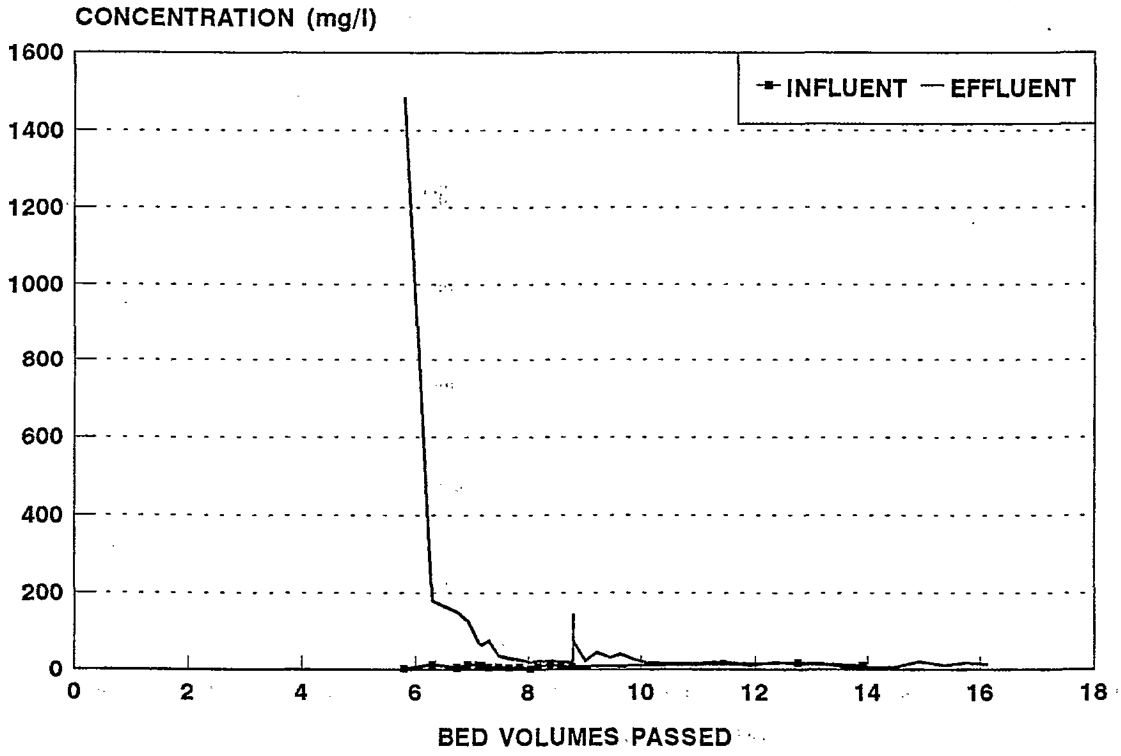


Figure 8a. Effluent pH during young refuse study

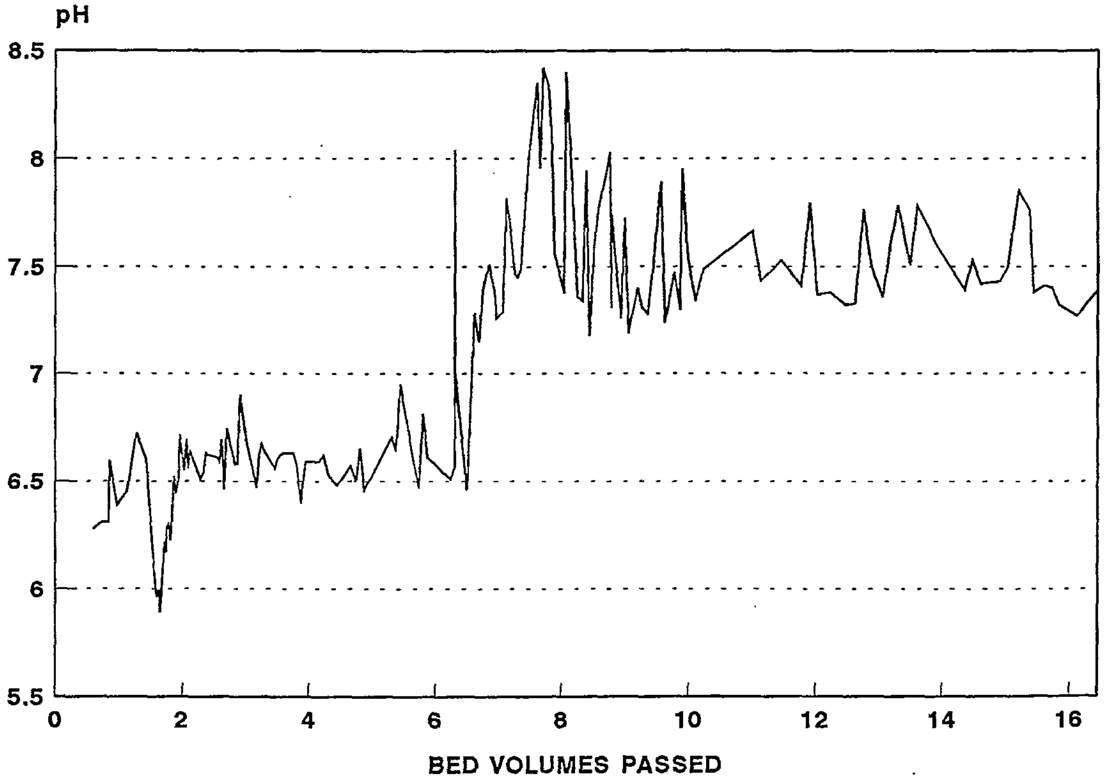


Figure 8b. Effluent pH during young refuse study

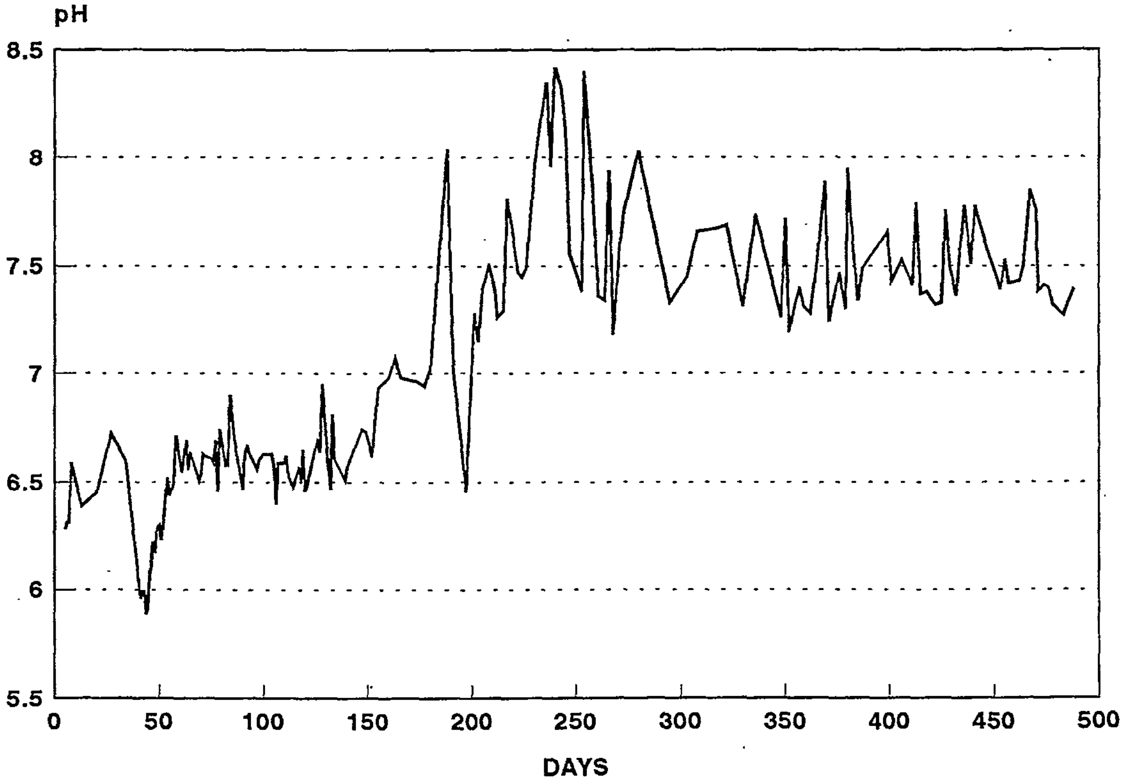


Figure 9a. Oxidised nitrogen removal rate in young refuse

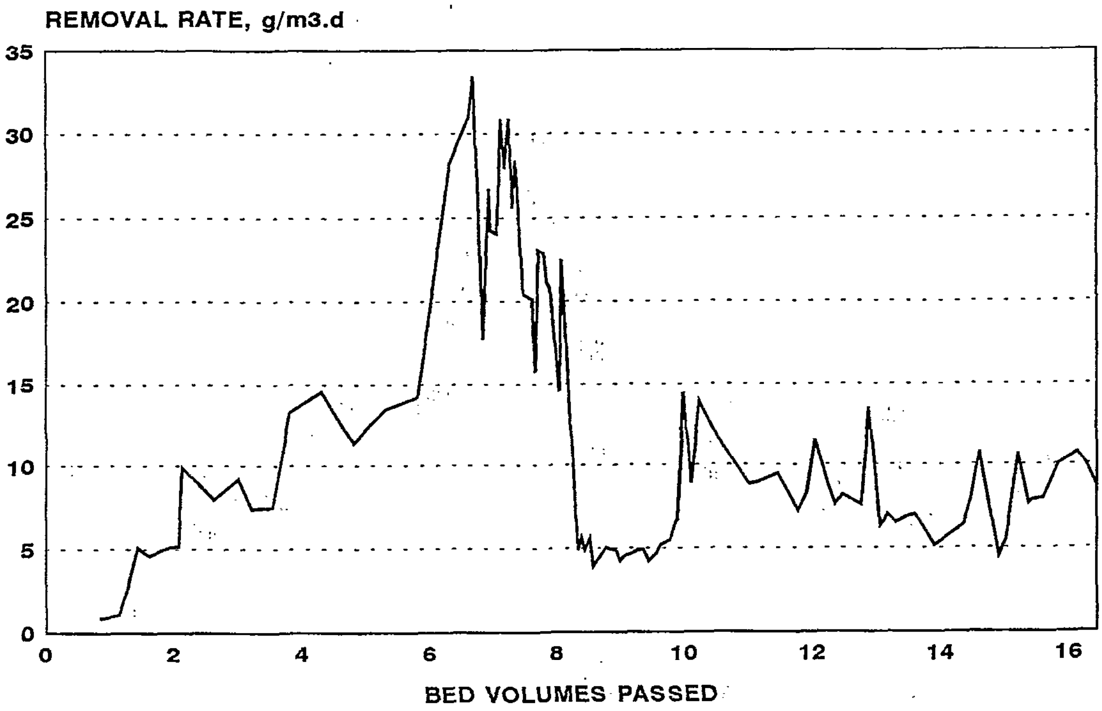


Figure 9b. Oxidised nitrogen removal rate in young refuse

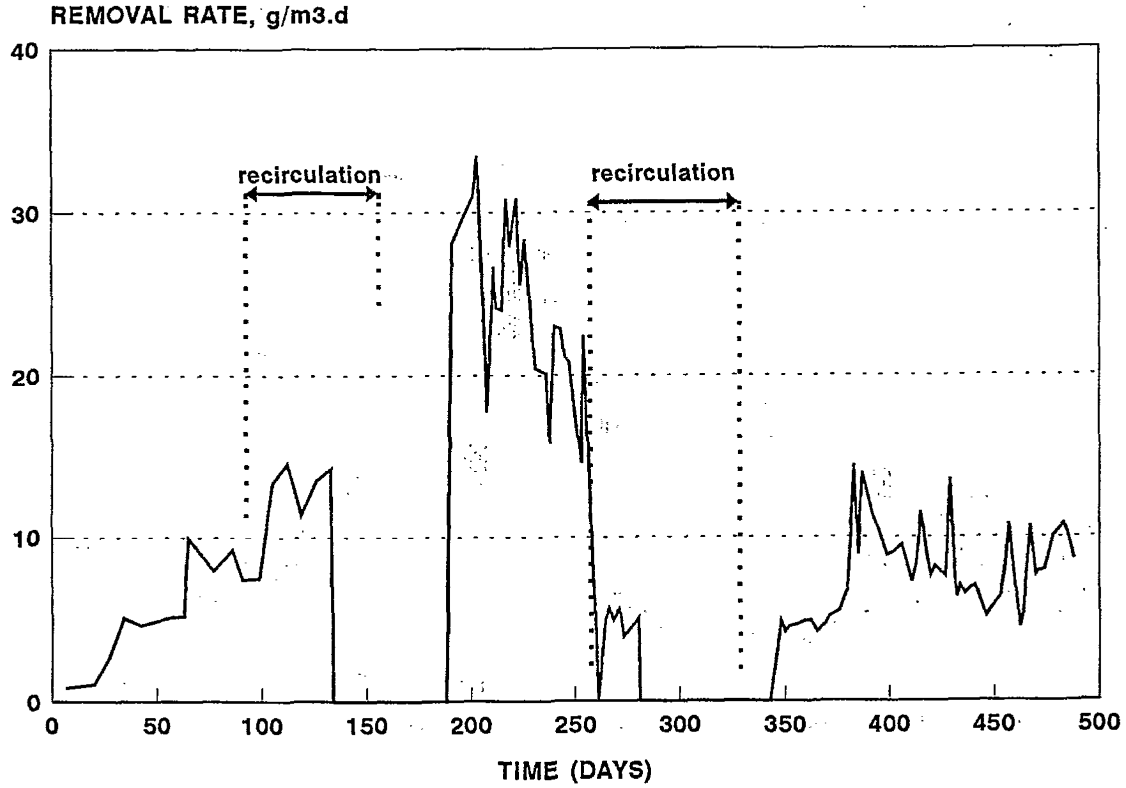


Figure 10a. Ammoniacal nitrogen results, young refuse study

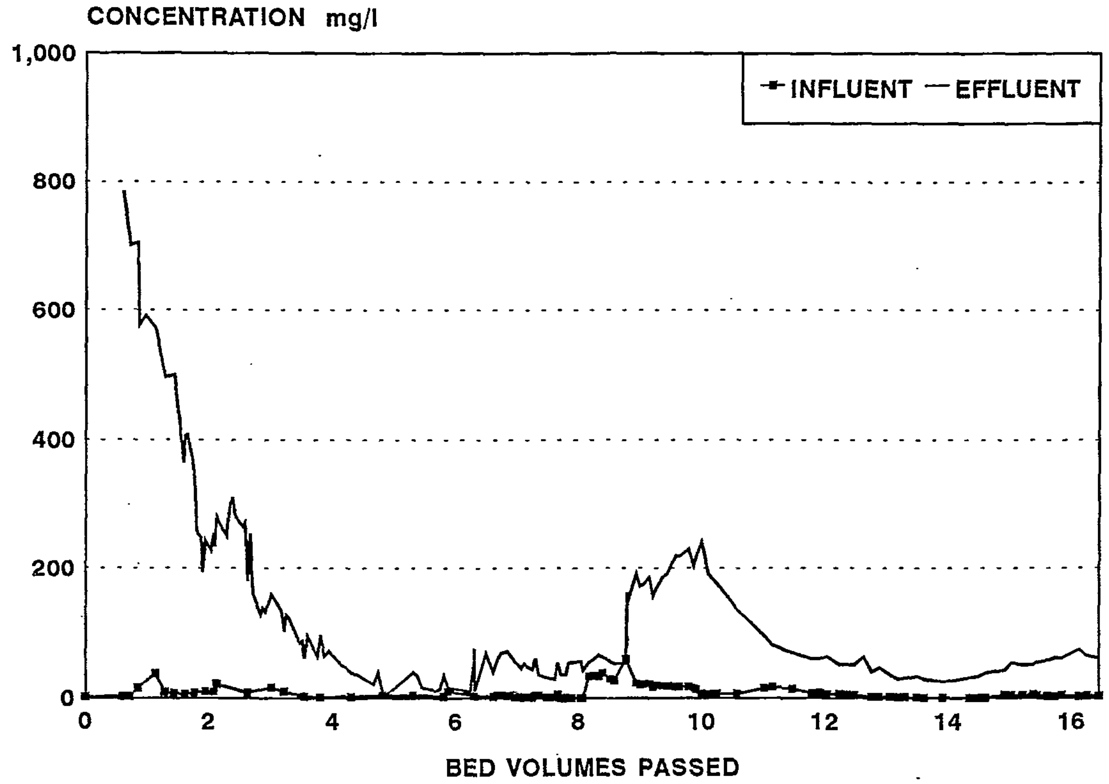


Figure 10b. Ammoniacal nitrogen results, young refuse study

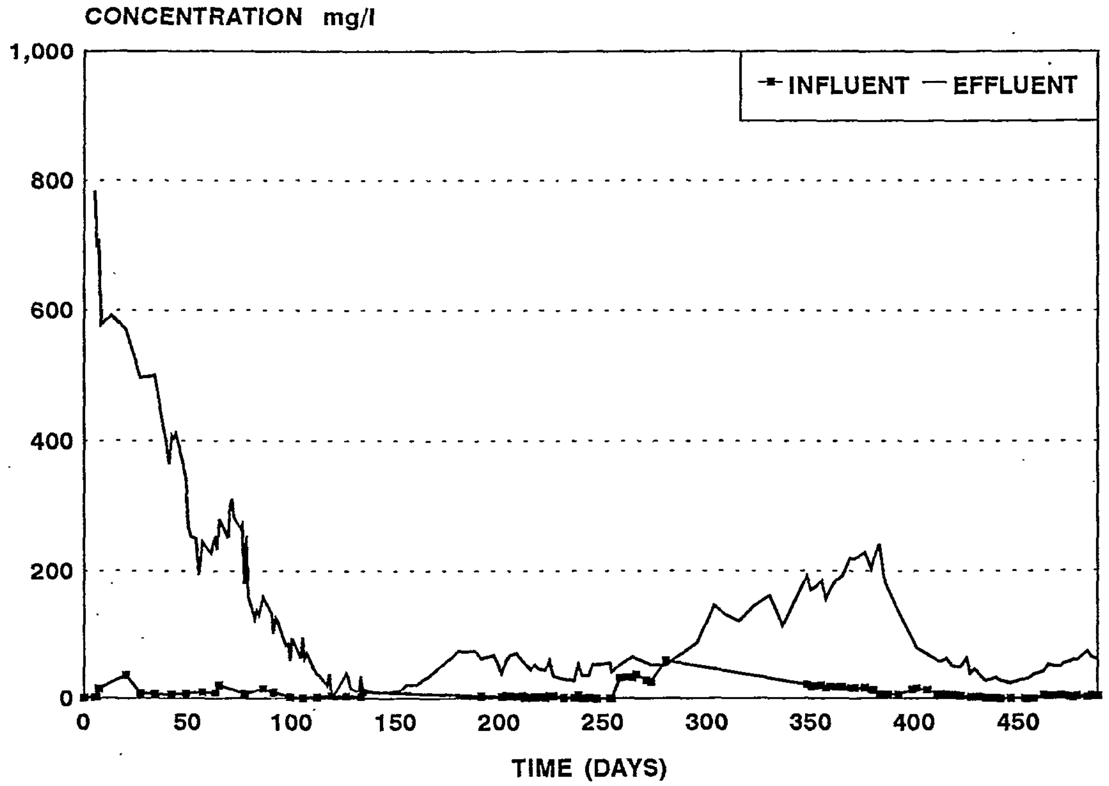


Figure 11. Normalised effluent TOC and NH3-N, young refuse study

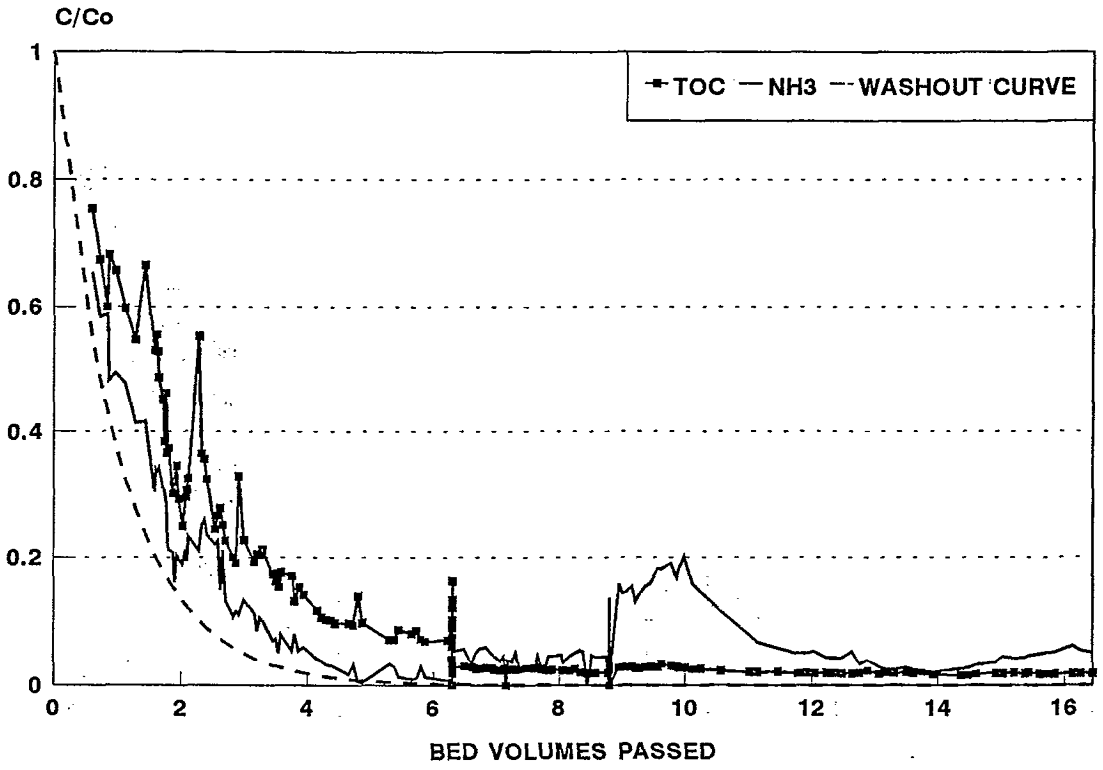


Figure 12. Leaching of potassium tracer during young refuse study

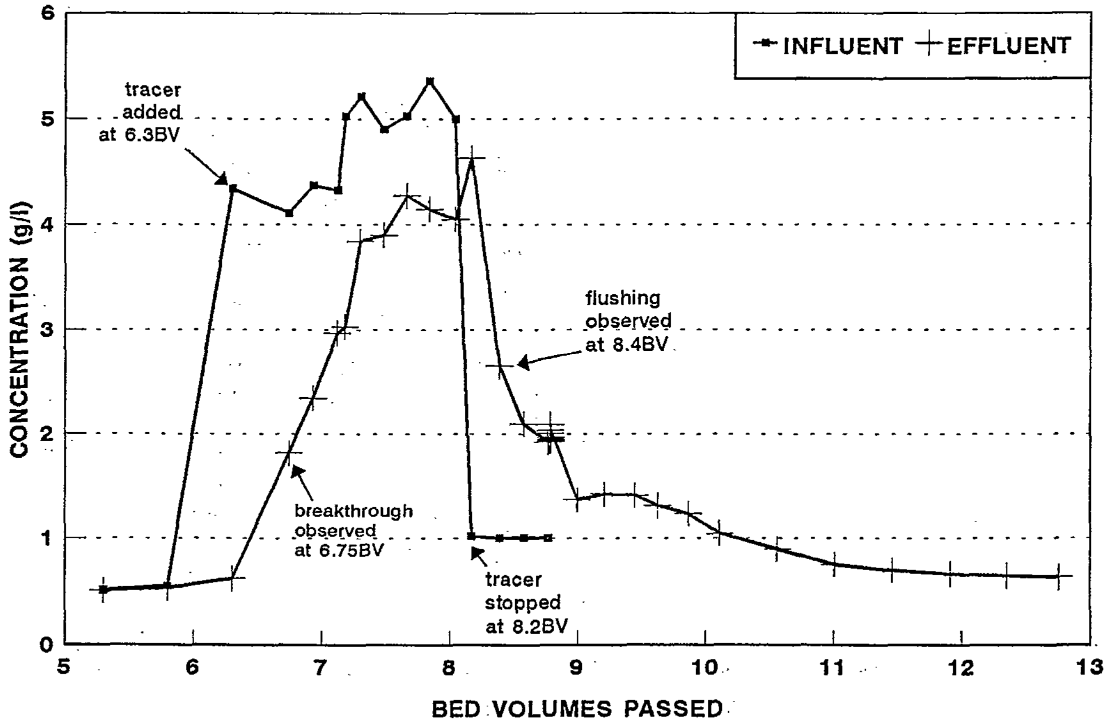


Figure 13a. Influent and effluent chloride results, young refuse study

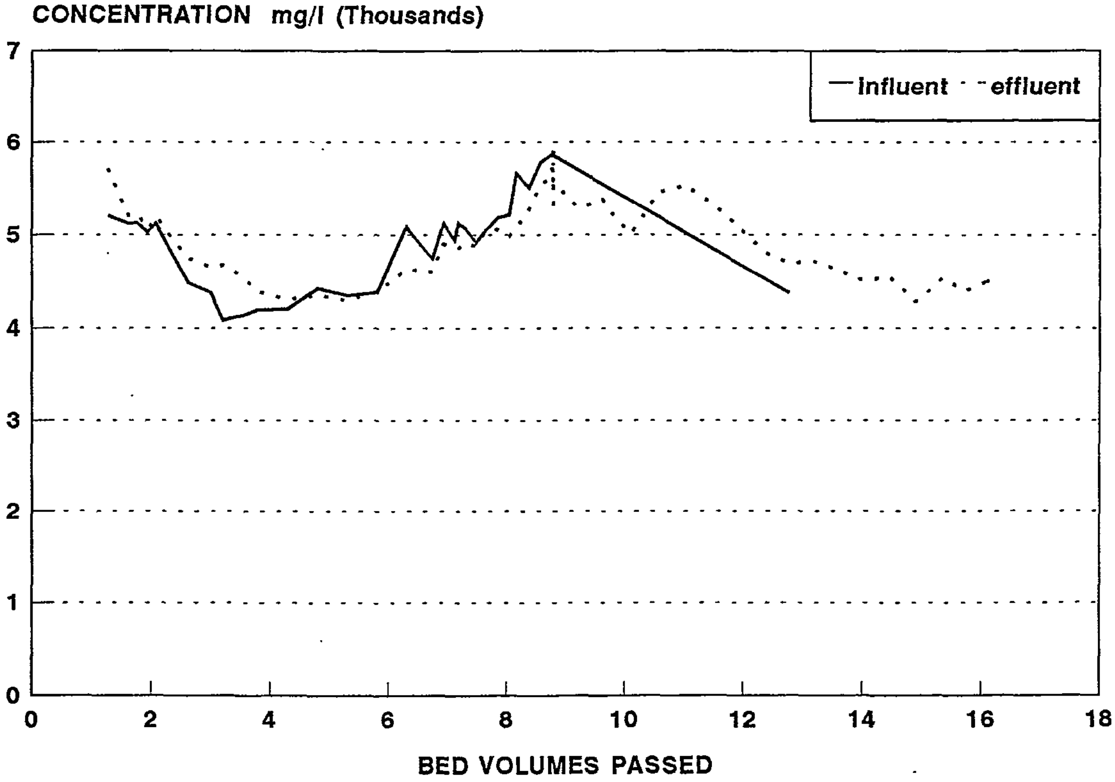


Figure 13b. Influent and effluent chloride results, young refuse study

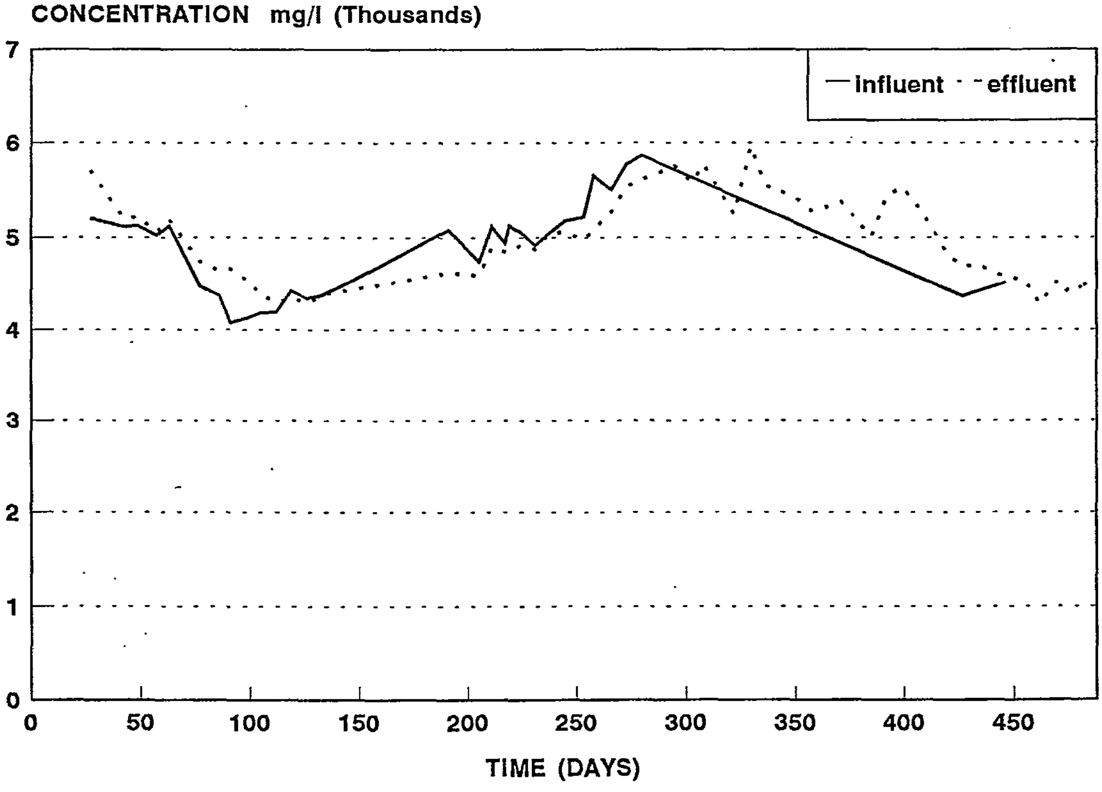


Figure 14. Influent and effluent alkalinity, young refuse study

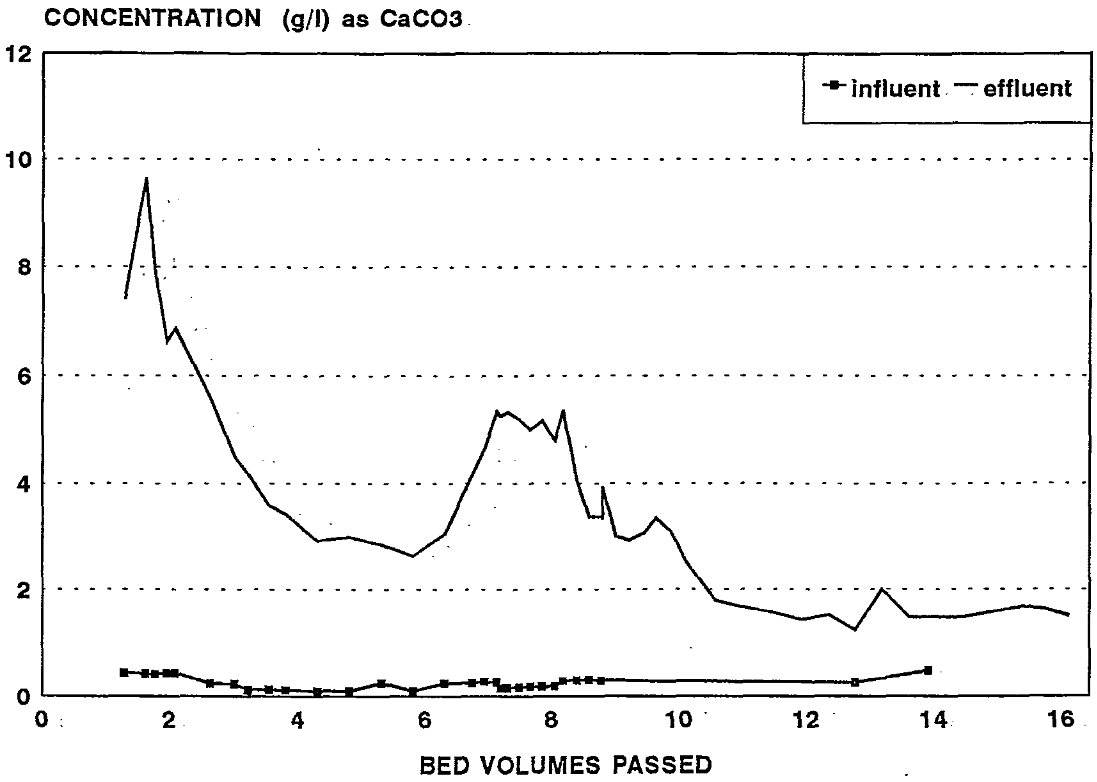


Figure 15. Influent and effluent sulphate results, young refuse study

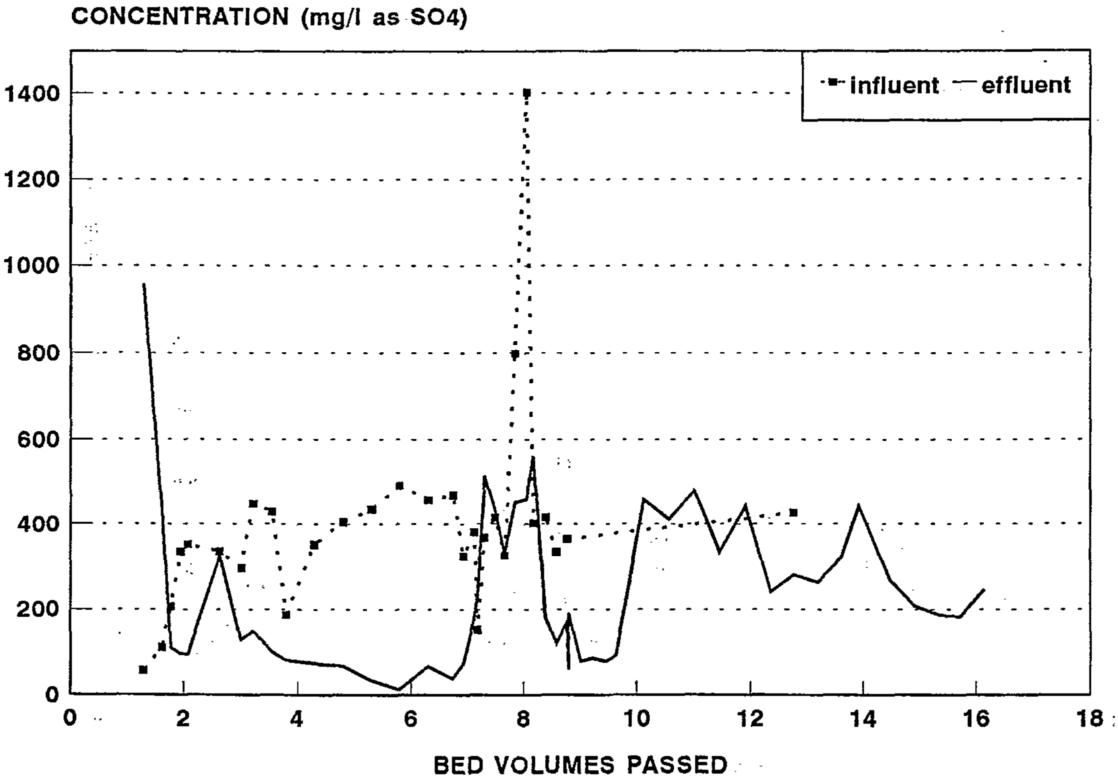


Figure 16. Influent and effluent TOC and TON results, aged refuse

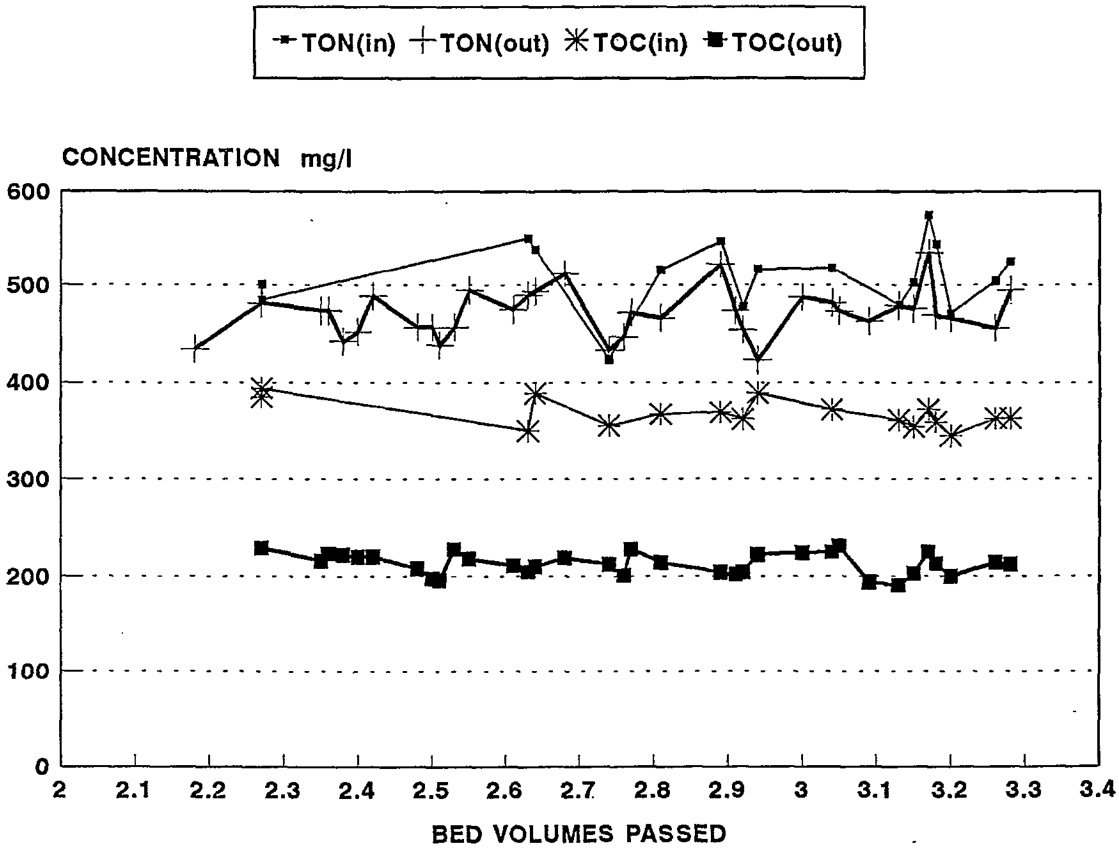


Figure 17. Influent and effluent NH3-N results, aged refuse

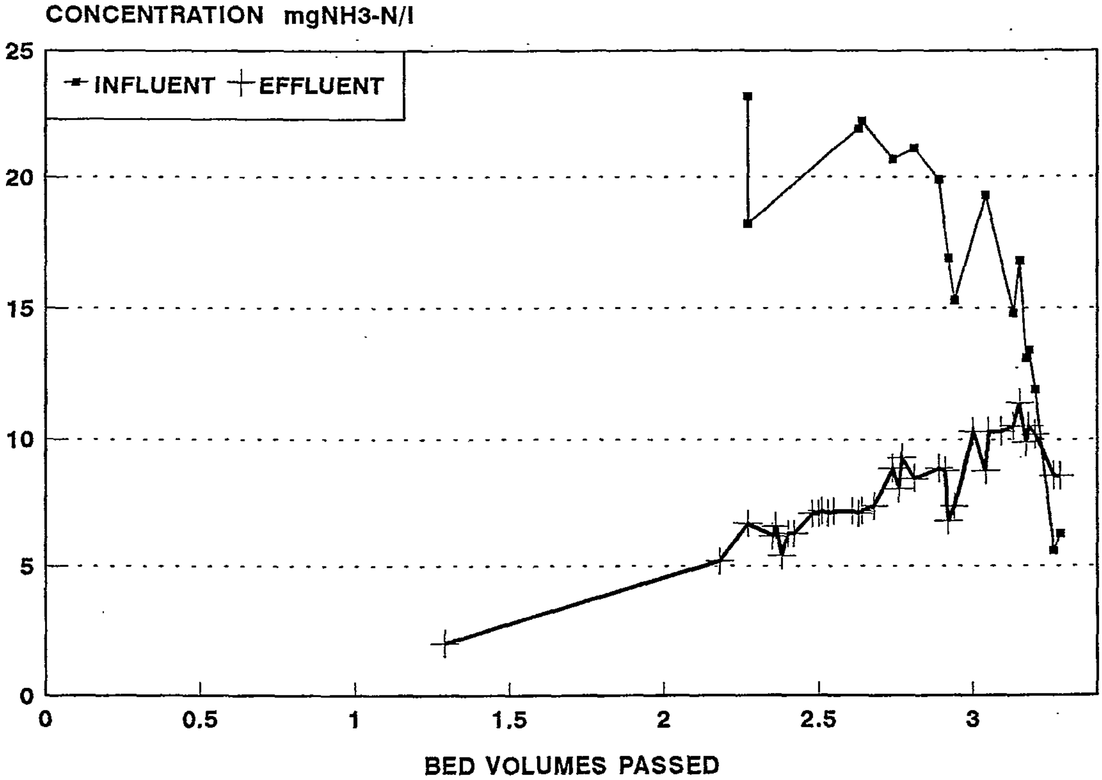


Figure 18. Influent and effluent alkalinity, aged refuse

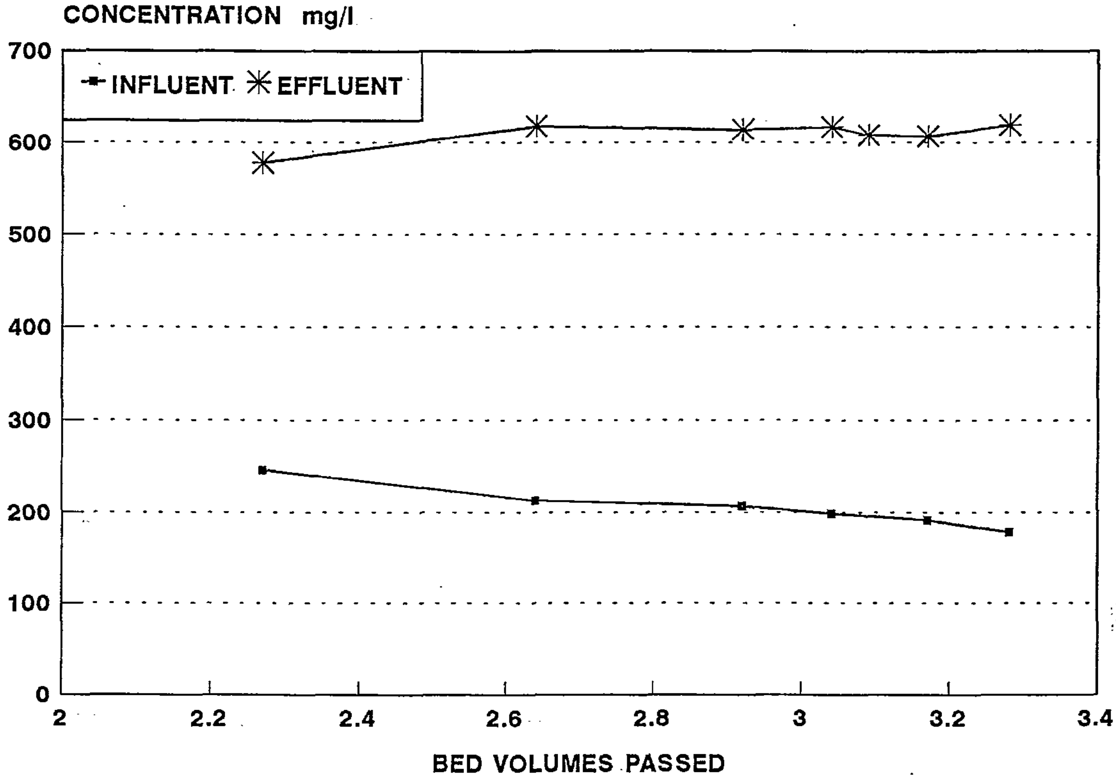
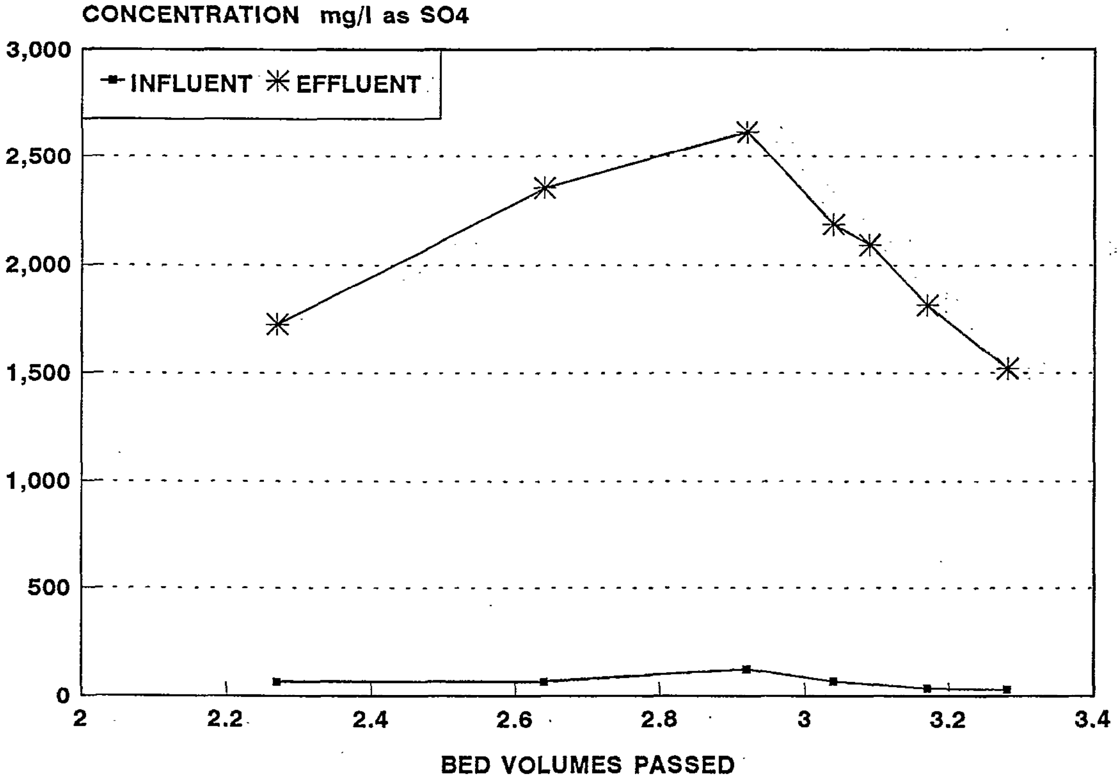


Figure 19. Influent and effluent sulphate, aged refuse



PLATES

1. General arrangement of reactor, without insulation.
2. General arrangement of reactor, with insulation.
3. Leachate distributor in position on top of upper sand layer.
4. Control cabinet and associated equipment.
5. Young refuse batch used in this study, packed into reactor.
6. 'Matured' young refuse emptied from reactor at the end of the study.
7. Old refuse batch prior to use in this study, showing rejects.
8. Ponding and settlement in young refuse.
9. Slime growth on leachate distributor, young refuse.
10. Colour removal from young and old refuse.

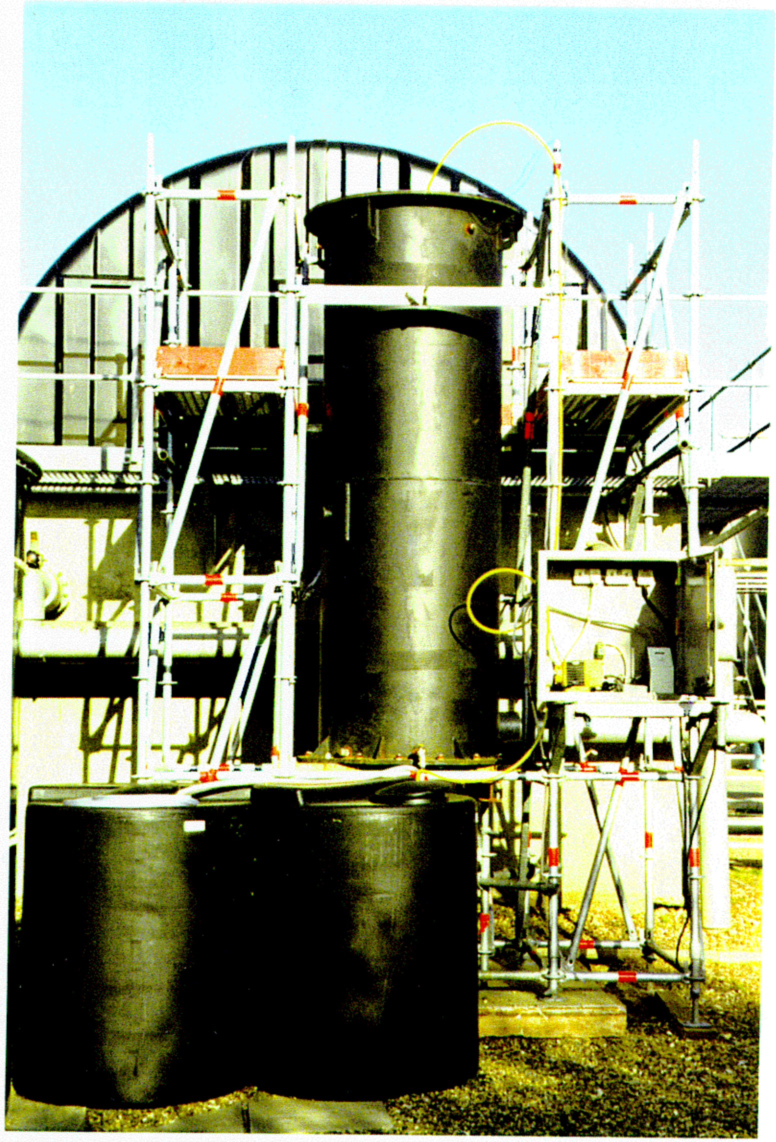


Plate 1. General arrangement of reactor, without insulation

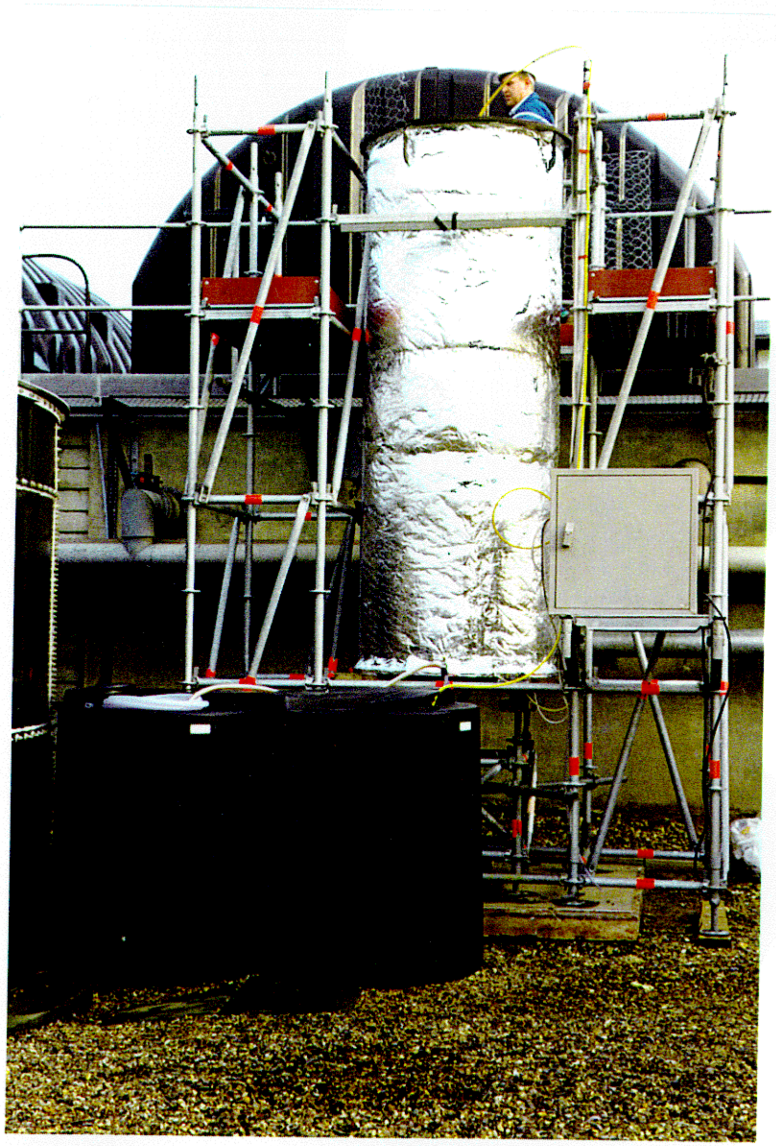


Plate 2. General arrangement of reactor, with trace heating and insulation

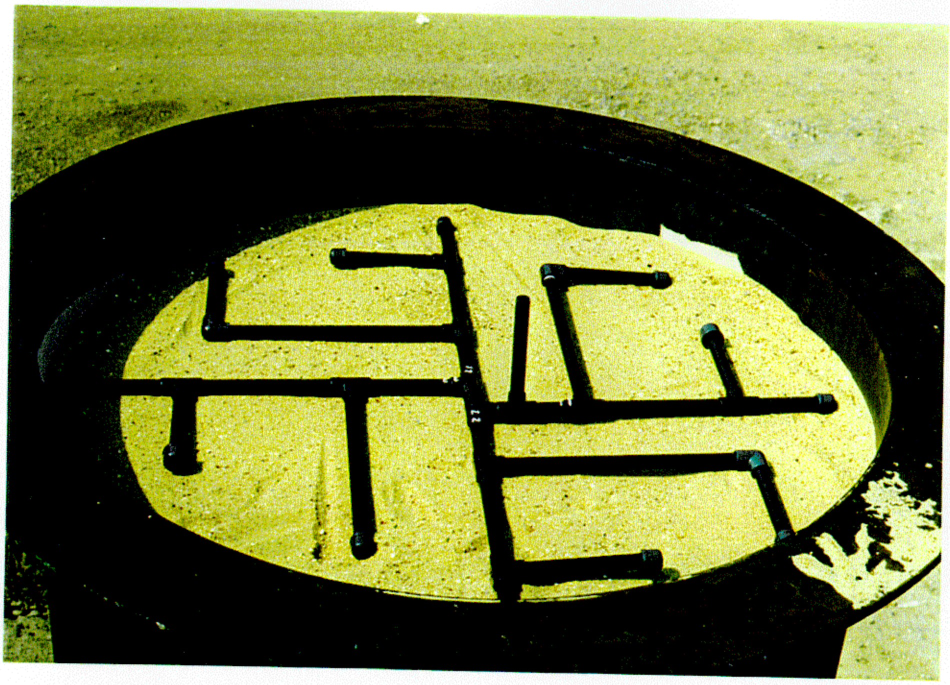


Plate 3. Leachate distributor in position on top of upper sand layer

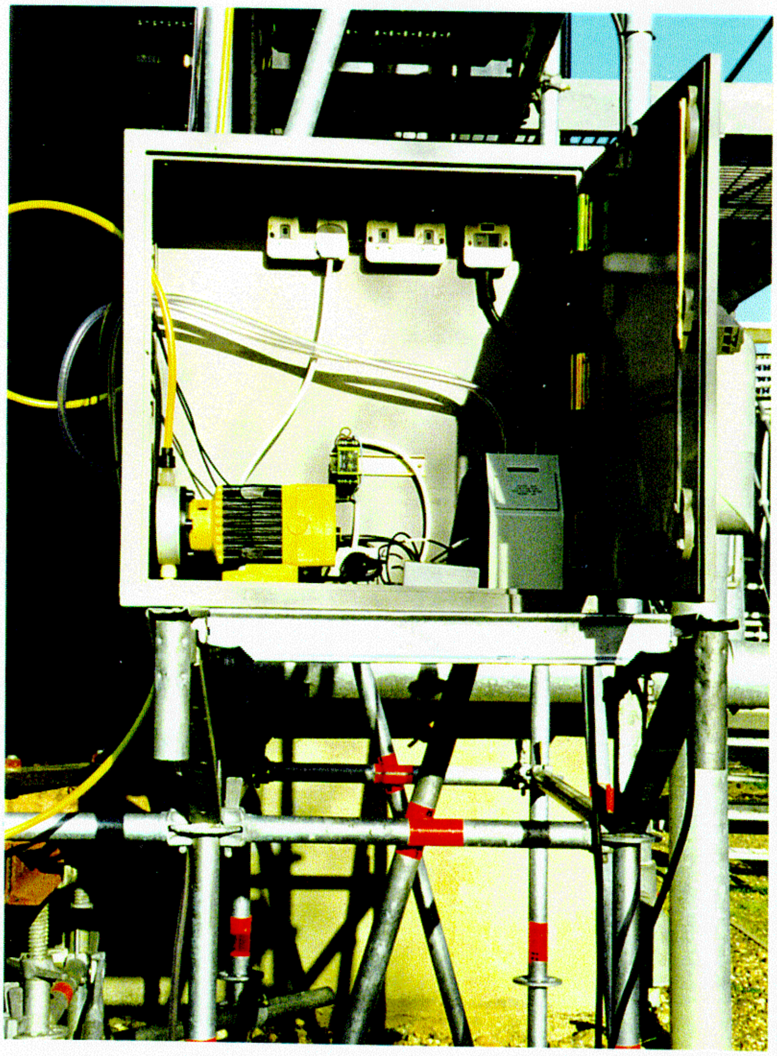


Plate 4. Control cabinet showing pump, timer, temperature logger and gasflow meter

Plate 5. Young refuse batch used in this study, packed into reactor

Plate 6. 'Matured', young refuse emptied from reactor at end of study

Plate 7(a). Old refuse batch, prior to hand-sorting

Plate 7(b). Old refuse as used in the study, showing rejects

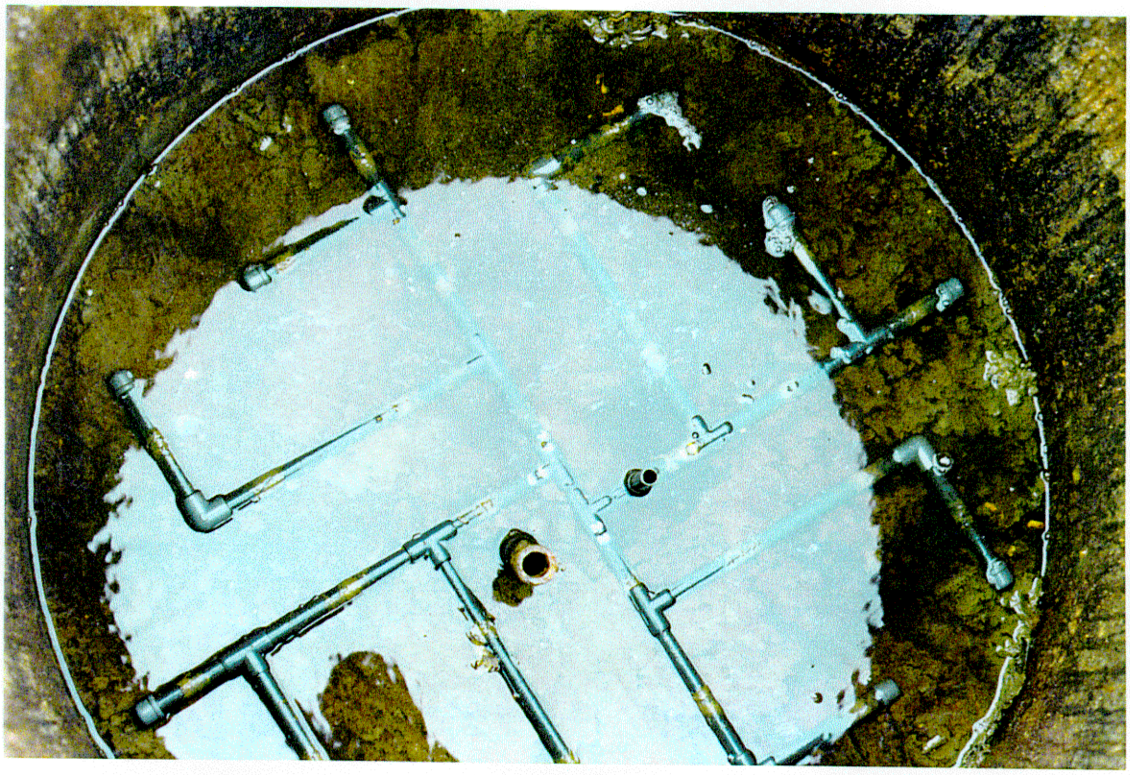


Plate 8(a). Ponding and settlement in young refuse study

Plate 8(b). Ponding and settlement in young refuse study

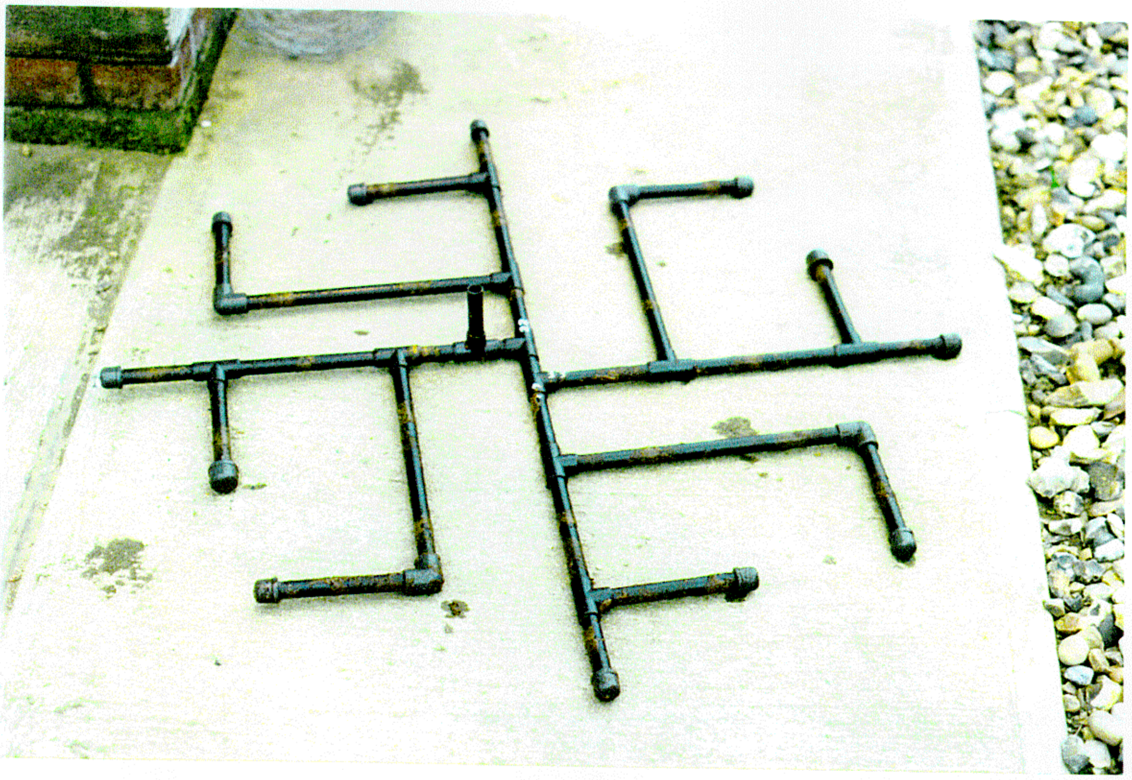


Plate 9(a). Slime growth on leachate distributor, young refuse

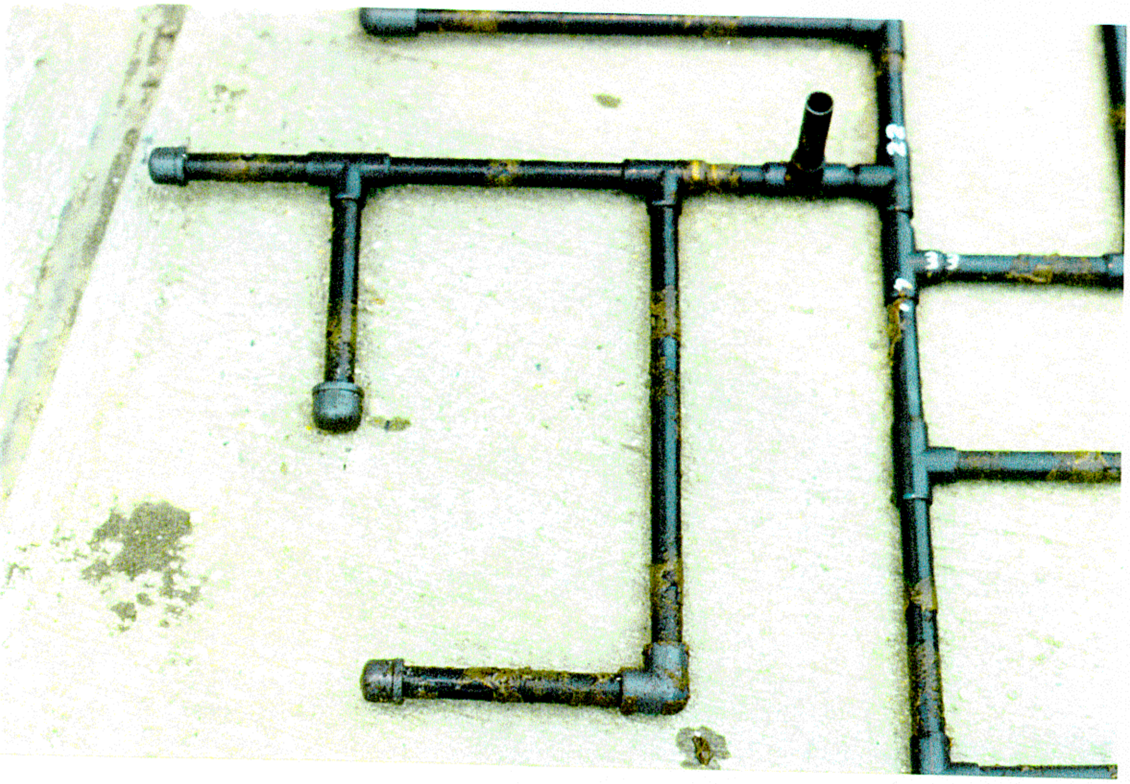


Plate 9(b). Slime growth on leachate distributor, young refuse

Plate 10(a). Colour removal in old refuse study

Plate 10(b). Colour removal at end of young refuse study

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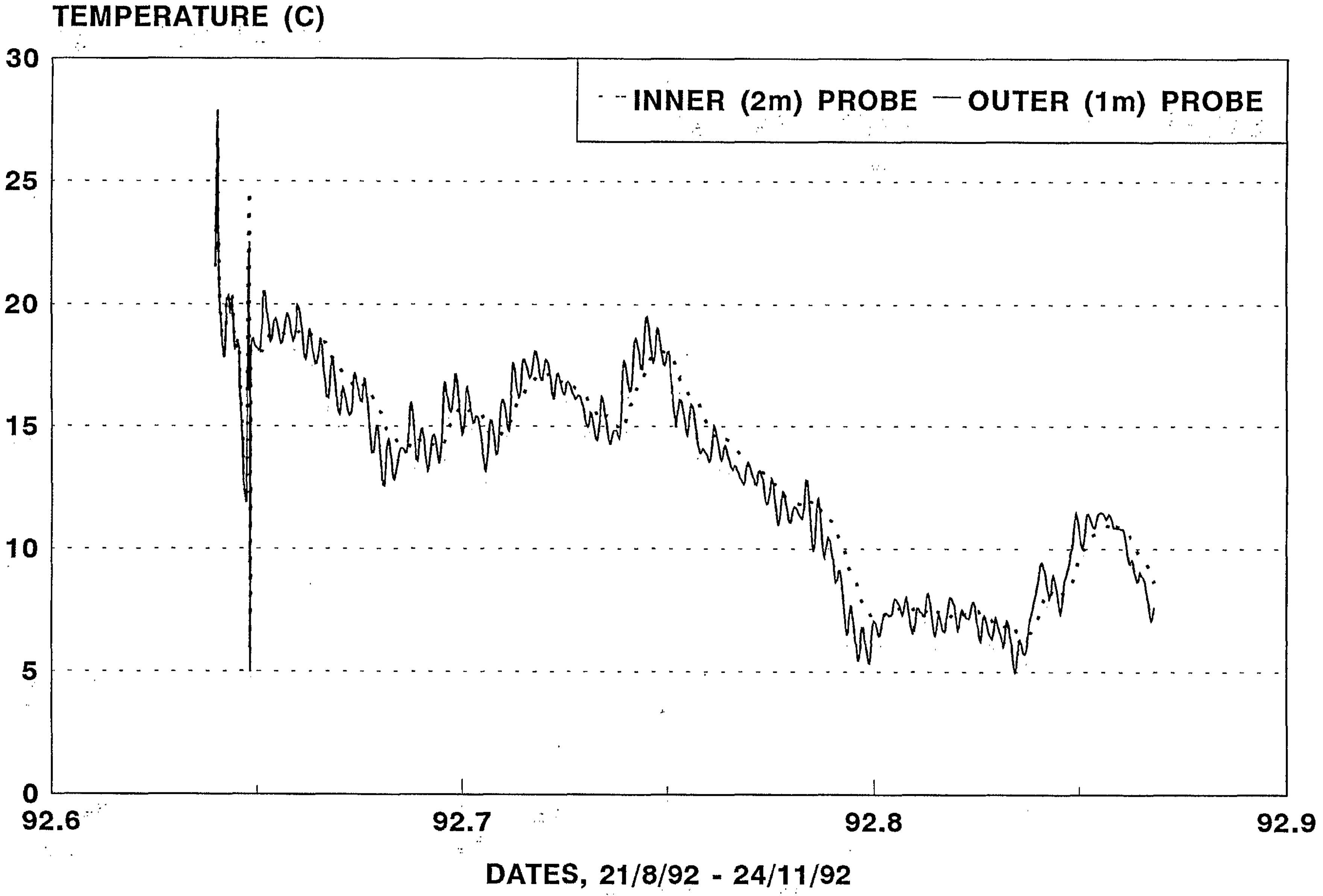
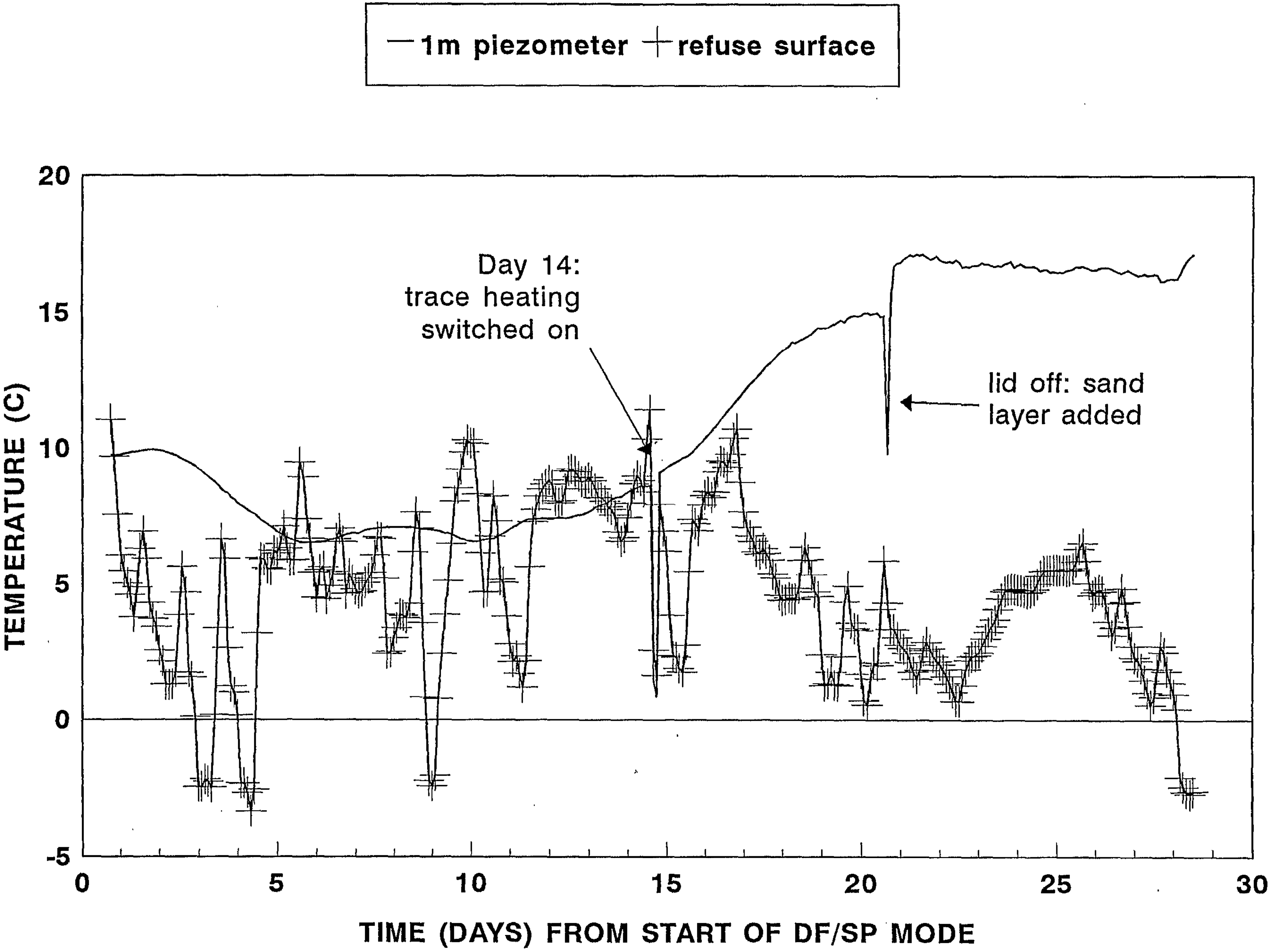
APPENDIX I

TEMPERATURE PROBE RESULTS IN OLD AND YOUNG REFUSE

Temperature probe results in old refuse



Temperature probe results in young refuse



APPENDIX II

YOUNG REFUSE: FLOW DATA AND BASIC CHEMICAL ANALYSES

YOUNG REFUSE: flow data and basic chemical analyses

date	duration	flow	flow	HRT	bed vols	TON		TOC		NH3-N		pH	
	(days)	(l/d)	(mm/d)	(days)	passed	In	Out	In	Out	In	Out	In	Out
25/11/92	0	120	139	8	0.00	603		357		1.4		9.22	
30/11/92	5	120	139	8	0.60	532	416	358	12070	2.5	784	8.77	6.28
01/12/92	6	120	139	8	0.72	558	438	528	10790	2.1	701	8.87	6.31
02/12/92	7	22	25	45	0.84	545	466	529	9589	15.5	705	8.79	6.31
03/12/92	8	22	25	45	0.86		331		10920		578		6.59
08/12/92	13	22	25	45	0.97		418		10510		592		6.39
15/12/92	20	22	25	45	1.13	509	412	680	9567	38.0	572	7.84	6.45
22/12/92	27	22	25	45	1.28	484	239	298	8748	8.6	497	7.75	6.72
29/12/92	34	22	25	45	1.43	508	46	310	10640	7.0	500	7.34	6.60
05/01/93	41	22	25	45	1.59		17.8		8478		366		5.96
06/01/93	42	22	25	45	1.61	436	14.9	381	8878	5.9	408	7.77	5.99
07/01/93	43	22	25	45	1.63		13		8455		404		5.99
08/01/93	44	22	25	45	1.65		8.6		7770		410		5.89
11/01/93	47	22	25	45	1.72		3.2		7214		373		6.22
12/01/93	48	22	25	45	1.74		2.3		6144				6.17
13/01/93	49	22	25	45	1.76	446	2	300	7376	8.1	342	7.73	6.29
14/01/93	50	22	25	45	1.79		1.4		5856		268		6.30
15/01/93	51	22	25	45	1.81		0.8		5981		254		6.23
18/01/93	54	22	25	45	1.87		0.1		4816		249		6.52
19/01/93	55	22	25	45	1.90		0.1		5120		194		6.44
21/01/93	57	22	25	45	1.94	468	0.8	324	5520	10.3	244	7.77	6.50
22/01/93	58	22	25	45	1.96		0.1		4685				6.71
25/01/93	61	22	25	45	2.03		0.1		3991		228		6.55
27/01/93	63	22	25	45	2.07	471	0.1	308	4731	9.4	254	8.17	6.69
28/01/93	64	22	25	45	2.09		0.1		4908		234		6.56
29/01/93	65	42	48	24	2.12	473	0.1	293	5194	21.4	279	7.07	6.64
02/02/93	69	42	48	24	2.28		0.1		8838		252		6.51
03/02/93	70	42	48	24	2.33		0.1		5835		299		6.54
04/02/93	71	42	48	24	2.37		0.1		5700		310		6.63
05/02/93	72	42	48	24	2.41		0.1		5170		282		6.62
08/02/93	75	42	48	24	2.54		0.1		3900		265		6.61
09/02/93	76	42	48	24	2.58		0.1		4252		271		6.59
10/02/93	77	42	48	24	2.62	381	0.1	322	4440	7.7	180	7.28	6.69
11/02/93	78	42	48	24	2.66		0.1				253		6.46
12/02/93	79	42	48	24	2.70		0.3		3615		160		6.74
15/02/93	82	42	48	24	2.83		0.1		3210		128		6.58
16/02/93	83	42	48	24	2.87		0.2		3060		139		6.58
17/02/93	84	42	48	24	2.91		0.1		5240		133		6.90
19/02/93	86	42	48	24	3.00	440	0.1	375	3633	16.0	159	7.5	6.70
23/02/93	90	42	48	24	3.17		0.1		3093		135		6.47
24/02/93	91	42	48	24	3.21	354	0.1	331	3283	9.6	103	6.91	6.62
25/02/93	92	42	48	24	3.25		0.1		3261		127		6.67
26/02/93	93	42	48	24	3.29		0.1		3388		122		6.64
02/03/93	97	42	48	24	3.46		5.7		2791		84		6.56
03/03/93	98	42	48	24	3.50		0.1		2616		87		6.60

YOUNG REFUSE: flow data and basic chemical analyses

date	duration	flow	flow	HRT	bed vols	TON		TOC		NH3-N		pH	
	(days)	(l/d)	(mm/d)	(days)	passed	In	Out	In	Out	In	Out	In	Out
04/03/93	99	42	48	24	3.54	358	0.1	323	2476	2.4	61	7.1	6.62
05/03/93	100	42	48	24	3.59		0.1		2827		95		6.63
09/03/93	104	42	48	24	3.75		4.1		2739		65		6.63
10/03/93	105	72	83	14	3.80	372	0.1	316	2098	1.2	96	7.4	6.58
11/03/93	106	72	83	14	3.87		0.1		2453		65		6.40
12/03/93	107	72	83	14	3.94		0.1		2264		72		6.59
15/03/93	110	72	83	14	4.15		0.1		1872		50		6.59
16/03/93	111	72	83	14	4.22		0.1		1702		46		6.62
17/03/93	112	72	83	14	4.30	407	0.2	363	1646	2.1	38.9	7.23	6.53
18/03/93	113	72	83	14	4.37		0.1		1629		37.4		6.50
19/03/93	114	72	83	14	4.44		0.1		1559		33.6		6.48
22/03/93	117	72	83	14	4.65		0.1		1555		21.1		6.57
23/03/93	118	72	83	14	4.73		0.7		1524		38.9		6.50
24/03/93	119	72	83	14	4.80	319	0.1	353	2232	4.0	8.1	6.8	6.65
25/03/93	120	72	83	14	4.87		0.1		1568		5.3		6.46
31/03/93	126	72	83	14	5.30	377	0.4	358	1143	4.2	40.4	7.65	6.7
01/04/93	127	72	83	14	5.37		0.5		1147		34.8		6.64
02/04/93	128	72	83	14	5.44		0.1		1388		16.1		6.95
05/04/93	131	72	83	14	5.66		0.4		1297		11.3		6.57
06/04/93	132	72	83	14	5.73		0.1		1368		14		6.47
07/04/93	133	72	83	14	5.80	398	0.1	354	1161	2.9	34.7	6.82	6.81
08/04/93	134	72	83	14	5.87		0.1	411	1110	10.1	15.7	6.54	6.61
13/04/93	139	72	83	14	6.23		0.2		1133		9.8		6.51
14/04/93	140	0	0	ERR	6.30		0.1		1441		10.4		6.57
19/04/93	145	0	0	ERR	6.30								
20/04/93	146	0	0	ERR	6.30								
21/04/93	147	0	0	ERR	6.30		0.1		1618		10.2		6.74
23/04/93	149	0	0	ERR	6.30		0.1		1939		11		6.73
26/04/93	152	0	0	ERR	6.30		0.1		2598		13.3		6.62
29/04/93	155	0	0	ERR	6.30		0.5		2118		21.9		6.93
04/05/93	160	0	0	ERR	6.30		11.8		1194		22.2		6.98
07/05/93	163	0	0	ERR	6.30		0.1		976		30.8		7.07
10/05/93	166	0	0	ERR	6.30		0.1		1003		36		6.98
18/05/93	174	0	0	ERR	6.30		0.1		590		58.7		6.96
21/05/93	177	0	0	ERR	6.30		0.1		633		65.7		6.94
24/05/93	180	0	0	ERR	6.30		0.1		301		75.4		7.02
01/06/93	188	0	0	ERR	6.30		0.1		380		75.2		8.04
04/06/93	191	32	36	32	6.30	1780	0.1	333	443	3.6	63.6	7.32	7.01
10/06/93	197	32	36	32	6.49		0.1		487		68.7		6.46
14/06/93	201	32	36	32	6.61	1962	0.9	284	459	2.5	40.8	7.63	7.28
16/06/93	203	32	36	32	6.68	2124	7.9	234	407	4.3	61	7.49	7.15
18/06/93	205	32	36	32	6.74	1766	0.1	309	426	4.3	69.4	7.33	7.39
21/06/93	208	32	36	32	6.84	1122	0.1	290	441	3.4	71.8	7.61	7.51
24/06/93	211	32	36	32	6.93	1689	0.1	319	447	4	59.6	7.45	7.39
25/06/93	212	32	36	32	6.96	1534	0.1	271	399	1.7	56.1	7.22	7.26

YOUNG REFUSE: flow data and basic chemical analyses

date	duration	flow	flow	HRT	bed vols	TON		TOC		NH3-N		pH	
	(days)	(l/d)	(mm/d)	(days)	passed	In	Out	In	Out	In	Out	In	Out
28/06/93	215	32	36	32	7.06	1522	0.1	288	378	1.5	46.1	7.59	7.29
30/06/93	217	32	36	32	7.12	1952	0.1	302	431	1.9	53.9	7.69	7.81
01/07/93	218	25	29	39	7.15								
02/07/93	219	25	29	39	7.18	2217	14.3	309	399	2.3	47.9	6.88	7.69
05/07/93	222	25	29	39	7.25	2470	37.4	300	410	1.7	44.7	7.01	7.47
07/07/93	224	25	29	39	7.30	2164	147	300	393	4.3	61	7.13	7.45
09/07/93	226	25	29	39	7.35	2400	164	326	405	4.5	36.1	7.23	7.49
14/07/93	231	25	29	39	7.48	1907	297	394	436	1.5	31.7	7.3	8.03
19/07/93	236	25	29	39	7.61	1777	192	378	441	1.4	29.4	7.27	8.35
21/07/93	238	25	29	39	7.66	1709	466	382	417	5.5	53.9	7.22	7.96
23/07/93	240	25	29	39	7.71	2113	300	326	396	0.1	36.6	7.63	8.42
26/07/93	243	25	29	39	7.79	2124	323	321	383	0.7	37	7.35	8.34
28/07/93	245	25	29	39	7.84	2193	526	313	375	0.6	54.3	7.5	8.13
30/07/93	247	25	29	39	7.89	2231	596	371	399	0.1	55	7.62	7.56
05/08/93	253	25	29	39	8.04	1533	387	364	387	0.2	56.5	7.81	7.38
06/08/93	254	25	29	39	8.07	2104	338	392	378	0.2	43.3	7.72	8.4
10/08/93	258	27	31	37	8.17	492	539	427	369	34	54.6	8.31	7.87
13/08/93	261	27	31	37	8.25	338	341	432	407	34.8	60	8.33	7.36
16/08/93	264	27	31	37	8.33	455	93.6	319	325	34.4	66.1	7.97	7.34
18/08/93	266	27	31	37	8.39	508	93.7	338	331	38.7	63.6	8.08	7.94
20/08/93	268	27	31	37	8.44	458	95.5	310	300			7.93	7.18
23/08/93	271	27	31	37	8.52	507	95.5	343	319	29.9	56.1	8.03	7.59
25/08/93	273	27	31	37	8.58	404	115	319	319	27	53.3	7.92	7.75
01/09/93	280	27	31	37	8.77	470	100	394	319	60.5	53.8	7.86	8.03
02/09/93	281	0	0	ERR	8.79								
16/09/93	295	0	0	ERR	8.79		24		373		88.6		7.33
24/09/93	303	0	0	ERR	8.79		0.1		579		147		7.45
29/09/93	308	0	0	ERR	8.79		0.1		517		134		7.66
06/10/93	315	0	0	ERR	8.79		0.1		484		123		7.67
13/10/93	322	0	0	ERR	8.79		0.1		446		145		7.69
21/10/93	330	0	0	ERR	8.79		0.1		435		162		7.31
27/10/93	336	0	0	ERR	8.79		0.1		528		116		7.74
03/11/93	343	30	34	34	8.79								
08/11/93	348	30	34	34	8.94	377	51.4	383	451	22.8	191	7.5	7.26
10/11/93	350	30	34	34	9.00	338	52.9	364	456	20.5	172	7.68	7.72
12/11/93	352	30	34	34	9.06	370	64.5	383	451	21.1	175	7.83	7.19
15/11/93	355	30	34	34	9.15	359	47.1	427	457	22.2	185	7.81	7.33
17/11/93	357	30	34	34	9.21	380	59.6	359	433	17.3	157	7.76	7.4
19/11/93	359	30	34	34	9.27	354	26	350	419	19.8	170	7.85	7.31
22/11/93	362	30	34	34	9.36	348	19.3	391	455	19.1	185	7.89	7.28
25/11/93	365	30	34	34	9.45	295	10.8	379	456	18.6	192	8.03	7.5
29/11/93	369	30	34	34	9.57	315	0.1	392	457	17.3	219	7.54	7.89
01/12/93	371	30	34	34	9.63	361	13.4	401	533	17.4	218	7.95	7.24
06/12/93	376	30	34	34	9.78	369	0.1	392	483	17.4	229	7.93	7.47
09/12/93	379	30	34	34	9.87	444	0.9	387	471	14.8	203	8.02	7.3

YOUNG REFUSE: flow data and basic chemical analyses

date	duration	flow	flow	HRT	bed vols	TON		TOC		NH3-N		pH	
	(days)	(l/d)	(mm/d)	(days)	passed	In	Out	In	Out	In	Out	In	Out
10/12/93	380	30	34	34	9.90	453	0.2	387	441	13.5	217	7.74	7.95
13/12/93	383	64	74	16	9.99	470	19.6	416	448	7.4	241	7.6	7.54
15/12/93	385	64	74	16	10.11	318	38.9	367	401	6.1	190	7.6	7.34
17/12/93	387	64	74	16	10.24	461	25.6		411	6.3	175	7.72	7.49
22/12/93	392	64	74	16	10.56	432	76	309	364	6	138	7.73	7.56
29/12/93	399	64	74	16	11.01	392	115	345	328	15.2	94.9	7.83	7.66
31/12/93	401	64	74	16	11.14	407	127	330	328	16.9	80.8	7.9	7.43
05/01/94	406	64	74	16	11.46	425	129	373	348	14.4	70.2	8.5	7.53
10/01/94	411	64	74	16	11.78	386	159	314	306	7.3	60.5	7.44	7.41
12/01/94	413	64	74	16	11.91	374	113	321	313	8.2	60.7	7.57	7.79
14/01/94	415	64	74	16	12.03	472	112	311	305	6	64.4	7.16	7.37
17/01/94	418	64	74	16	12.23	428	150	307	314	5.8	52.2	7.43	7.38
19/01/94	420	56	65	18	12.35	393	120	324	312	5.1	51.5	7.6	7.35
21/01/94	422	56	65	18	12.47	401	108	317	298	4.2	51.1	7.66	7.32
24/01/94	425	61	70	16	12.63		82.3		302		63.7		7.33
26/01/94	427	61	70	16	12.76	355	106	345	317	2.5	40.6	7.49	7.76
28/01/94	429	61	70	16	12.88	523	81.3	367	369	2.4	47.1	7.45	7.5
31/01/94	432	61	70	16	13.06	298	90.3	304	299	2.1	35.6	7.39	7.36
02/02/94	434	61	70	16	13.18	307	76.1	399	322	1.3	29.6	7.65	7.6
04/02/94	436	61	70	16	13.30	310	95.1	317	308	1.6	30.6	7.83	7.78
07/02/94	439	61	70	16	13.49	304	77.5	316	325	1.4	34.1	7.75	7.51
09/02/94	441	61	70	16	13.61	293	63.2	314	299	0.4	29.5	7.83	7.78
14/02/94	446	62	72	16	13.91	288	122	306	274	0.1	25.2	7.93	7.6
21/02/94	453	62	72	16	14.35	298	91.9	281	262	0.5	32.1	7.89	7.39
23/02/94	455	62	72	16	14.47	316	60.6	269	257	0.3	33.3	7.78	7.53
25/02/94	457	62	72	16	14.60	411	63	304	291	0.3	38.9	8.08	7.42
02/03/94	462	58	67	17	14.91	203	47.3	275	302	5	43.5	7.69	7.43
04/03/94	464	58	67	17	15.02	234	44.3	321	303	4	54.4	7.6	7.5
07/03/94	467	58	67	17	15.20	397	29.7	338	314	4.1	51.2	8.35	7.85
10/03/94	470	58	67	17	15.37	281	16.7	320	295	4.7	51.7	8.11	7.76
11/03/94	471	58	67	17	15.43	281	9.6	363	326	4.2	55.7	8.02	7.38
14/03/94	474	58	67	17	15.60	287	11.9	293	288	3.2	58.5	8.12	7.41
16/03/94	476	58	67	17	15.72	320	10.1	321	290	2.1	61.9	8.56	7.4
18/03/94	478	58	67	17	15.83	373	27.7	305	281	4.5	61.6	7.39	7.32
23/03/94	483	63	73	16	16.12	359	17.4	329	302	2.3	74.3	7.44	7.27
25/03/94	485	63	73	16	16.25	328	6.5	308	304	3.9	65.5	7.49	7.32
28/03/94	488	63	73	16	16.44	282	8.6	320	300	3.2	61.6	7.59	7.39

APPENDIX III

YOUNG REFUSE: COMPREHENSIVE CHEMICAL ANALYSES

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		22/12/92	06/01/93	13/01/93	21/01/93	27/01/93	10/02/93	19/02/93	24/02/93
duration (days):		27	42	49	57	63	77	86	91
bed volumes passed:		1.28	1.61	1.76	1.94	2.07	2.62	3.00	3.21
determinand									
pH	in	7.75	7.77	7.73	7.77	8.17	7.28	7.5	6.91
	out	6.72	5.99	6.29	6.5	6.69	6.69	6.7	6.62
conductivity (uS/cm)	in	15500	14500	15300	12830	10530	11190	11480	11500
	out	21400	19200	18500	12600	11980	11420	12730	12440
chloride	in	5201	5117	5123	5020	5121	4479	4378	4081
	out	5707	5242	5215	5053	5189	4747	4651	4671
ammonia as N	in	8.6	5.9	8.1	10.3	9.4	7.7	16	9.6
	out	497	408	342	244	254	180	159	103
total oxidised nitrogen	in	484	436	446	468	471	381	440	354
	out	239	14.9	2	0.8	<0.1	<0.1	<0.1	0.1
sulphate as SO4	in	57	110	206	335	351	335	297	449
	out	957	430	109	95	94	326	128	148
TOC	in	298	381	334	324	308	322	375	331
	out	8748	8878	7376	5520	4731	4440	3633	3283
COD	in	981	969	982	960	1004	1014	1003	737
	out	23482	24674	18918	15345	13532	11844	7435	6474
BOD	in		12	11	32	7	14	12	7
	out		14820	14420	10600	12600	9450	5850	5050
alkalinity as CaCO3	in	438	425	420	439	439	234	226	119
	out	7407	9650	7878	6632	6868	5605	4514	4186
hardness as CaCO3	in	1207	1244	1113	1161	1404	1279	1268	1231
	out	7065	8208	5302	4908	5013	4768	3390	3052
calcium	in	166	171	160	166	200	185	177	154
	out	2371	2818	1784	1570	1575	1524	1006	884
magnesium	in	190	196	171	179	217	196	198	203
	out	273	279	202	236	258	230	210	202
potassium	in	618	668	637	613	617	530	551	551
	out	1080	1003	873	734	754	684	624	573
sodium	in	3429	3537	3490	3631	3608	2769	2896	2838
	out	3795	3513	3384	3554	3646	3008	3014	2881

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		04/03/93	10/03/93	17/03/93	24/03/93	31/03/93	07/04/93	03/06/93	18/06/93
duration (days):		99	105	112	119	126	133	190	205
bed volumes passed:		3.54	3.80	4.30	4.80	5.30	5.80	6.30	6.74
determinand									
pH	in	7.1	7.4	7.23	6.8	7.65	6.82	7.32	7.33
	out	6.62	6.58	6.53	6.65	6.7	6.81	7.12	7.39
conductivity (uS/cm)	in	11090	12200	12050	13200	12900	13100	16600	12600
	out	11720	12800	12910	13300	12800	12900	11750	11200
chloride	in	4135	4190	4198	4426	4347	4379	5084	4743
	out	4540	4388	4302	4351	4293	4386	4631	4604
ammonia as N	in	2.4	1.2	2.1	4	4.2	2.9	3.6	4.3
	out	60.6	95.5	38.9	8.1	40.4	34.7	72.6	69.4
total oxidised nitrogen	in	358	372	407	319	377	398	1780	1766
	out	<0.1	<0.1	0.2	0.1	0.4	<0.1	3.8	<0.1
sulphate as SO4	in	430	187	352	405	436	492	458	469
	out	100	81	74	67	35	13	67	39
TOC	in	323	316	363	353	358	354	333	309
	out	2476	2098	1646	1592	1143	1161	513	426
COD	in	743	932	774	710	699	1106	1028	826
	out	5299	6058	3869	3100	2919	3012	1122	1278
BOD	in	4	2	6	6	5	3	13	5
	out	3700	4200	2295	2820	1269	1485	179	150
alkalinity as CaCO3	in	117	112	100	93	249	94	241	248
	out	3581	3414	2917	2984	2834	2622	3053	4190
hardness as CaCO3	in	1228	1258	1233	1333	1282	1337	1236	1222
	out	2766	2586	2404	2193	2073	2062	1705	1404
calcium	in	156	158	150	163	161	168	131	132
	out	768	701	625	539	501	473	372	255
magnesium	in	201	207	206	222	211	220	218	214
	out	203	200	202	203	197	211	186	184
potassium	in	495	493	505	532	509	550	4342	4114
	out	553	518	536	538	507	531	620	1819
sodium	in	2675	2655	2641	2850	2721	2896	3130	3057
	out	2830	2708	2815	3851	2721	2872	2888	2898

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		24/06/93	30/06/93	02/07/93	07/07/93	14/07/93	21/07/93	28/07/93	05/08/93
duration (days):		211	217	219	224	231	238	245	253
bed volumes passed:		6.93	7.12	7.18	7.30	7.48	7.66	7.84	8.04
determinand									
pH	in	7.45	7.69	6.88	7.13	7.3	7.22	7.5	7.81
	out	7.39	7.81	7.69	7.45	8.03	7.96	8.13	7.38
conductivity (uS/cm)	in	11500	10400	17900	18400	16100	19400	19000	17900
	out	10600	10000	15200	16000	13600	18100	17200	16600
chloride	in	5116	4941	5122	5067	4919	5059	5178	5214
	out	4900	4853	4850	4919	4878	5055	5056	4977
ammonia as N	in	4	1.9	2.3	4.3	1.5	5.5	0.6	0.2
	out	59.6	53.9	47.9	60.8	31.7	53.9	54.3	56.5
total oxidised nitrogen	in	1689	1952	2217	2164	1907	1709	2193	1533
	out	<0.1	<0.1	14.3	147	297	466	526	387
sulphate as SO4	in	325	381	151	368	416	326	799	1403
	out	74	178	230	515	436	329	452	459
TOC	in	319	302	309	300	394	382	313	364
	out	447	431	399	393	463	417	375	387
COD	in	1032	940	904	939	932	997	949	918
	out	1335	1110	1152	1049	1001	1109	997	989
BOD	in	13	12	11	6	7	6	7	2
	out	128	72	64	76	35	30	26	19
alkalinity as CaCO3	in	277	257	157	153	168	174	176	187
	out	4684	5330	5249	5323	5194	4996	5170	4806
hardness as CaCO3	in	1278	1400	1354	1298	1320	1295	1330	1340
	out	1287	1277	1208	1178	1180	1200	1140	1160
calcium	in	133	150	135	139	156	144	160	144
	out	228	184	173	153	160	132	128	136
magnesium	in	227	246	244	228	223	224	223	235
	out	172	196	186	191	187	209	197	197
potassium	in	4375	4329	5027	5211	4902	5028	5360	4996
	out	2346	2969	3029	3845	3902	4279	4150	4052
sodium	in	3246	3236	3153	3278	3122	3185	3248	3305
	out	3093	3144	3281	3282	3037	3233	3130	3113

YOUNG REFUSE: DETAILED ANALYSES (*concentrations in mg/l*)

date:		10/08/93	18/08/93	25/08/95	01/09/93	16/09/93	27/10/93	10/11/93	17/11/93
duration (days):		258	266	273	280	295	336	350	357
bed volumes passed:		8.17	8.39	8.58	8.77	8.79	8.79	9.00	9.21
determinand									
pH	in	8.31	8.08	7.92	7.86				
	out	7.87	7.94	7.75	8.03	7.33	7.74	7.72	7.4
conductivity (uS/cm)	in	13100	8490	15200	16900				
	out	15100	9090	15700	17600	13700	16800	16800	16800
chloride	in	5658	5506	5774	5866				
	out	5079	5279	5545	5613	5756	5557	5428	5291
ammonia as N	in	34	38.7	27	60.5				
	out	54.6	63.6	53.3	53.8	88.6	116	172	157
total oxidised nitrogen	in	492	508	404	470				
	out	539	93.7	115	100	24	<0.1	52.9	59.6
sulphate as SO4	in	403	416	334	365				
	out	561	181	120	170	138	88	79	86
TOC	in	427	338	319	394				
	out	369	331	319	319	373	528	456	433
COD	in	1131	898	675	937				
	out	997	788	969	955	1059	1684	1007	1360
BOD	in	7	14	7	7				
	out	22	22	19	18	21	26	22	45
alkalinity as CaCO3	in	289	297	307	292				
	out	5360	4056	3365	3366	3322	3938	3002	2920
hardness as CaCO3	in	1320	1318	1292	1440				
	out	1010	1131	1125	1316	1240	1078	943	993
calcium	in	104	123	127	146				
	out	140	104	111	143	126	108	94	107
magnesium	in	254	242	234	258				
	out	158	209	203	230	222	197	170	174
potassium	in	1026	1008	1009	1006				
	out	4630	2652	2100	1927	1935	2038	1372	1425
sodium	in	3683	3617	3511	3481				
	out	3498	3456	3398	3349	3558	3469	3112	3374

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		25/11/93	01/12/93	09/12/93	15/12/93	22/12/93	29/12/93	05/01/94	12/01/94
duration (days):		365	371	379	385	392	399	406	413
bed volumes passed:		9.45	9.63	9.87	10.11	10.56	11.01	11.46	11.91
determinand									
pH	in								
	out	7.5	7.24	7.3	7.34	7.62	7.66	7.53	7.79
conductivity (uS/cm)	in								
	out	16600	17800	17400	13100	9530	9240	10890	129000
chloride	in								
	out	5331	5379	5159	5007	5449	5536	5339	5095
ammonia as N	in								
	out	192	218	203	190	138	80.5	70.2	60.7
total oxidised nitrogen	in								
	out	10.8	13.4	0.9	38.9	76	115	129	113
sulphate as SO4	in								
	out	78	91	267	458	412	179	334	443
TOC	in								
	out	456	533	471	401	364	337	348	313
COD	in								
	out	1237	1151	1200	1065	1028	1036	1067	995
BOD	in								
	out	31	40	26	18	16	15	20	11
alkalinity as CaCO3	in								
	out	3068	3346	3092	2516	1788	1657	1558	1422
hardness as CaCO3	in								
	out	993	861	936	1170	1163	1098	1118	1138
calcium	in								
	out	107	91	91	128	127	114	117	125
magnesium	in								
	out	174	152	170	204	203	195	198	198
potassium	in								
	out	1409	1314	1237	1046	900	750	695	662
sodium	in								
	out	3352	3300	3326	3289	3382	3247	3268	3134

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		19/01/94	26/01/94	02/02/94	09/02/94	14/02/94	23/02/94	02/03/94	10/03/94
duration (days):		420	427	434	441	446	455	462	470
bed volumes passed:		12.35	12.76	13.18	13.61	13.91	14.47	14.91	15.37
determinand									
pH	in		7.49			7.93			
	out	7.35	7.76	7.6	7.78		7.53	7.43	7.76
conductivity (uS/cm)	in		13800			12100			
	out	13000	14400	12500	12900		12510	12740	12780
chloride	in		4373			4518			
	out	4815	4693	4711	4622		4540	4281	4537
ammonia as N	in		2.5			<0.1			
	out	51.5	40.6	29.6	29.5		33.3	43.5	51.7
total oxidised nitrogen	in		355			288			
	out	120	106	76.1	63.2		60.6	47.3	16.7
sulphate as SO4	in		427			443			
	out	240	280	263	322		268	208	185
TOC	in		345			306			
	out	312	317	322	299		257	302	295
COD	in		1029			855			
	out	799	898	867	878		816	744	774
BOD	in		18			10			
	out	19	14	15	6		6	21	11
alkalinity as CaCO3	in		250			482			
	out	1508	1227	2002	1474		1470	1566	1677
hardness as CaCO3	in		1386			1358			
	out	1108	1224	1188	1094		1098	1034	1040
calcium	in		171			175			
	out	123	138	130	121		126	122	126
magnesium	in		230			221			
	out	192	211	207	190		188	175	174
potassium	in		527			508			
	out	645	634	632	592		573	564	526
sodium	in		2614			3114			
	out	3200	2880	3273	3043		3047	2931	2857

YOUNG REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		16/03/94	23/03/94
duration (days):		476	483
bed volumes passed:		15.72	16.12
determinand			
pH	in		
	out	7.4	7.27
conductivity (uS/cm)	in		
	out	12630	11900
chloride	in		
	out	4395	4507
ammonia as N	in		
	out	61.9	74.3
total oxidised nitrogen	in		
	out	10.1	17.4
sulphate as SO4	in		
	out	183	246
TOC	in		
	out	290	302
COD	in		
	out	857	753
BOD	in		
	out	17	14
alkalinity as CaCO3	in		
	out	1635	1490
hardness as CaCO3	in		
	out	1015	968
calcium	in		
	out	116	112
magnesium	in		
	out	174	165
potassium	in		
	out	550	525
sodium	in		
	out	2927	2803

APPENDIX IV

OLD REFUSE: FLOW DATA AND BASIC CHEMICAL ANALYSES

Old refuse: flow data and basic chemical analyses

date	duration	flow	flow	HRT	bed vols	TON		TOC		NH3-N		pH		ALK		SO4	
	(days)	(l/d)	(mm/d)	(days)	passed	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
24/08/92	0	55	64	20	0.00												
03/09/92	10	120	139	9	0.51	453	522										
10/09/92	17	50	58	21	1.29		501				2						
29/09/92	36	50	58	21	2.18		434				5.2						
01/10/92	38	50	58	21	2.27	485	482	394	229	18.2	6.7	7.88	7.16		578	67	1725
01/10/92	38	20	23	54	2.27	501		385		23.2		7.15		247			
05/10/92	42	20	23	54	2.35		474		216		6.2		7.11				
06/10/92	43	20	23	54	2.36		474		223		6.6		7.13				
07/10/92	44	20	23	54	2.38		442		222		5.4		7.29				
08/10/92	45	20	23	54	2.40		452		220		6.3		7.21				
09/10/92	46	20	23	54	2.42		489		220		6.3		6.95				
12/10/92	49	20	23	54	2.48		457		208		7.1		7.27				
13/10/92	50	20	23	54	2.50		457		198		7.1		7.08				
14/10/92	51	20	23	54	2.51		438		196		7.2		6.99				
15/10/92	52	20	23	54	2.53		457		228		7.1		7.08				
16/10/92	53	20	23	54	2.55		495		218		7.2		7.13				
19/10/92	56	20	23	54	2.61		475		211		7.2		7.01				
20/10/92	57	20	23	54	2.63	550	490	350	205	21.9	7.1	7.28	7.22				
21/10/92	58	20	23	54	2.64	538	494	389	210	22.2	7.2	7.17	7.03	213	618	67	2355
23/10/92	60	20	23	54	2.68		512		219		7.4		7.36				
26/10/92	63	20	23	54	2.74	423	433	355	212	20.7	8.9	7.21	7.25				
27/10/92	64	20	23	54	2.76		447		201		8.1		7.13				
28/10/92	65	20	23	54	2.77		472		228		9.3		7.03				
30/10/92	67	20	23	54	2.81	516	466	367	214	21.1	8.5	7.13	7.42				
03/11/92	71	20	23	54	2.89	547	522	369	204	19.9	8.9	7.28	7.34				
04/11/92	72	20	23	54	2.91		474		202		8.8		7.22				
05/11/92	73	20	23	54	2.92	478	454	362	204	16.9	6.8	7.29	7.16	207	614	125	2613
06/11/92	74	20	23	54	2.94	517	423	389	222	15.3	7.4	7.42	7.04				
09/11/92	77	20	23	54	3.00		488		224		10.3		6.97				
11/11/92	79	20	23	54	3.04	518	482	372	225	19.3	8.8	6.73	6.87	199	617	69	2188
12/11/92	80	20	23	54	3.05		473		231		10.3		7.07				
14/11/92	82	20	23	54	3.09		463		194		10.3		7.21		608		2094
16/11/92	84	20	23	54	3.13	480	479	361	191	14.8	10.5	7.42	7.31				
17/11/92	85	20	23	54	3.15	503	476	354	203	16.8	11.4	7.49	7.3				
18/11/92	86	20	23	54	3.17	575	535	372	225	13.1	9.9	7.31	7.24	192	607	37	1815
19/11/92	87	20	23	54	3.18	544	469	359	213	13.4	10.5	7.01	7				
20/11/92	88	20	23	54	3.20	471	466	345	200	11.9	10.2	7.17	7.07				
23/11/92	91	20	23	54	3.26	505	456	363	214	5.6	8.6	7.22	7.06				
24/11/92	92	20	23	54	3.28	525	495	363	212	6.3	8.6	7.42	7.1	179	619	31	1520

[concentrations in mg/l]

APPENDIX V

OLD REFUSE: COMPREHENSIVE CHEMICAL ANALYSES

OLD REFUSE: DETAILED ANALYSES (concentrations in mg/l)

date:		01/10/92	21/10/92	05/11/92	11/11/92	14/11/92	18/11/92	24/11/92
duration (days):		38	58	73	79	82	86	92
bed volumes passed:		2.27	2.64	2.92	3.04	3.09	3.17	3.28
determinand								
pH	in	7.15	7.17	7.29	6.73		7.31	7.42
	out	7.16	7.03	7.16	6.87	7.21	7.24	7.1
conductivity (uS/cm)	in	16500	15700	15100	12380		13200	14100
	out	15400	16200	15200	12810	16200	14100	14200
chloride	in	6632	5999	6900	6721		6752	6704
	out	5614	5313	5873	6550	6536	6521	6733
ammonia as N	in	23.2	22.2	16.9	19.3		13.1	6.3
	out	6.7	7.2	6.8	8.8	10.3	9.9	8.6
total oxidised nitrogen	in	501	538	478	518		575	525
	out	482	494	454	482	463	535	495
sulphate as SO4	in	67	67	125	69		37	31
	out	1725	2355	2613	2188	2094	1815	1520
TOC	in	385	389	362	372		372	363
	out	229	210	204	225	194	225	212
COD	in	1225	1174	1044	1152		1116	714
	out	600	611	639	658	646	712	712
BOD	in	9	8	9	6		8	8
	out	1	3	3	2	3	2	1
alkalinity as CaCO3	in	247	213	207	199		192	179
	out	578	618	614	617	608	607	619
hardness as CaCO3	in	1411	1400	1394	1403		1429	1418
	out	4887	4674	4921	4842	4684	4691	4327
calcium	in	176	175	176	176		175	177
	out	1408	1333	1455	1435	1402	1393	1304
magnesium	in	233	231	229	231		238	234
	out	328	322	308	301	283	290	256
potassium	in	865	784	762	756		796	797
	out	511	469	482	485	492	520	556
sodium	in	4250	3959	4179	4294		4376	4225
	out	3264	3462	3660	3846	3892	3969	3881