UNIVERSITY OF CAPE TOWN
Department of Civil Engineering
Water Research Group

DESIGN AND PERFORMANCE OF BNR ACTIVATED SLUDGE SYSTEMS WITH FLAT SHEET MEMBRANES FOR SOLID-LIQUID SEPARATION

By

Geoff J.G. du Toit
BSc, Engineering (Hons.) – Civil
University of Cape Town

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DECLARATION BY CANDIDATE

I

GEOFFREY JOHN GUINNESS DU TOIT

Hereby declare that I know the meaning of plagiarism and state that all the work in this document, save for that which is properly acknowledged, is my own. This work has not been submitted for a degree at another University.

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SYNOPSIS

1. BACKGROUND

Wastewater treatment technologies have developed out of the need to protect receiving water bodies from the increasingly concentrated municipal and industrial waste streams generated through human activity. Of the methods available to clean wastewaters, biological nutrient removal (BNR) activated sludge (AS) is applied throughout South Africa and internationally as it has many advantages, notably it is cheaper to operate, does not introduce salinity into the water and is a simple and robust process. One of the key steps in the BNR AS process is the separation of biomass from the water. This is traditionally achieved by means of secondary settling tanks (SSTs), however recently the use of membranes for solid-liquid separation has gained popularity for the following reasons:

- Membranes are able to retain all solids and thus are insensitive to the settling characteristics of sludges,
- they can be run at high concentrations and hence smaller reactor volumes are required,
- membranes can produce a guaranteed high quality effluent free of pathogens and in some cases viruses too.
- Additionally smaller reactor volumes and the obviation of SSTs allow a substantial wastewater treatment plant footprint reduction.

Hence the combination of membranes in BNR AS is being increasingly applied. Membrane applications are becoming common in Europe, North America and Asia where much research has been conducted on the performance of membranes. The majority of the research has focused on the physical membrane performance, investigating the mechanisms of fouling, or on the membrane biological reactor (MBR) performance in removing organic compounds or nitrogen compounds from wastewater. There are however few case studies investigating BNR using membranes despite speculation that the inclusion of membranes may indeed affect the nature of the activated sludge biomass (Witzig *et al.*, 2002).

In this investigation 6 case studies are reported from the literature in which various BNR configurations using membranes were proposed and investigated:

- Monti *et al.* (2006) compared two AS systems in a UCT configuration, one a MBR and the other using a conventional SST, with the same system design and operational parameters. Both systems had the same sludge mass and hence the influence of sludge concentration on BNR performance was not assessed.
- Lesjean *et al.* (2003, 2005) conducted a 4-year study on pre-denitrification and post-denitrification configurations of MBR wastewater treatment systems at bench and pilot scale. The systems were run at varying sludge ages and high solids concentrations. Excellent nutrient removal was observed in both configurations without additional carbon dosing in the post-denitrification system. However the systems were found to be generally under loaded, and precipitation of P due to calcium and ferric ions was observed which compromised observations of biological P removal.

- Ahn *et al.* (2003) operated two lab scale MBR systems as a sequencing anaerobic/anoxic MBR (SAM) and the other a MLE system. P removal was observed in the SAM system, but at the cost of poor N removal. BNR removal was observed but not optimised.
- Mouthon-Bello and Zhou (2005) conducted a study on a submerged MBR in an anoxic-anaerobic-aerobic configuration at 20 and 50 day sludge ages. Alum was dosed to the aerobic reactor to aid P removal. This configuration made the anaerobic reactor redundant and biological P removal could not be observed.
- Fleisher *et al.* (2005) investigated the BNR performance of an MBR system in a 5-stage configuration in order to ascertain whether biological and chemical P removal could be achieved concurrently. They successfully demonstrated that BEPR could be achieved, in addition using chemical precipitation in the MBR reactor to completely remove all remaining P. The 5-stage configuration was also successful in reducing TN to <3mgN/ℓ. Fleischer *et al.* (2005) also modelled the observed system performance and suggested that current simulations (IWA ASM2d) adequately predicted the BNR performance of the system. Lastly they investigated the solids produced from the membrane system in order to determine if they differed from conventional solids and observed that a higher density cake could be produced from the MBR sludge than from conventional sludge.
- Ramphao *et al.* (2004) investigated the BNR performance of two systems in UCT configurations. In contrast to the study by Monti *et al.* (2006) the systems were run at their design solids concentrations, i.e. aerobic solids concentrations were 4500mgTSS/ℓ in the conventional system compared to 18000mgTSS/ℓ in the MBR system. The MBR system produced an effluent that was consistently equal to, or better than, the conventional effluent. It was found that the current BNR simulations could adequately predict system performance, but solids production in the MBR system was substantially higher than expected.

The research has shown that the inclusion of membranes in the system does not adversely affect the BNR performance, and also that at high concentration sludges, as are characteristic of MBR systems, the BNR performance remains consistent. However these studies have only indicated that MBRs are feasible and have not investigated in depth how the performance is affected – notably how to optimise BNR in MBR systems. The studies have demonstrated the inability to compare systems without the kinetic constants for modelling being established, as each investigation is on different wastewaters and serves different BNR objectives. Additionally information important to design such as the oxygen transfer efficiency in high solids concentration sludges remains much debated in the literature (Wagner and Pöpel, 1998, Günder and Krauth, 1999).

2. RESEARCH OBJECTIVES

This investigation followed on directly from the work reported in Ramphao *et al.* (2004) in which the feasibility of a MBR for BNR treatment was investigated. From the conclusions drawn in Ramphao *et al.* (2004) it was recommended that further investigations into the kinetics of the MBR system be undertaken, to better understand the influence of the membranes and how the concentration of the sludge impacts on the biological activity and behaviour of the micro-organisms in the system.

Additionally design specific information on the oxygen transfer of the high concentration sludge required further investigation. Thus the research objectives for this investigation were:

- To verify the results obtained in the initial investigation (Ramphao *et al.*, 2004) with particular emphasis on explaining the phenomena of increased sludge production;
- To gain a better understanding of the operating conditions and considerations of MBR BNR systems including oxygen transfer in high concentration sludges;
- To provide a parent system from which further testing into the kinetics of a MBR BNR system could be performed (Parco *et al.* 2006).

3. RESEARCH APPROACH

In order to address these objectives two parallel lab-scale membrane (MBR) and conventional (CAS) activated sludge systems (Figs. 1 and 2) were operated under laboratory conditions allowing their behaviour to be monitored and their performance compared. In order to verify the previous results of Ramphao *et al.* (2004) the same original experimental apparatus and operational conditions were adopted and testing continued.

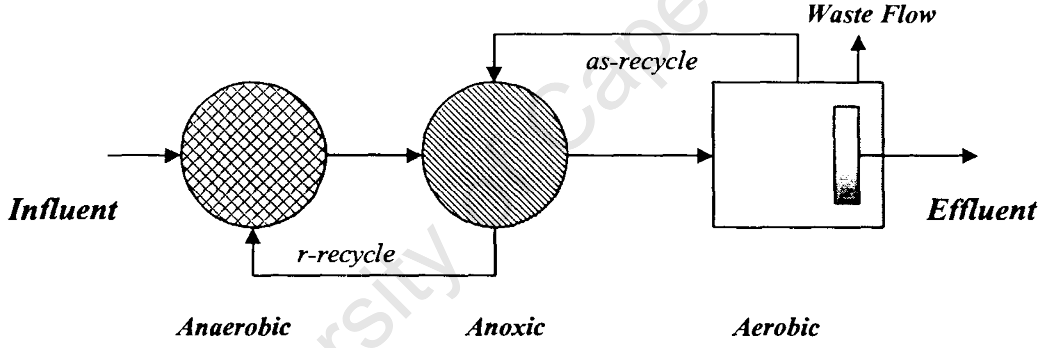

Figure 1: *Schematic layout of the MBR UCT system*

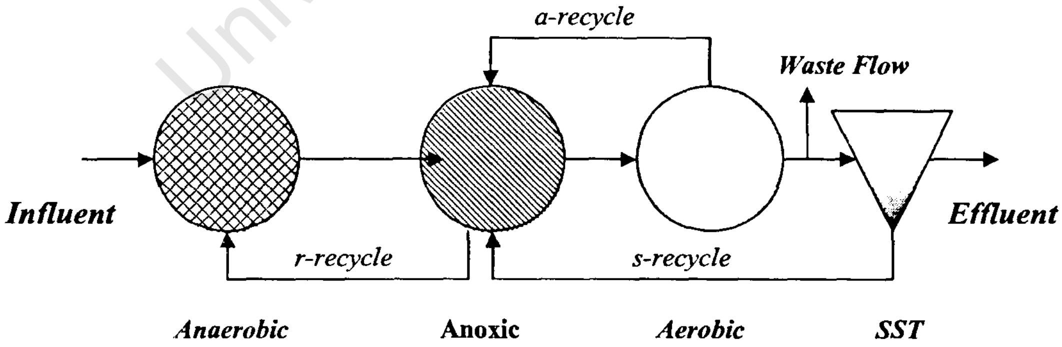

Figure 2: *Schematic layout of the conventional UCT system*

- Both systems were run in a UCT configuration, which was chosen because it allows denitrification and P removal to act independently of each other; the anaerobic reactor is protected from recycled nitrate from the anoxic reactor – provided the recycles do not overload the anoxic reactor with nitrate. As far as possible system design and operational parameters such as zone mass fractions and inter-reactor recycles were kept the same in both systems. A summary of the system design and operating parameters is presented in Table 1.

Table 1: *MBR and conventional UCT systems' design and operating parameters.*

SYSTEM PARAMETERS	MBR UCT	CAS UCT
Sludge Age (d)	20	20
Anaerobic (R1) Volume (ℓ)	19	5.6
Anoxic (R2) Volume (ℓ)	21	6.2
Aerobic (R3) Volume (ℓ)	34[1]	13.2
Anaerobic (R1) Mass Fraction (%)	12.6[2]	12.6[2]
Anoxic (R2) Mass Fraction (%)	27.9[2]	27.9[2]
Aerobic (R3) Mass Fraction (%)	59.5[2]	59.5[2]
s-sludge Return Recycle (SST to R2)	-	1:1
a-recycle Return Recycle (R3 to R2)	3:1	2:1
r-recycle Return Recycle (R2 to R1)	1:1	1:1
Hydraulic retention time (d)	0.53	1.67
Aerobic MLVSS conc. (mgVSS/ ℓ)	12 500	3 600
Aerobic MLSS conc. (mgTSS/ ℓ)	18 000	5 000
Influent flow (ℓ /d)	140	15
Feed COD concentration (mg/ ℓ)	1000	1000
Waste flow from Aerobic Reactor (ℓ /d)	2.85	1.1
OUR (mgO/ ℓ)	135	37
Membrane Flux ($m^3/m^2/d$)	0.239	-

[1] Effective aerobic volume. MBR UCT Aerobic reactor is in fact 32 ℓ , with a side OUR -aeration reactor for OUR measurement of 2 ℓ .

[2] For the given a, s and r recycle values

There were however some differences between the two MBR and CAS UCT systems:

- The major difference between the two systems was the influent flow to the MBR system, which was fed a little over three times (3.1) the organic load of the CAS system in order to generate the solids concentration required for effective cross-flow scour (greater that 12000 mgTSS/ ℓ versus 4000 mgTSS/ ℓ). As the same feed was used for both systems, the higher influent flow rate to the MBR system resulted in a decreased hydraulic retention time (13 hours versus 40 hours).
- Sludge distribution and zone mass fractions in the MBR UCT system differed slightly from that in the conventional UCT system, in that they are linked to the a- and r-recycles due to the solids liquid separation step occurring in the aerobic reactor creating a concentration effect (Ramphao *et al.*, 2004). Additionally in the MBR UCT system the measured recycles were found to differ from the design recycles resulting in system mass fractions that differed slightly from the design mass fractions: Average mass fractions for the MBR UCT system were anaerobic:anoxic:aerobic = 0.139:0.277:0.584 versus the original design values of 0.126:0.279:0.595. In the conventional UCT system only the r-recycle influenced the system mass fractions and was found to

remain close to the design value, hence the system mass fractions were assumed to be the same as those determined in design, 0.126:0.279: 0.595. This resulted in slight differences in the system mass fractions of the two systems.

The two UCT systems were fed screened (1mm mesh) raw (unsettled) sewage diluted to 800 mgCOD/ℓ, increased to 1000mgCOD/ℓ by adding 200 mgCOD/ℓ sodium acetate to accentuate BEPR. Ammonia was added to maintain an influent TKN/COD ratio of 0.10 and phosphorus was added to ensure no P limitation. Additionally sodium bicarbonate was added to the feed to maintain pH > 7 in both systems. The sewage was collected in $2m^3$ batches from the Mitchells Plain Wastewater Treatment Plant (Cape Town), stored at 4°C and served as feed for about two weeks.

Both systems were monitored daily via the standard engineering parameters presented in Table 2. Additionally recycle flow rates and trans-membrane pressure (TMP, constant flux $0.24m^3/m^2/d$) were monitored daily. Mixed liquor samples were analysed microscopically for filaments and floc structure monthly. Sewage readily biodegradable COD (RBCOD) was measured daily according to Ekama et al., (1986) and as a check by flocculation-filtration (Mbewe *et al.,* 1995). Daily sludge was wasted from the systems in accordance with the required sludge age of 20 days. OUR was measured in a side stream reactor to the aerobic reactor. This was necessitated by the requirement for constant aeration in the aerobic reactor in order to achieve effective scour across the membranes.

Table 2: *Sampling position and parameter measurement*

TEST	COD	TKN	FSA	NO_3	NO_2	T-P	TSS	VSS	OUR	DSVI	pH
	1	2	3	4	5	6	7	8	9	10	11
Influent	U	F; U	F			U					
Anaerobic				F	F	F	U	U			
Anoxic				F	F	F	U	U			
Aerobic	U	U		F	F	F	U	U	*	*	*
Final Effluent	F; U	F; U	F	F	F	F					

F = Filtered through Schleicher & Schull ME 25/21 0.45 μm membrane filters.
U = Unfiltered samples
* = Direct measurement taken (filtering not applicable)

The numbers on the test methods below refer to Standard Methods (1985), though some have been adapted to suit the requirements of the UCT wastewater research laboratory (WRL).

1. COD	Chemical Oxygen Demand, open reflux method; 5220 (B)
2. TKN	Total Kjeldahl Nitrogen, micro-kjeldahl method; 4500 – Norg (C)
3. FSA	Free and Saline ammonia, titrimetric method; 4500 – NH_3 (B), (E)
4. NO_3	Hydrazine reduction (Technicon Auto-Analyzer); 4500 – NO_3 (H)
5. NO_2	Hydrazine reduction (Technicon Auto-Analyzer); 4500 – NO_2 (H)

6. T-P	Total Phosphorus; Sulphuric acid/Persulphate digestion at 100°C followed by molybdate-vanadate colour development for ortho-phosphate (Standard Methods, 1985 – Method 424C III)
7. TSS	Total suspended solids dried at 103 - 105°C; 2540 (D)
8. VSS	Volatile suspended solids ignited at 600 °C; 2450 (E)
9. DSVI	Dilute Sludge Volume Index; (Ekama and Marais, 1984b), 271 (D)
10. OUR	Oxygen Utilization Rate; automated (Randall, *et al.*, 1991), 271 (B)
11. pH	pH meter, Hanna Instruments model HI9023; 4500 – H^+ (B)

In order to investigate the oxygen transfer efficiencies of the system unsteady state aeration testing and steady state aeration testing were conducted in the aerobic reactor with tap water and mixed liquor at various concentrations respectively. Due to the disruptive nature of these tests this testing was conducted once the main investigation had been completed

4. EXPERIMENTAL SYSTEM RESULTS

4.1. Steady-State Periods

The steady-state investigation was conducted for 449 days with a total of 29 sewage batch periods. Each sewage batch was accepted as a steady-state period. For every sewage batch data outside the range mean ± 1.96 x sample standard deviation (95% confidence interval), were rejected. All remaining data were considered valid and averaged to represent the "average" response of the system for that sewage batch (steady-state) period. These steady-state averages were used to calculate average ratios of process characteristics.

4.2. Mass Balances

Nitrogen and COD mass balances were performed for each sewage batch period in order to verify the accuracy and reliability of the analytical data, and to provide an early warning sign if the data was poor. Good N and COD mass balances were achieved for the MBR system of 96% and 103% respectively. However consistently low mass balances were achieved for the conventional system of 80% and 83% respectively. The poor mass balances in the conventional system were investigated extensively and the low balances attributed to unaccounted for sludge losses which were largely as a consequence of spillages.

4.3 Mixed Liquor Solids

For all the MBR and conventional system reactors the mixed liquor solids parameters, MLSS, MLVSS, COD and TKN were monitored regularly from the beginning of the investigation. The information on the variation of mixed liquor concentrations with time was necessary in order to interpret the BNR performance of the systems.

4.3.1 Sludge Age (Rs)

As far as possible the sludge age of the system was consistently maintained at 20 days by wasting the appropriate mixed liquor volume from the aerobic reactor. In the event of an unintentional mixed liquor loss from the system due to i) a spill from the reactors, ii) a burst interconnecting pipe, or iii) foam removal, knowledge of the total solids content of the system allowed the mass of mixed liquor lost to be determined and approximate mixed liquor mass to be wasted reduced accordingly over the subsequent days.

4.3.2 MLSS and MLVSS concentrations

Throughout the investigation there were minor and major unintended mixed liquor losses, typically through spillages or while cleaning the system. Where ever possible sludge was retained, filtered through a 2mm mesh to break up sludge "clots" and to prevent the accidental addition of foreign objects into the system, and returned to the system. When sludge was lost the total mixed liquor lost was calculated from the difference in solids concentration from the day prior to the spill, and the loss compensated for by not wasting for the equivalent number of days following the spill.

The MLSS concentration in the aerobic reactor remained within the range 16 000 to 19 000 mgTSS/ℓ and the anoxic and anaerobic concentrations were within the ranges of 12000 – 14000 mgTSS/ℓ and 6000 – 8000 gTSS/ℓ respectively for the MBR system. This is less than the design solids concentration, but is attributed to a lower average S_{ti} and higher $f_{S,up}$ than were used for design.

Similarly the conventional system showed lower MLSS concentrations than expected with aerobic mixed liquor solids concentrations consistently within the range 2500 – 3500 mgTSS/ℓ compared to the expected range 4500 – 5500 mgTSS/ℓ.

4.3.3 Mixed Liquor Characteristics

In order to quantify the mixed liquor in both systems the VSS, TSS, COD and TKN concentrations of the mixed liquor were measured. Investigation average ratios between these parameters are listed in Table 4.

Table 3: *Mixed liquor parameters*

Parameter	Unit	MBR System	Conv. System
VSS/TSS	mgVSS/mgTSS	0.809	0.814
COD/VSS	mgCOD/mgVSS	1.402	1.496
TKN/VSS	mgN/mgVSS	0.085	0.094

- Both systems exhibited high VSS/TSS ratios which are not characteristic of BEPR systems. In BEPR systems the development of a PAO population is encouraged. PAO's have internally a low VSS/TSS ratio due to the additional inorganic polyphosphate in their cell mass.
- Although the COD/VSS ratios differ substantially from each other in the two systems, they both fall very close to the expected and theoretical f_{CV} values of 1.48 and 1.42 respectively (WRC., 1984).
- The COD/VSS ratio indicates that the COD incorporated into the mixed liquor was lower in the MBR system than in the conventional system. However the comparison of mass balances showed a greater proportion of COD was removed from the MBR system via the mixed liquor wasted than in the conventional system. In order for this to occur proportionally more mixed liquor would need to be wasted from the MBR system than the conventional

system in order to achieve higher COD removals through wasting, particularly with lower COD incorporated in the mixed liquor. This is only possible, at the same sludge age, if the sludge production in the MBR system was substantially greater than that in the conventional system.

4.3.4 Sludge Production

Ramphao *et al.* (2004) reported that sludge production in the two UCT systems differed significantly. A number of explanations were suggested, however more data was required in order to validate the observations. Hence one of the objectives for this investigation was to validate the observed discrepancy in sludge production in the two systems. However the poor COD balances in the conventional system make the sludge production data incomparable.

- With the exception of sewage batch 4 the sludge production in the MBR system was consistently higher than that of the conventional UCT system by on average 50%.
- Average sludge productions for the two systems were 0.311 and 0.205 (mgVSS/d)/(mgCOD/d) for the MBR and conventional UCT systems respectively. Ramphao *et al.* (2004) reported similar results, 0.32 and 0.22 (mgVSS/d)/(mgCOD/d) respectively.
- The higher sludge production in the MBR UCT system can be accommodated in the steady state design model by increasing the unbiodegradable particulate COD fraction ($f_{S,up}$). This was demonstrated by the high $f_{S,up}$ values observed in the MBR system of 0.224 in the investigation of Ramphao *et al.* (2004) and 0.200 in this investigation.

As was noted by Ramphao *et al.*, (2004) a number of factors contribute to the higher sludge production in the MBR system:

- The retention of solids by membranes in the MBR system resulted in approximately 17.2 mgTSS/ℓ accumulating in the MBR system that would have been lost through the SST in the conventional UCT system. This would have "increased" sludge production by 0.018(mgVSS/d)/(mgCOD/d).
- In the MBR UCT system, organics that would be considered as soluble in the conventional system are retained. This is demonstrated by the difference in the 0.45µm filtered effluent COD system averages from the MBR and conventional UCT systems of 8mgCOD/ℓ. This would account for approximately 0.008 in the difference in the $f_{S,up}$ values above.

Additionally Ramphao *et al.*, (2004) proposed two other explanations for the difference in sludge production in the two systems.

- Higher P removal in the MBR UCT system suggests a greater PAO population which would produce more sludge per unit influent COD than OHOs due to their lower endogenous respiration rates (Wentzel *et al.*, 1990).
- Particulate organics that are biodegradable in the conventional UCT system are no longer biodegradable in the MBR system due to factors such as high MLSS concentrations, or different floc morphology.

In the literature previous studies comparing conventional and MBR BNR systems run under the same operating conditions have indicated that the sludge production of the two systems were very similar (Masse *et al.*, 2006, Monti *et al.*, 2006), however in both investigations the systems were run at the same COD loading rate per unit reactor volume. Masse *et al.*, (2006) included the sludge lost through the SST in sludge wasting calculations in order to compare sludge productions in the two systems.

Additionally sludge production in nitrification-denitrification (ND) and ND biological excess phosphorus removal (BEPR) systems operated using the same wastewater source, for sludge ages in the region of 20 days, have produced sludge in comparable magnitudes to those observed in the conventional system ranging from 0.18 to 0.31 (mgVSS/d)/(mgCOD/d). Thus it would appear that there is an increase in sludge production in the MBR system linked to the increased MLSS concentration in the MBR system and the retention by membranes of all solids.

4.4 SYSTEM REMOVALS AND EFFLUENT QUALITY

The average removals of both the MBR and conventional UCT systems for this investigation are summarised in Table 4.

Table 4: *Summary of the influent and effluent qualities, and the resultant removals, of both UCT systems.*

Parameter		Influent	MBR UCT		Conv. UCT	
			Effluent	Efficiency	Effluent	Efficiency
COD	mgCOD/l	951.2	42.0	95.6%	74.6[1] (50[2])	92.2%
TKN	mgN/l	106.5	1.7	98.4%	3.7[1] (2.0[2])	96.5%
FSA	mgN/l	81.7	0.7	99.1%	1.3	98.4%
NO3	mgN-NO3/l	0	18.0	-	18.1	-
TN	mgN/l	106.5	19.7	81.5%	21.*	79.5%
TP	mgP/l	30.3	9.0	21.3 mgP/linf	13.6	16.7 mgP/linf
TSS	mgTSS/l	N/A	0.0	-	21.5	-
e. coli	CFU/100ml	N/A	<10	-	2250	-

[1] unfiltered sample; [2] 0.45 filtered sample;
N/A = value not available

4.4.1 COD Removals

The COD removal efficiency of the MBR system (96%) was superior to that of the conventional system (92% unfiltered, 95% 0.45 μm filtered). These results were comparable to those observed by Ramphao *et al.* (2004) of 96% COD removal in the MBR UCT system and 93% unfiltered and 94% 0.45μm filtered in the conventional UCT system.

The difference in filtered COD removals from both systems is attributed to the smaller pore size of the membranes which retain organics that would otherwise be considered soluble in a conventional system. However membrane specifications state that the nominal pore size of the Kubota® membranes used in this study were 0.4μm, while the membranes used to filter the conventional system effluent are only marginally larger (0.45μm), thus the improved filterability of the membrane system is attributed rather to the development of a dynamic gel layer which reduces the effective pore size of the membranes.

The MBR unfiltered "effluent" COD values (measured from the supernatant of the DSVI test on MBR aerobic sludge) were consistently higher than those in the conventional system which confirmed that the MBR system retains and accumulates unsettleable material which would flow out with the effluent in a conventional system. This was observed in the DSVI test in which the supernatant of the conventional system mixed liquor would become clear in time, whereas the MBR supernatant remained cloudy.

The difference between the filtered (50mgCOD/ℓ) and unfiltered (75mgCOD/ℓ) effluent COD measured in the conventional UCT system is attributed to the loss of non-settleable solids through the SST. Approximately 21.5mgTSS/ℓ were lost as COD in the effluent.

After Ramphao *et al.* (2004), differences in the MBR UCT effluent COD and the conventional UCT effluent are accommodated in the steady state design models as differences in the soluble COD fractions ($f_{S,us}$) which were 0.044 and 0.068 respectively.

4.4.2 N Removals

The TKN removal efficiency of the MBR system (98%) was marginally better than that of the conventional system (97% unfiltered, 98% 0.45μm filtered). This is again attributed to the retention of solids by the membranes that would have been lost in the effluent of the conventional UCT system. FSA removal was also very similar for both systems 99% in the MBR system and 98% in the conventional system. Thus near complete nitrification was achieved in both systems.

Effluent nitrate concentrations were virtually the same for both systems (18.0 and 18.1 mgN-NO_3/ℓ in the MBR and conventional UCT systems respectively) resulting in similar total nitrogen (TN) removals, (81.5% for the MBR system versus 79.5% for the conventional system).

Nitrogen is removed from BNR systems either by incorporation of nitrogen in mixed liquor and its subsequent removal through wasting, or through nitrification/ denitrification.

- The influent N incorporated in the mixed liquor was lower in the MBR UCT system than in the conventional UCT system. This corresponds to the observation above of lower COD incorporated in the MLVSS.
- Regardless, N removal through sludge wasting was higher in the MBR UCT system than the conventional UCT system, this is largely due to the higher sludge production in the MBR system, and consequent increased sludge mass wasted per unit influent N.
- The MBR UCT system additionally displayed higher N removals through denitrification. This was achieved despite similar mass fractions and that the conventional UCT system anoxic reactor was frequently fully loaded.

4.4.3 P Removals

In both systems TP was dosed in excess of the amount the system could remove in order to demonstrate BEPR. Thus P removal performance is represented by P removals. System average P removals of 21.3mgP/ℓ and 16.7mgP/ℓ were achieved. Clearly however, the P removal performance of the conventional UCT system was inferior to that of the MBR system. This was because:

i) The anoxic P uptake was more prevalent in the conventional system with 22.1% of P uptake taking place in the anoxic reactor, in contrast to only 8.5% anoxic P uptake in the MBR system. Additionally the conventional anoxic reactor was regularly overloaded with NO_3 as evidenced by consistent anoxic NO_3 concentrations >1mgNO_3/ℓ . Ekama and Wentzel (1999) and Hu *et al.* (2002) report a reduction in BEPR with increasing anoxic P uptake BEPR.

ii) The above observations indicate that the conventional system was not operated optimally (anoxic reactor overloaded). Low MLSS concentrations, as reported earlier reduced the denitrification potential of the anoxic reactor, thus allowing NO_3 to be recycled to the anaerobic reactor. Hence, as the conventional system was not performing optimally no comparison could be drawn between the two systems on whether the presence of membranes changed the P removal efficiency of the MBR system.

4.4.4 Microbial Removals

Periodic effluent samples were tested from both systems for the indicator micro-organism *e-coli* using the membrane filtration method. Results indicated pathogen counts were not detectable in the MBR UCT system whereas in the conventional UCT system pathogen counts ranged from 580 to 5600 CFU/100ml.

Clearly from the removals described above the MBR UCT system produced an effluent that was equal, if not superior in quality to the conventional UCT system. Due to complete retention of solids, and pathogens, the membrane effluent has a higher quality for reuse purposes.

4.5 OXYGEN TRANSFER RATE TESTING

Presently, one of the most important considerations for the design of MBR plants is the feasibility of running the systems at high solids concentrations. In previous literature it has been noted that the oxygen transfer efficiency (OTE) of systems decreases substantially at high solids concentrations (Cornel *et al.*, 2003, Krampe and Krauth, 2003).

Following the intensive study on BNR performance in the MBR system oxygen transfer efficiencies of the activated sludge at high MLSS concentrations were determined by performing tests on the sludge in the aerobic reactor. Oxygen mass transfer co-efficient (K_{LA}) values were determined for a number of air flow rates in the operating range of the aeration system. Steady state tests were then carried out on the activated sludge once it had reached endogenous conditions (to reduce the interference by variations in feed characteristics). For a single MLSS concentration a number of readings were taken at different airflow rates and the alpha values observed were averaged. Alpha values of 0.17-0.28 (21000mgTSS/ℓ), 0.38-0.68 (17000mgTSS/ℓ) and 0.53-0.80 (11000mgTSS/ℓ) were observed.

The wide range of Alpha values observed is a concern. It was concluded that the predominant reason for the variations in observed Alpha values was the sensitivity of the steady state equation to variations in the OUR and C_L values, and fluctuations in the airflow readings. As the system was run at a long sludge age under endogenous conditions, limited OUR activity resulted in OUR readings that were typically very low and conversely C_L readings were very high, hence small differences have large effects. In order to compensate for high C_L values only low airflows could be run, at which the air flow rotameter was less sensitive and variable. It was assumed that by averaging a number of Alpha readings at the same MLSS concentration a more accurate Alpha value could be determined for that MLSS concentration. In conclusion it is recommended that future tests are run on sludge with a far shorter solids retention time, thus providing a greater active fraction in the activated sludge, and hence an increased OUR at endogenous respiration. Additionally sufficiently sensitive air flow rate instrumentation is required to accurately monitor the airflow into the aerobic reactor. It was noted that a number of factors affect the oxygen transfer into the sludge. At a lab scale the geometry of the system and the nature of the aeration (coarse bubble aeration) have a substantial influence on the Alpha value. Thus only the OTE of the lab scale MBR can be calculated and must be interpreted with care on full scale. Hence further studies in conditions resembling full scale are required to accurately calculate Alpha and OTE.

Previous studies on high concentration sludge had indicated a close correlation between viscosity and oxygen mass transfer. Samples from the OTR testing were analysed for rheology. A linear relationship between Alpha and viscosity was observed suggesting further investigations into the viscosity of high concentration sludges should be undertaken to better understand and predict Alpha values.

5. MEMBRANE PERFORMANCE

Although the focus of this investigation was the BNR performance of the MBR system, the performance of the membranes was also monitored. Throughout the investigation, the TMP of the membranes was measured in order to ascertain how the membrane filterability deteriorated over time. A constant increase in TMP of approximately 0.29mm/d was observed. However the presence of unbiodegradable colloidal material in the mixed liquor adversely influenced the TMP, which agreed with observations of Fleischer *et al.* (2005). On completion of the investigation a full chemical clean was performed on the membranes using a 1.0% Hypochlorite solution. Applying a negative pressure on the effluent line of the membranes encouraged the hypochlorite to flow through the membranes. Within 24 hours of the chemical clean the membrane TMP had returned to its original TMP at the start of the investigation. This indicated that the increase of TMP is reversible with effective cleaning of the membranes.

6. CONCLUSIONS

From this investigation, the following conclusions could be drawn:

- Membranes in a BNR system are a feasible nutrient removal solution with excellent organic and nutrient removal performance. The presence of membranes and consequently operating the system at high sludge concentrations did not adversely affect BNR performance, but produced an effluent of equal or superior quality to that produced by a conventional system using SSTs. In addition pathogen counts indicated that all pathogens were retained by the membranes. Thus the membrane effluent is safer and more viable for reuse purposes.
- Higher sludge productions of 0.311 and 0.320 (mgVSS/d)/(mgCOD/d) were observed in the MBR system in both this investigation and by Ramphao *et al.* (2004). This higher sludge production is accommodated in steady state design theory by increasing the unbiodegradable particulate COD fraction ($f_{S,up}$) to 0.200 in this investigation and 0.224 for Ramphao *et al.* (2004). The increased sludge production in the MBR is justified in part by the retention of all solids by the membranes. Similarly the unbiodegradable soluble COD fraction ($f_{S,us}$) must be decreased to account for the additional retention of "soluble" COD which is attributed to the finer membrane pore size.
- A theoretical evaluation of the BNR performance of the MBR system indicated that the current steady state BNR theory was able to closely predict the system performance for COD removal and nitrification. However for denitrification the D_{PP} was under predicted requiring $K_{2'T}$ to be adjusted from 0.145 to 0.216 mgN/mgVSS/d at 20°C in order to match observed and predicted values. The BEPR predictions for aerobic P uptake BEPR were close to those observed when the system PAO population reached a steady state (sewage batches 18 – 25). f_{XBGP} observed in this period (0.376mgP/mgVSS) was close to that determined theoretically of 0.38mgP/mgVSS (Wentzel *et al.*, 1990).
- Aeration testing was performed on the system, in order to determine alpha values for the high concentration sludge. Alpha values of 0.5-0.6 for ~15 000mgTSS/ℓ and 0.2-0.3 for ~20 000mgTSS/ℓ were determined, which are higher than other values reported in the literature. These values are however specific to the laboratory system run in which factors such as reactor geometry and high aeration turbulence would have affected oxygen transfer in the system. Additionally the low sensitivity of the measuring apparatus resulted in substantial variance of results.
- The filterability of the membranes can be influenced by fine colloidal material, however observations indicated that the filterability would return to previous levels once colloids are removed from solution by assimilation into the mixed liquor.

7. RECOMMENDATIONS FOR FURTHER STUDY

Following from this investigation two recommendations are proposed:

- Accurate knowledge of the oxygen transferability in high concentration sludge is an important design consideration. However in this investigation the difficulty in measuring this parameter at a lab scale was realised. It is recommended that this parameter needs to be quantified on a full scale and be determined at a fully operational BNR MBR WWTP.

- The relationship between Alpha and viscosity of activated sludge needs to be investigated further in order to better understand the influence of high concentration sludges on oxygen mass transfer.

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LIST OF SYMBOLS

AA	Anoxic-Aerobic (filaments)
A_C	Acetate, sodium acetate (CH_3COONa)
ADWF	Average Dry Weather Flow
AE	Aerobic
AOB	Ammonia-Oxidising Bacteria
AS	Activated Sludge
ASM	Activated Sludge Model
AVSS	Active volatile suspended solids
AX	Anoxic
BEPR	Biological Excess Phosphorus Removal
B	Beta – effect of impurities on C_S
b_{HT}	Specific endogenous mass loss rate of OHOs at temperature T (1/d)
b_{GT}	Specific endogenous mass loss rate of PAOs at temperature T (1/d)
BNR	Biological Nutrient Removal
BSP	Bench Scale Plant
CAS	Conventional Activated Sludge
cfu	Colony forming units
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
C_S	Saturated DO concentration under site conditions (mgO/ℓ)
C_L	DO concentration in reactor (mgO/ℓ)
CLSM	Confocal Laser Scanning Microscopy
d	Day
˚C	Degrees Celcius
Δ	Indicates a change in parameter value
ΔOUR	Change in OUR (mgO/ℓ/h)
DO	Dissolved Oxygen (mgO)
DPAO	Denitrifying Phosphate Accumulating Organism
D_{PP}	Total system denitrification potential (mgN/ℓ)
DSVI	Diluted Sludge Volume Index (ml/gTSS)
EPS	Extracellular Polymeric Substances
EBPR	Excess Biological Phosphorus Removal
f	Fraction of (unbiodegradable) endogenous residue.
F/M	Food to Micro-organism ratio
f_{CV}	COD to VSS ratio of the mixed liquor (COD/VSS)
f_{EH}	Endogenous residue fraction of OHOs
f_{EG}	Endogenous residue fraction of PAOs
f_i	VSS to TSS ratio of the mixed liquor (mgN/mgCOD)
FISH	Fluorescence *In Situ* Hybridization
fm	Reactor zone mass fraction
f_n	Nitrogen to COD ratio of the mixed liquor (mgN/mgCOD)
f_N	Fractional TKN content of VSS (mgN/mgVSS)
FSA	Free and Saline Ammonia
f_{ts}	RBCOD fraction with respect to total COD in wastewater
f_{up}	Fraction of unbiodegradable particulate (with respect to total)COD in the influent wastewater

f_{us}	Fraction of unbiodegradable soluble (with respect to total) COD in the influent wastewater
f_{XBPG}	Fractional polyp content of PAOs
g	gram
GAO	Glycogen Accumulating Organism
h	Hour
HgCl	Mercury chloride
HPLC	High Pressure Liquid Chromatograph
HRT	Hydraulic Retention Time
IWA	International Water Association (formerly IAWQ, IAWPRC)
IAWPRC	International Association for Water Pollution Research and Control
IAQW	International Association on Water Quality (formerly IAWPRC)
ISS	Inorganic Settleable Solids (mgISS/ℓ)
K_{1T}	Specific denitrification rate with RBCOD as substrate (mgN/mgAVSS/h), at temperature T
K_{2T}	Specific denitrification rate with SBCOD as substrate (mgN/mgAVSS/h), at temperature T
K_{3T}	Specific denitrification rate with endogenous generated SBCOD as substrate (mgN/mgAVSS/h), at temperature T
K_{LA}	Oxygen mass transfer co-efficient (1/h)
Kpa	Kilo-Pascal
kWh	Kilo-Watt hour
ℓ	Litres
m	Meters
MBR	Membrane Biological Reactor
mg	Milligram
min	Minute
ML	Mixed Liquor
MLE	Modified Lutzack-Ettinger (activated sludge system)
MLSS	Mixed Liquor Suspended Solids
mm	Millimeters
MPWWTP	Mitchells Plain Wastewater Treatment Plant
M_{Sti}	Mass of total COD in the influent wastewater (mgCOD)
MUCT	Modified UCT system
M_{Xa}	Mass of active biomass (mgAVSS)
M_{Xv}	Mass of volatile suspended solids (mgVSS)
N	Elemental Nitrogen
N_2	Molecular dinitrogen
NaCl	Sodium Chloride
N_{ae}	Effluent ammonia concentration (mgN/ℓ)
N_C	Nitrification Capacity
ND	Nitrification-Denitrification
NDBEPR	Nitrification-Denitrification Biological Excess Phosphorus Removal
NH_4	Ammonium (mgN/ℓ)
N_{nd}	NOx concentration denitrified (mgN/ℓ)
N_{ne}	Effluent NOx (mgN/ℓ)
N_{nL}	Nitrate Load
NO_2	Nitrite (mgN/ℓ)
NO_3	Nitrate (mgN/ℓ)
NO_x	Nitrite and Nitrate (mgN/ℓ)

NOB	Nitrite-Oxidising Bacteria
N_{ousi}	Organic unbiodegradable soluble influent Nitrogen (mgN/ℓ)
O	Elemental Oxygen
O_2	Molecular Oxygen
OHO	Ordinary Heterotrophic Organism
OSR	Oxygen Supply Rate
OTE	Oxygen Transfer efficiency
OTR	Oxygen Transfer Rate
OUR	Oxygen Utilization Rate (mgO/ℓ/h)
P	Elemental Phosphorus
P	Atmospheric Pressure
p	Saturated vapour pressure
PAO	Polyphosphate Accumulating Organism
PHA	Polyhydroxyalkanoate
PolyP	Polyphosphate
PP	Pilot Plant
PWWF	Peak Wet Weather Flow
Q_i	Influent wastewater flowrate (ℓ/d)
Q_w	Sludge waste flow (ℓ/d)
RBCOD	Readily Biodegradable COD (mgCOD/ℓ)
R_s	Sludge Age (d)
R_{sm}	Minimum Sludge Age for nitrification to occur (d)
RTD	Residence Time Distribution
s	Second
SAFR	Specific Air Flow Rate
SB	Sewage Batch
SBCOD	Slowly Biodegradable COD (mgCOD/ℓ)
S_{bi}	Biodegradable COD in the influent wastewater (mgCOD/ℓ)
S_{bs}	Biodegradable soluble COD (mgCOD/ℓ)
SCFA	Short-Chain Fatty Acids
SMBR	Submerged Membrane Biological Reactor
SQW	Square-wave (fed activated sludge system)
SRT	Solids Retention Time
SSD	Sample Standard Deviation
SST	Secondary Settling Tank
S_{ti}	Total influent wastewater COD concentration (mgCOD/ℓ)
S_{te}	Total effluent COD
S_{us}	Unbiodegradable COD in influent
T	Temperature (°C)
TKN	Total Kjeldhal Nitrogen concentration (mgN/ℓ)
TMP	Trans-Membrane Pressure (mm)
TP	Total Phosphorus
TSS	Total suspended solids (mgTSS/ℓ)
µm	Micro-meter (micron)
UCT	University of Cape Town
UF	Ultra-Filtration
V	Volume
VFA	Volatile Fatty Acids
V_p	Total system (process) volume
VSS	Volatile Suspended Solids (mgVSS/ℓ)

WW	Wastewater
WRC	Water Research Commission
WRG	Water Research Group
WRL	Water Research Laboratory
X_a	Active biomass concentration (mgAVSS/ℓ)
X_V	Volatile suspended solids concentration (mgVSS/ℓ)
Y_H	Ordinary heterotrophic cell yield coefficient
$Y_{H,AE}$	Ordinary heterotrophic cell yield coefficient under aerobic conditions

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Throughout the world development and population growth are placing an increasing strain on water resources as demand for water for agriculture, industry and municipal use increase. Growing out of this increased demand is a awareness by individuals and governments that water bodies need to be safeguarded from pollutants, both in order to protect the environment and maintain the quality of life of the people who use and are in contact with these water bodies.

In South Africa, which is a water scarce country, the protection of water resources has long been (since the 1960's) a national priority. With a rapidly growing population, particularly in urban areas, the importance of protecting receiving water bodies from pollution is vitally important. Of the methods available to clean wastewaters, biological nutrient removal (BNR) is applied throughout South Africa as it has many advantages, notably it is cheaper to operate, does not introduce salinity into the water and is a simple and robust process to operate.

An essential step of the BNR process is the separation of solids from liquids in activated sludge systems. Traditionally this has been achieved using secondary settling tanks (SSTs), however more recently the use of membrane filters for solid-liquid separation has gathered momentum internationally as membranes offer certain significant advantages over conventional SST separation techniques. These are:

1) The membranes retain all reactor solids, preventing solids overflow with the effluent. This ensures a high quality effluent.
2) In addition to retaining all biological solids membranes, due to pore sizes of ~0.1μm, are also effective in filtering pathogens and in some cases viruses from the effluent allowing the upgrading of the water to reuse or even potable standards easier to achieve.
3) Systems can be run at high reactor sludge concentrations, 15 to 20g/ℓ, which require smaller reactor volumes. This not only means that the plant footprint is reduced, but also that plant capacity can be greatly increased with the existing plant infrastructure.
4) The plant footprint is further reduced as no SSTs are required.

Thus, coupled with the conventional BNR activated sludge technology, membranes for solid liquid separation are a very viable option for present and future wastewater applications. Many research groups internationally have focused their attention on investigating the performance of membranes, as certain factors, namely cost, fouling, and uncertainty on the lifespan of the membranes have limited their widespread application. Additionally a number of groups have investigated the biological performance of activated sludge systems using membranes, confirming that the high concentrations induced by the membranes do not adversely affect the biological performance of COD removal and nitrification.

Stricter water quality guidelines internationally have made nutrient removal from wastewaters a far greater priority (Lesjean *et al.*, 2003, Howell, 2004, Gunder and Krauth, 1999). These guidelines require a guaranteed quality effluent which can be achieved far easier with a secure solids-liquid separation medium, such as is provided by membranes. In some cases where water reclamation is required the water can be treated up to potable standards with substantially less infrastructure than would have been required with conventional water treatment techniques. Hence there is a need to understand the impact of membranes on biological nutrient removal (BNR) activated sludge processes. However only a limited number of studies have been conducted on BNR system performance with membranes.

1.2 IMPACT OF MEMBRANES ON BNR ACTIVATED SLUDGE DESIGN AND PERFORMANCE

The design of BNR systems and the approach to wastewater treatment plant design is significantly influenced by the introduction of membranes for solid-liquid separation (Ramphao *et al.*, 2005). As membranes retain all solids, and are more economically run at high solids concentrations they impose different selection criteria on the organisms present and can alter the bioceonosis of the system mixed liquor (Kraume *et al.*, 2005).

Ramphao *et al.* (2005) provided an elegant discussion on the influence of membranes on design. They concluded that, with the zone mass fractions determined, the aerobic reactor is sized on the volume required to house the membranes and aeration devices, with the membrane surface area determined by the peak wet weather flow (PWWF). The system sludge age is determined by the desired solids concentration in the reactors. This design contrasts to conventional designs in that the reactor volumes are based on the membrane surface area required to meet the peak wet weather flow rather than the system organic load and required reactor solids concentration.

1.3 PREVIOUS WORK ON MBR BNR

Previous studies have been conducted on BNR in MBR systems. Monti *et al.* (2006) compared two AS systems in a UCT configuration, one a MBR and the other using a conventional SST, with the same system design and operational parameters. Both systems had the same sludge mass and hence the influence of sludge concentration on BNR performance was not assessed.

Lesjean *et al.* (2003, 2005) conducted a 4-year study on pre-denitrification and post-denitrification configurations of MBR wastewater treatment systems at bench and pilot scale. The systems were run at varying sludge ages and high solids concentrations. Excellent nutrient removal was observed in both configurations without additional carbon dosing in the post-denitrification system. However the systems were found to be generally underloaded, and precipitation of P due to calcium and ferric ions was observed which compromised observations of biological P removal.

Ahn *et al.* (2003) operated two lab scale MBR systems as a sequencing anaerobic/anoxic MBR (SAM) and the other a MLE system. P-removal was observed in the SAM system, but at the cost of poor N removal. BNR removal was observed but not optimised.

Fleisher *et al.* (2005) investigated the BNR performance of an MBR system in a 5-stage configuration in order to ascertain whether biological and chemical P removal could be achieved concurrently. They successfully demonstrated that BEPR could be achieved, using chemical precipitation in the MBR reactor to completely remove all remaining P. The 5-stage configuration was also successful in reducing TN to <3mgN/ℓ. In addition Fleischer *et al.* (2005) modelled the observed system performance and suggested that current simulations (IWA ASM2d) adequately predicted the BNR performance of the system. Lastly they investigated the solids produced from the membrane system in order to determine if they differed from conventional solids and observed that a higher density cake could be produced from the MBR sludge than from conventional sludge.

Ramphao *et al.* (2004) investigated the BNR performance of two systems in UCT configurations. In contrast to the study by Monti *et al.* (2006) the systems were run at their design solids concentrations, ie aerobic solids concentrations were 4500mgTSS/ℓ in the conventional system compared to 18000mgTSS/ℓ in the MBR system. The MBR system produced an effluent that was consistently equal to, or better than, the conventional effluent. It was found that the current BNR simulations could adequately predict system performance, but solids production in the MBR system was substantially higher than expected.

The research has shown that the inclusion of membranes in the system does not adversely affect the BNR performance, and also that at high concentration sludges, as are characteristic of MBR systems, the BNR performance remains consistent. However these studies have only indicated that MBRs are feasible and have not investigated in depth how the performance is affected – notably how to optimise BNR in MBR systems. Additionally information important to design such as the oxygen transfer efficiency in high solids concentration sludges remains much debated in the literature (Wagner and Popel, 1998, Gunder and Krauth, 1999).

1.4 OBJECTIVES OF RESEARCH

This investigation followed on directly from the work reported in Ramphao *et al.* (2004) in which the feasibility of a MBR for BNR treatment was investigated. From the conclusions drawn in Ramphao *et al.* (2004) it was recommended that further investigations into the kinetics of the MBR system be undertaken, to better understand the influence of the membranes and how the concentration of the sludge impacts on the biological activity and behaviour of the micro-organisms in the system. Specific areas requiring further research included:

- Verifying the results obtained in the initial investigation (Ramphao *et al.*, 2004) with particular emphasis on explaining the phenomena of increased sludge production;
- Gaining a better understanding of the operating conditions and considerations of MBR BNR systems;

- Providing a parent system from which further testing into the kinetics of a MBR BNR system could be performed (Parco *et al.* 2006).

1.5 RESEARCH APPROACH

In order to address these objectives two parallel lab-scale conventional and membrane activated sludge systems were operated under laboratory conditions allowing their behaviour to be monitored and their performance compared. In order to verify the previous results the same original experimental apparatus and operational conditions were adopted from Ramphao *et al.* (2004) and testing continued. Samples drawn from these parent systems would enable kinetic testing of the membrane sludge to be performed. The kinetic studies on the MBR system are reported in Parco *et al.* (2006). Additionally the MBR system was, subsequent to the completion of the parallel investigation, run at a longer sludge age by Mahimba *et al.* (2006) in order to investigate sludge production in the MBR system further.

Chapter 2 of this report is a literature review of current knowledge in MBR systems for BNR applications. The methodology of the research approach is presented in Chapter 3, followed by the results of the MBR and conventional systems presented in Chapters 4 and 5 respectively. A comparative discussion is presented in Chapter 6 while conclusions and recommendations for further study are presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The application of membranes to solid liquid separation in biological reactors was first suggested in 1969 (Smith 1969, cited in Brindle *et al.*, 1996). Since then membranes have evolved significantly, particularly in the last decade through research and application. Churchouse *et al.* (1999) note that up until the mid 90s the advancement of MBR technology was hindered by two primary disadvantages, namely that it was expensive and there was concern over the membrane failure rate. "MBR's were untested, complex and generally small scale" (Churchouse *et al.*, 1999). However in the last 10 years there has been a dramatic increase in their use for wastewater treatment with typical applications to industrial wastewaters, domestic wastewaters and specific municipal wastewaters where a smaller plant footprint, water reuse or stringent discharge standards were required (Lesjean *et al.*, 2004; Yang *et al.*, 2005).

Advantages reported for MBR systems are that:

1) All biological solids and high molecular weight solutes (Sutton *et al.*, 1994, cited in Brindle and Stephenson, 1996) are retained in the bioreactor producing an effluent that is of consistently completely solids free and of a high quality. This makes membrane systems very suitable for reuse applications (Howell, 2003).
2) As all solids are retained in the bioreactor the solids concentration can be increased substantially, thus reducing the required volume of the bioreactors.
3) The process can be run at long sludge ages (>50 days) which favours slower growing micro-organisms making the system more robust to load variations and toxic shocks (Lesjean *et al.*, 2004, Brindle *et al.*, 1996).
4) The microscopic pore size prevents pathogens and micro-organisms passing into the effluent making tertiary treatment, and reuse of the wastewater easier.

Applications for MBRs range from small to large scale aerobic municipal water treatment plants, and aerobic and anaerobic industrial water treatment plants. Anaerobic MBRs have been shown to be very efficient (Brindle *et al.*, 1996). Various membrane sizes based on pore sizes are available from micro-filtration (0.1-0.3μm) which will retain all bio-solids and some viruses, ultra-filtration (5nm-0.1μm) retaining all solids and viruses, and nano-filtration (2nm) which serves specific niche applications. Due to their excellent performance, low trans-membrane pressure (TMP) requirements and cost, micro-filtration units are used for most applications (Fane and Chang, 2002).

2.2 CURRENT MEMBRANE TECHNOLOGY

2.2.1. Membrane Configurations

Currently three membrane configurations, hollow fibre submerged membranes, plate-and-frame submerged membranes and external tubular side stream modules are available on the marketplace (Lesjean *et al.*, 2004).
Up until the mid-90's mainly external side-stream configurations were used whereby sludge from the reactor was pumped from the bioreactor and through an external membrane. High power requirements with resulting high costs were thus the primary limiting factor to the widespread application of MBR's up to this point. In the late 80's it was proposed to include membranes in the bioreactor (Yamamoto *et al.*, 1989) and by the mid 90's the submerged membrane bioreactor (SMBR) had become more common place. To scour the membranes cross-flow velocities were applied to the surface of the membranes. Initially cross flow velocities were achieved by hydraulic means, for instance using paddles. However the use of aeration to provide cross flow velocity instead greatly improved the viability of MBRs by reducing power requirements (solid liquid separation occurred in the bioreactor) and the biological oxygen requirements and membrane scouring could be achieved with one process (Brindle *et al.*, 1996).

Lesjean *et al.* (2004) drew the following conclusions from comparing the three configurations:

1) Submerged membrane configurations required less capital costs and consumed substantially less energy.
2) Although hollow fibre modules were more cost-competitive than flat-sheet modules, they required more equipment.
3) A broader range of materials is available for flat sheet and tubular side-stream membranes making them more versatile for various applications where properties like resistance to chemicals and heat are important. Hence flat sheet and tubular side-stream membranes are more suitable to difficult industrial applications.
4) Due to higher MLSS concentrations external side-stream MBR systems are generally more compact and require a smaller surface area.
5) Both submerged configurations require the biological reactor to be large enough to accommodate the membranes. Flat sheet membranes require a greater volume to surface area than hollow fibre membranes. Thus in applications where the volume required for the solid liquid separation step is limited, hollow fibre, or external tubular configurations would be preferential.

The majority of municipal wastewater MBR applications use an SBMR configuration whereas industrial applications commonly use the external configuration.

2.2.2. Commercial Membrane Application

Up until the early 90's commercial membrane technology was limited to small flow applications where connections to larger treatment works were not feasible. As noted above this limitation was due to the high power costs of external MBRs and was overcome with the advent of SMBR systems (Yang *et al.*, 2005).

In North America four main manufacturers provide membrane bioreactor systems. They are Zenon Environmental Inc. (Canada), USFilter Memcor (USA), Kubota (Japan) and Mitsubishi-Rayon (Japan) (Yang *et al.*, 2005). Of these Kuboto supplies flat sheet panel membranes, whereas the other three all supply hollow fibre membranes. Other major membrane producers include Puron AG for hollow fibre membrance; Toray Industries Inc., Hans Huber AG and A3 GmbH for plate and frame configurations; Anglagentechnik GmbH, Techsep and Wehrle who provide external side-stream membranes (Lesjean *et al.*, 2004).

According to Yang *et al.* (2005), in 2005 there were 2259 MBR wastewater plants worldwide, of which 1527 were municipal plants and 732 industrial. Most MBR applications are still on a medium to small scale in terms of capacity: In North America of the 219 municipal wastewater treatment plants using MBR technology only 17 are larger than 10 000m^3/d, with the largest capacity plant in operation a 29 600 m^3/d. In Japan small scale SMBRs are used extensively for water recycling (Judd, 2002).

It is interesting to note the distribution of membrane configurations internationally. Hollow fibre membranes dominate the North American market, while in contrast flat-panel membranes dominate the international market. This is attributed to the presence of Zenon in North America and Kuboto in South East Asia where MBR systems are enjoying strong support (Yang *et al.*, 2005).

Lesjean *et al.,* (2004), argue that for medium to large scale municipal wastewater applications hollow fibre configurations are most competitive, whereas in small to medium scale municipal wastewater applications plate and frame technologies would have an advantage. Judd (2002) compared hollow fibre and plate-and-frame configurations from two full scale plants. He noted that the hollow fibre membranes were cheaper, but more complex, requiring backwashing equipment and regular cleaning. In contrast plate-in-frame systems were more expensive, but provided greater hydrodynamic control, were easier to maintain and ran at a lower flux. Both systems produced no significant odours, but foaming did occur in the aeration basin due to the high aeration rates.

For industrial applications external side-stream MBRs have enjoyed preference due to their perceived suitability to high temperature, high organic strength, extreme pH, high toxicity and low filterability (Yang *et al.*, 2005). However Yang et al (2005) reports that there are no apparent reasons submerged membranes could not treat such industrial wastewaters as well. Lesjean *et al.* (2004) are in agreement and argue that all three MBR configurations are competitive for industrial wastewater treatment.

2.3. MEMBRANE DESIGN CONSIDERATIONS

2.3.1. System Design

Ramphao *et al.* (2004a) conducted a study on BNR AS system design with a SMBR in place of a conventional SST. They concluded that the use of membranes for solid-liquid separation in BNR AS systems makes a significant difference to the design of BNR systems and the approach to wastewater treatment plant design. In particular anaerobic, anoxic and aerobic zone mass fractions can be varied (within a range) by adjusting the inter-reactor recycles allowing the optimization of biological N and P removal corresponding to the influent wastewater characteristics. Essentially the simplified design procedure is as follows: With the zone mass fractions and recycle ratios determined for biological nutrient removal the PWWF determines the surface area of membranes required based on their specified operational flux. The membranes have an aerobic zone volume and aeration requirement. If the aeration requirement for the membranes can meet the biological aeration demand then the membrane one requirement will size the aerobic reactor. If the membrane aeration requirement cannot meet the biological aeration requirement then the aerobic reactor must be sized to include the membranes and additional aeration devices. Thus accurate aeration information is essential to the design. The sludge age of the system is then determined by the required MLSS concentration in the aerobic reactor. For a detailed design procedure examining the impact of submerged membranes on the design of BNR AS systems see Ramphao *et al.* (2004a).

Bratby (2002) presented considerations for the choice of membranes for a WWTP upgrade, where space constrictions and high water reuse quality necessitated the use of membranes. Both hollow fibre and flat sheet membranes were considered with principle differences in their design being the operational MLSS concentration (10 000mgTSS/ℓ and 12 500mgTSS/ℓ respectively), the aerobic zone volume of the membranes and the biological and membrane aeration requirements. The flat sheet membranes, in a single storey configuration, had a lower surface area to reactor volume ratio ($8.5m^2/m^3$), compared to the hollow fibre membranes ($27.6m^2/m^3$), resulting in difficulties accommodating both the membranes and adequate aeration devices. However double storey plate and frame configurations (as recommended by Kubota for such an application) were not considered. Bratby (2002) indicated concern regarding several uncertainties in the operation of MBR full scale plants including operation and aeration performance at high MLSS concentrations.

2.3.2. Modelling of MBR Systems

In order to design activated sludge systems using membranes a theoretical model is required. Bratby (2002) reported doubt in design that the simulation package BioWin could adequately predict the system performance due to high MLSS and retention of all solids, and recommended that simulations be calibrated to full scale plants to resolve this. Cornel *et al.* (2003) state that operational experience shows the MBR's can be modelled by the activated sludge models ASM1 and ASM3 by the International Water Association (IWA). Lee *et al.*, (2002b) developed a model combining ASM 1 with a membrane fouling model in order to predict the performance of the membranes. Guadix *et al.* (2004) developed a model for the prediction of membrane performance and life-cost.

2.4. OPERATIONAL ISSUES OF MBR SYSTEMS

2.4.1. Operational Experience of MBR Systems

Yang *et al.* (2005), conducted a survey of MBR plant operators in North America to assess the performance of full scale MBR systems. Benefits of MBR's cited by operators in Yang *et al.* (2005) include:

1) High quality effluent
2) Space savings enabling plant upgrading without land expansion
3) Shorter start up times compared to conventional plants
4) Low operating and maintenance manpower requirements

Disadvantages cited in Yang *et al.* (2005) included:

1) Bioreactor foaming
2) Low Oxygen transfer efficiencies
3) Membrane fouling
4) Requirement for rigorous membrane cleaning
5) Lower than anticipated membrane permeability

Of these disadvantages membrane fouling remains the primary concern amongst operators.

2.4.2. Sludge Production

COD is removed from biological systems by the utilization of carbon compounds with oxygen for synthesis of new biomass, production of CO_2 and energy. However Pirt (1965, cited in Witzig, 2002)) noted that micro-organisms use available COD mainly for maintenance at low growth rates, thus reducing sludge production. As sludge production and its subsequent need for disposal is a major cost of wastewater treatment plants, Kraume *et al.* (2005) argue that "wastewater treatment plants should be designed and operated such that pollutants are diverted from assimilation via biosynthesis to energy requiring functions associated with non-growth activities". In theory this is achievable by keeping biomass as close to a food limited environment as possible thereby uncoupling metabolism so that catabolism of substrate continues unaffected while anabolism is constrained (Stephenson, cited in Gander *et al.*, 2000), thus achieving a reduction in biomass yield. The above can be achieved in long sludge ages (Low F/M) activated sludge systems but the COD mass balance measures that influent COD not harvested as sludge production is COD directed to oxygen demand.

Maintaining low F/M ratios result in minimum sludge production (Brindle *et al.*, 1996). Low sludge productions of 0.26kgTSS/kgBOD for an aerobic MBR with sludge age of 57 days (Davies *et al.*, 1998) and 0.2kgTSS/kgCOD for a MLE MBR system with 50 day sludge age (Buisson *et al.*, 1998) have been reported. Rosenberger *et al.* (2002) ran a submerged membrane bioreactor with anoxic and aerobic zones for 534 days with minimal sludge wasting and concluded that for very low feed to micro-organism (F/M) ratios virtually no excess sludge was produced apart from the accumulation of inorganic particulates. Rosenberger *et al.*, (2002) suggested that bacteria in the highly concentrated sludge of an MBR are limited by organic carbon and the physiological state of most cells was not characteristic for growing cells. Masse et al (2006) reported a decrease of sludge production from 0.31 to 0.13 mgVSS/mgCOD as SRT increased from 9 to 110 days in a fully aerobic SMBR system. In terms of COD balance based activated sludge models, the low sludge production at long sludge ages means high oxygen demand because the endogenous process has continued for a long time equivalent to enhanced aeration in which aeration sludge digestion as well as wastewater treatment takes place in the activated sludge reactor.

The minimal sludge production in the MBR at long sludge ages was also investigated by Witzig et al (2002). They noted that net biomass production is limited by the amount of energy provided, the maintenance energy demand, and cell decay and lysis which led to two hypotheses for zero net biomass generation:

1) Growth-death concept: Whereby limited substrate results in the growth rate decreasing until it equals and death rate. Hence a net zero sludge production. This hypothesis however assumes that all dead material is reused, and makes no account of inorganic material accumulating in the reactor as is suggested by Marais and Ekama (1976).
2) Maintenance energy concept: Proposed by Pirt (1965, cited in Witzig, 2002) energy for maintenance is used in preference to growth. Therefore bacterial growth will only occur if energy is supplied in excess of the maintenance energy requirements of the sludge. This hypothesis does not take into account death of organisms.

Long SRTs do have two specific drawbacks: decreased biomass viability, and the retention and accumulation of non-reactive compounds which can lead to microbial inhibition and toxicity, fouling and limited sludge disposal alternatives (Brindle et al, 1996). In industrial anaerobic MBRs with long sludge ages the accumulation of sulphur compounds is of concern (Brindle et al, 1996).

Sludge production is expected to be very similar for MBR and conventional activated sludge (CAS) systems receiving the same waste water for the same SRT, with a small increase in sludge production in the MBR system due to the retention of all solids by the membrane versus the loss of some solids through the SST (Urbain *et al* (1994), Masse *et al.*, 2006). Masse *et al.* (2006) operated two parallel aerobic AS systems, one with membrane solid liquid separation, the other with a SST. The solids lost in the effluent of the SST were measured and incorporated into the sludge wasted daily. At a SRT of 10 days the sludge production for both systems was very close demonstrating that sludge production in MBR and CAS systems is the same at the same SRT and same wastewater source (unbiodegradable particulate COD fraction, $f_{S,up}$)

2.4.3. Aeration

Aeration system design required knowledge of the capacity of the aeration device to transfer oxygen to the wastewater (Baker *et al.,* 1975). Factors impact on this capacity relate both to physical variables (reactor geometry, the mixing intensity, temperature, viscosity, reactor depth etc.) and process-related variables (SRT, nutrient and organic loading, process configuration) in the system (Baker *et al.,* (1975), Wagner and Pöpel (1998), Günder and Krauth (1999), Cornel *et al.*, (2003))

Baker *et al.*, (1975) proposed that viscosity, not MLSS concentration is a fundamental factor affecting oxygen transfer. Viscosity has a more direct influence on oxygen transfer as viscosity decreases the rate of oxygen movement from the gaseous to the liquid phase (Baker *et al.,* 1975, Rosenberger *et al.* 2002b and Gunder 2001 cited in Krampe and Krauth, 2003). The increased concentration of soluble organic matter associated with the mixed liquor increases with the increase in solids concentration.

From experimentation over a large range of solids concentrations (up to 50mgTSS/ℓ) Baker *et al.*, 1975 concluded that oxygen transfer rate (K_{LA}) decreases logarithmically with an increase in viscosity.

Krampe and Krauth (2003) investigated the oxygen transfer efficiencies (OTE) of various aeration devices and found fine bubble aerators to be the most efficient at solids concentrations up to 18mgTSS/ℓ. Thereafter the device efficiencies converged. Günder and Krauth (1999) ran three membrane bioreactors with submerged plate and frame, hollow fibre and external tubular membranes respectively. All three systems were fed the same wastewater and the sludges generated showed no significant differences. Alpha (the ratio of oxygen transfer rates in mixed liquor and pure water) was monitored as the sludge concentration in the systems increased. They noticed a significant decrease in alpha with increased MLSS concentration, from 0.5 at 8gTSS/ℓ to 0.15 at 25gTSS/ℓ. Judd (2002) noted that "Clearly the effectiveness of aeration is a key aspect of MBR technologies". The drive for low sludge production MBRs clearly has cost implications on the oxygen demand and hence transfer rate costs of the system.

2.4.4. Membrane Flux and Fouling

Membranes retain all solids larger than their pore size in the mixed liquor solution. Thus membrane failure does not compromise the effluent, instead the membranes foul and the effluent flux (m^3 effluent/m^2 surface area/ d) decreases (Trussel *et al.*, 2006). Factors that affect membrane performance (after Rosenberger *et al.*, 2006) can be listed as:

1) Membrane material and construction
2) Hydrodynamic conditions (flux, trans-membrane pressure (TMP), cross-flow velocity)
3) Operational conditions (temperature, SRT, inflow, dissolved oxygen concentration)
4) Activated sludge characteristics (MLSS, extra-cellular polymeric substances (EPS), viscosity)

Initially the solids fraction of the activated sludge was believed to have the greatest impact on membrane fouling (Brindle and Stephenson, 1996). However more recently the non-settleable fraction of activated sludge, containing colloids and solutes, is attributed to membrane fouling (Rosenberger *et al.*, 2006, Trussel *et al.*, 2006, Fleischer *et al.*, 2005). Rosenberger *et al.* (2006) concluded that the concentration of polysaccharides and other non-settleable organic compounds (eg. proteins and organic colloids), and hydrophilic properties impacted on fouling. The analysed organic substances, extra-cellular polymeric substances (EPS), are of microbial origin and are produced and degraded in the activated sludge, making the fouling of membranes by EPS a dynamic process, and easily disturbed. Factors that influence EPS include dissolved organic carbon concentrations, SRT (Trussel *et al.*, 2006), substrate type, COD:N:P ratio (Mahendraker *et al.*, 2005), feed concentration, organic loading rate, reactor type, aeration rates (Ji and Zhou, 2006) and temperature.

Ishiguro (1994, cited in Brindle and Stephenson, 1996) noted the phenomenon of concentration polarization whereby solutes would accumulate on the membrane surface forming a gel layer. This gel layer acts as a secondary membrane which reduces the flux, but retains smaller particles improving the membrane filtration. Chiemchaisri (1993, cited in Brindle and Stephenson, 1996) showed that due to the gel effect membranes with differing manufactured pore sizes (0.03μm and 0.1 μm) produced permeate with virus concentrations in the same order, i.e. both membranes had effectively the same pore size. Rosenberger *et al.*, (2006) confirmed the presence of a dynamic gel layer by demonstrating that the retention of polysaccharides improved from 70% to 100% in new and used membranes respectively while operating at similar fluxes.

Howell (1995, cited in Gander *et* al., 2000) hypothesised that there is a critical flux below which membrane fouling is minimal. Thus if membranes were run at a "sub-critical" flux the fouling is greatly reduced. Ognier *et al.*, (2002, 2004) and Cho and Fane and Chang (2002) both cited in Rosenberger *et al.*, (2006) explain membrane failure by assuming a gradual decrease of membrane pore size over time due to macro-molecular adsorption, increasing permeate velocity in pores. As the permeate velocity increases the critical flux is approached ultimately causing failure.

Thus membrane deterioration will occur over time requiring an increasing TMP to maintain the system flux (Fane and Chang, 2002). This can be achieved either by allowing an increase in the reactor head, or applying a suction pressure on the permeate line. Membrane fouling is typically controlled by surface shear often applied as a crossflow velocity, or back-flushing, or a combination of the two (Fane and Chang, 2002).

Most manufacturers recommend periodic chemical cleaning to remove biofouling or chemical precipitation (scaling) using a 0.5-2 % hypochlorite solution and 1-2% citric acid solution respectively (Darton, 1997, Kennedy, *pers com*). SMBR membranes typically require cleaning every 6 months, but systems that are run at low fluxes have been run for 18 months without cleaning and maintained operational flux, while external tubular membranes, run at high fluxes with rapid cross flow velocities reportedly require cleaning on a weekly basis (Gander *et al.*, 2000).

2.4.5. MBR Foaming

Foaming in the aerobic or anoxic reactors of MBR systems has been reported (Monti *et a*l., 2006, Trussel *et al.*, 2006) and is attributed to the high solids concentration in the reactors, and a lack of flow though in reactor design. Trussel *et al.* (2006) who observed foaming in an aerobic system controlled the foaming by placing the outlet from the aerobic reactor at the surface level of the mixed liquor recycling the foam and preventing its accumulation over time.

2.4.6. Energy Consumption

Cornel *et al.* (2003) reported high power consumption in MBR plants, 2 to 3 times higher than in conventional activated sludge plants. At MLSS concentrations of 15mgTSS/ℓ power requirements for filtration and aeration only of 1.0 to 2.0 kWh/m^3 and 2.5 to 3.5kWh/m^3 were reported for submerged MBR systems and external side-stream systems respectively (Günder and Krauth, 1999; Cornel, 2003). Of the submerged membrane power requirement 2/3 of the energy was required for generating sufficient cross-flow to control fouling. For all configurations low alpha values (section 2.4.3) due to the higher MLSS concentrations increased the power requirement for aeration. Günder and Krauth (2003) note that for the plate-and-frame and hollow fibre configurations, running the system at MLSS concentrations of 25gTSS/ℓ resulted in aeration power requirements closer to 3.0 kWh/m³.

2.5. MICROBIOLOGY OF MBR SYSTEMS

2.5.1. Microbiology

Many advantages of membranes have already been listed above, however their impact on the biology of MBRs is also significant. Witzig *et al.* (2002) note the following modifications to the activated sludge biology in MBRs:

i) a higher, often substantially so, MLSS concentration;
ii) The retention, and hence selective cultivation of slow growing, non-settleable bacteria which would otherwise be washed out in CAS plants (Liebig et al ,2001);
iii) The complete retention of cysts of parasites, eggs of worms and virtually all bacteria thus providing an effluent of very high quality.

Witzig *et al.* (2002) conducted a study into the microbial community structure and physiological state of high concentration biomass in an MLE type MBR nitrogen removal system. The system was run with minimal excess sludge removal and observations were made at sludge ages from 20d to 60d. They concluded that the bacterial population was able to mineralize the substrates (COD and N) at high and stable rates despite high biomass concentrations. Comparisons with CAS systems treating the same wastewater suggested that the MBR sludge population was more substrate limited than CAS systems. Grazing organisms were absent in the MBR reactor which are an important mechanism for cell elimination and ecological selection in CAS systems. Masse *et al.* (2006) operated two parallel aerobic AS systems at the same loading rates and SRT's, one a MBR and the other a CAS system, and conducted investigations on the sludge morphology. They observed a higher number of non-flocculating bacteria in the MBR, but the same mean floc size in both systems. As the SRT increased the floc size in the MBR system decreased and more dispersed micro-organisms were observed in the MBR. Conversely, in the CAS system, as SRT increased more filamentous organisms were observed.

Manser *et al.* (2005) undertook an investigation specifically into the performance of nitrifiers in MBR reactors. In their study two pilot scale plants in identical MLE configurations, one a MBR, the other a CAS system, were run over an 8 month period using the same influent wastewater. Systems were run at a 20d sludge age with the same operation parameter, i.e. the same wastewater, average MLSS concentrations (3680 mgTSS/ℓ and 3650 mgTSS/l respectively) and the anoxic and aerobic mass fractions were kept the same ($f_{manx} = f_{maer} = 0.50$). The only difference was the scale at which the systems were run. The CAS system had a total reactor volume of 15 m^3, while the MBR system had a total reactor volume of 0.35m^3.

Manser *et al.* (2005) noted that both systems exhibited similar maximum nitrification rates. Biofilm development on the membranes was found to have negligible contribution to overall nitrification, suggesting that cross-flow velocities and aeration prevent development of stable biofilm on the membranes.

Manser *et al.* (2005) concluded, based on observations on CAS and MBR systems run at the same sludge concentrations, that the presence of membranes does not directly influence the nitrifying community, rather the nitrifying community is influenced by operating conditions (sludge age and MLSS concentration) and wastewater characteristics. Manser *et al.* (2005) hypothesised that this is also true of other microbiological populations. The membrane does not enhance nitrification performance or protect the system from overloading as these are biological processes. However Manser *et al.* (2005) noted that smaller MBR floc sizes due to vigorous aeration result in less mass transfer effects. Manser *et al.* (2005) suggested that conventional models are adequate for nitrification, however further research would be required at the operating conditions suggested for MBR systems (ie high sludge concentrations).

2.5.2. Effluent Quality

Membrane separation provides an effluent of high quality. Membranes are able to disinfect waters resulting in the retention of all pathogenic micro-organisms in the sludge mass (Gander *et al.*, 2000). Günder and Krauth (1999) report that in three membrane systems that they investigated salmonella was absent from the system effluents, as were all indicator bacteria.

2.6. ORGANIC AND NUTRIENT REMOVAL PERFORMANCE

2.6.1. COD Removal

An abundance of literature has been published on the COD removal performance of MBR systems in either submerged (Cote *et al.* 1997, Trussel *et al.* 2006, Gander *et al.*, 2000) or external configurations (Günder and Krauth, 1999). COD removal is performed by the utilization of COD for metabolism with oxygen supplied to the system, or the incorporation of COD in the activated sludge which is removed through regular sludge wasting. Due to the inherent ability of membranes to retain all solids within the system COD removal is reliable. Consistently impressive COD removals ranging from 90-98% are reported at sludge ages from 2 to >50 days (Trussel *et al.*, 2006, Buisson *et al.*, 1998, Masse *et al.* 2006).

Günder and Krauth (1999) ran three membrane systems using submerged hollow fibre membranes, submerged plate in frame membranes and external tubular membranes with pore sizes of 0.1µm, 0.4µm and 0.1µm respectively. However the COD removals for all three systems were virtually the same due to the formation of the dynamic gel layer described in Section 2.4.4.

Masse *et al.*, (2006) reported excellent retention of EPS in the supernatant of the sludge, which contribute significantly to the improved COD removal of membrane biological reactors. Ramphao *et al.* (2004) showed the effluent COD of their nitrification-denitrification (ND) biological excess phosphorus removal (BEPR) submerged flat plate MBR system was substantially lower (35mgCOD/ℓ) than the

0.45μm membrane filtered COD (57mgCOD/ℓ) of a control system fed the same influent COD.

2.6.2. Nitrogen Removal

The mechanism for nitrogen removal in MBR systems is the same as in conventional activated sludge systems (Kraume *et al.*, 2005). Ammonia, from the influent and released into solution from the utilization of organics in the wastewater and sludge, is converted first to NO_2 then to NO_3 in the aerobic reactor by autotrophic nitrifier organisms. NO_3 in the anoxic reactor is used as a terminal electron acceptor by facultative heterotrophic organisms for the utilization of COD and is converted to nitrogen gas and released into the atmosphere. Additionally nitrogen is incorporated into the sludge mass through synthesis and removed through sludge wasting.

Nitrification

Nitrogen removal has been shown to be equal or better in MBRs than in conventional activated sludge (CAS) systems due to longer SRT and smaller floc sizes which allow better transport of nutrients and dissolved oxygen to the flocs (Hakani *et al.*, 1990, cited in Gander *et al.*, 2000). Kraume *et al.* (2005) report that most MBR plants achieve total nitrification (<1mgN-NH_4/ℓ). However the high MLSS concentrations, which increase the sludge viscosity and affect its rheology, result in poor mixing and the formation of anoxic micro-zones, which can induce simultaneous nitrification denitrification (Rosenberger *et al.*, 2002) in the aerobic MBR. This can be beneficial but is at the cost of membrane fouling and poor aeration performance induced by high MLSS concentrations.

As with CAS systems nitrification in MBR systems is sensitive to feed characteristics and operational parameters: SRT (Trussel *et al.*, 2006), DO concentration (Hakani *et al.* 1990, cited in Gander *et al.*, 2000), temperature (Kisino *et al.*, 1996), organic loading, pH and levels of key nutrients in the feed.

As discussed in Section 2.5.1 the ability of the membranes to retain all micro-organisms can affect the microbial population. Kraume *et al.* (2005) suggest that this will change the specific nitrification rate due to the shift in biocoenosis. Li *et al.* (2005) compared the nitrification performance of a SMBR to a CAS system. Both systems were run at long sludge ages and fed a synthetic ammonia containing inorganic wastewater. The nitrification performance of the systems was monitored as the hydraulic retention time (HRT) of the systems was decreased. In the CAS system, as the flow through the reactor increased, washout of micro-organisms with the effluent occurred. However Li *et al.* (2005) reported that this was not selective as the microbial community structure remained unchanged from before washout occurring, as non-settleable solids would wash out regardless of the HRT. In the SMBR system, as all microbial organisms were retained, the microbial community diversity only increased with the extension of the operating period. In both systems nitrification efficiency of 98% was achieved for hydraulic retention times of ≥10h and ≥20h for the SMBR and CAS systems respectively, illustrating the insensitivity of the SMBR system to high flow through rates. Fleischer *et al.* (2005) noted that the nitrifiers in an

MBR system could recover from nitrification inhibition far faster than nitrifiers in conventional systems indicating that nitrification in MBR systems is far more robust.

Parco *et al*, (2006) showed that the specific growth rate of nitrifiers (μ_{nm}) decreases in the MBR system compared with a conventional system. It is hypothesised that the decrease in μ_{nm} is due to the retention of non-settleable, slower growing nitrifiers in the MBR system. Parco *et al.* (2006) however concluded that an increase in the minimum sludge age for nitrification (R_{sm}) has little influence on the performance of MBR systems as they are typically run at sludge ages substantially longer than R_{sm}.

Denitrification

Two configurations for denitrification were reviewed in the literature: Pre-denitrification and post-denitrification.

Pre-denitrification utilizes a primary anoxic reactor, placed upstream of the aerobic reactor and receives the influent flow. A recycle from the aerobic reactor loads NO_3 and sludge mass to the anoxic reactor where the NO_3 can be utilized as electron acceptor for synthesis of biomass and the N released as nitrogen gas. Advantages of the pre-denitrification configuration cited in Kraume *et al.* (2005) are:

1) Substantially higher denitrification rates are possible due to the presence of influent COD: the readily available carbon source stimulates faster denitrification rates compared to endogenous denitrification rates.
2) As NO_3 is used as electron acceptor the oxygen demand in the aerobic reactor is reduced.
3) Half the alkalinity removed in the nitrification step is recovered by denitrification, stabilizing the pH.

With a pre-denitrification reactor, nitrate removal is limited by the rate of the recycle, and so complete N removal is practically not possible.

Post-denitrification utilizes the secondary anoxic reactor downstream of the aerobic reactor, ensuring all NO_3 generated in the aerobic reactor passes through the anoxic reactor and so theoretically can be denitrified. However, as most of the influent COD is degraded in the upstream aerobic reactor denitrification in the post-anoxic reactor is carbon limited, typically with slow endogenous denitrification rates. COD (methanol) dosing to the secondary anoxic reactor may be required to increase denitrification rates and to enable complete denitrification. Gnirss *et al.* (2003) states the following advantages for post-denitrification with carbon dosing over pre-denitrification in MBR systems:

1) The saving in biological oxygen demand by using influent organics in preference to carbon dosing is considered insignificant due to the high energy requirements in the aerobic MBR for aeration and cross flow velocity scour of the membranes.
2) MBR systems tend to result in poor primary anoxic denitrification rates (K_1) making denitrification in primary and secondary anoxic reactors comparable. Reasons for decreased K_1 values in MBR systems cited by Vocks *et al.*, 2005 were the increased MLSS concentration and high oxygen carry over from the

aerobic reactors. Vocks *et al.* (2005) also reported increased secondary anoxic denitrification (K_3) rates linked to an increased glycogen accumulating organism (GAO) population that could utilise stored glycogen as carbon source in the post-anoxic reactor. The occurance of GAO bacteria in full scale plants fed municipal wastewater is rare and so this observation should not be accepted as a general conclusion for all secondary anoxic reactors.

3) Less pumping and recycling equipment is required to obtain N removal and complete N removal is possible.

Kraume *et al.* (2005) proposes post-denitrification with carbon dosing, on the basis of (1) above, as a promising configuration in MBR technology.

2.6.3. Phosphorus Removal

Two methods of P removal are typically employed. The first is chemical precipitation whereby phosphate is transformed to a precipitating iron, aluminium or calcium salt which accumulates in the sludge and is removed in the waste stream (Kraume *et al.*, 2005). Disadvantages of this method, listed in Lesjean *et al.* (2003), are an increase in sludge production (up to 25%), additional chemical consumption, increase in the salinity in the effluent, adverse impacts on biological nitrification and reduced sludge reuse in agricultural and other applications.

The second method to remove P is for it to be incorporated into the biological sludge mass. Although this occurs normally to a small degree (0.03mgP/mgVSS) it can be augmented by biological excess phosphorus removal (BEPR). With BEPR the growth of specialised organisms in the sludge, phosphorus accumulating organisms (PAOs) that store substantial intracellular polyphosphates (0.38mgP/mgVSS, Wentzel 1990), are encouraged through the implementation of an anaerobic reactor at the head of the activated sludge reactor. The presence of PAOs in significant numbers, which take up volatile fatty acids (VFAs) produced from the influent readily biodegradable COD in the anaerobic reactor, increase the overall P content of the sludge, and excess P removal is achieved through normal sludge wasting. Wentzel and Ekama (1997) noted that increasing sludge age above 5 days decreases P removal per unit influent COD. This is due to the reduced PAO active fraction of the sludge as only active PAOs retain internal polyP which, upon death the P is returned to solution through lysis. Thus the sludge age of the system cannot be increased without impacting significantly on P removal efficiency. Hence for MBRs with longer sludge ages, P removal has been ensured with additional chemical precipitation (Kraume *et al.*, 2005).

Because MBRs consistently retain all solids in the bioreactor, the significant contribution that the loss of solids in the effluent makes in CAS systems to the effluent P concentration is prevented. Additionally the aerobic separation step in MBRs "fixes" the phosphorus in the sludge when the effluent is separated from the sludge (Gnirss *et al.*, 2003). Therefore MBRs can produce better consistent P removal.

2.7. PREVIOUS STUDIES ON BNR IN MBR SYSTEMS

2.7.1. Ruhleben WWTP, Berlin, Germany.

In order to investigate NDBEPR in MBR systems under pre-denitrification and post-denitrification conditions Lesjean *et al.* (2003, 2005) ran a bench scale plant (BSP) and two pilot plants (PP1 and PP2) in parallel with the conventional Ruhleben WWTP in Berlin. The BSP plant was run first in the pre-denitrification MUCT configuration (BSP1), and subsequently in the post-denitrification configuration (BSP2), in both cases with an upstream anaerobic reactor. PP1 was a UCT configuration, and PP2 a post-denitrifying system with upstream anaerobic reactor. All systems were fed wastewater from the same source and monitored over a 2-year period. System configurations and parameters are listed in Table 2.1.

Table 2.1: *System parameters for the Ruhleben MBR investigation*

	Unit	MBR			Conv.
System		BSP1	PP1	PP2	Ruhleben
Influent Flow	m^3/d	0.24	2.6	2.9	240 000
Influent COD	mgCOD/ℓ	998	740	740	740
Influent TN	mgN/ℓ	70	61	61	61
Influent TP	mgP/ℓ	10.5	9.1	9.1	9.1
Reactor Vol.	m^3	0.21	2.0	2.2	198 500
Sludge Age	d	15	26	26	15-18
Aerobic TSS	gTSS/ℓ	6.2	10	10	3-5
Approx f_{Mana}	%	0.09	0.10	0.10	not available
Approx f_{Manx}	%	0.40	0.45	0.50	not available
Approx f_{Maer}	%	0.51	0.45	0.40	not available

In all MBR systems the COD and nutrient removal was comparable or better than the conventional system indicating that the membranes did not adversely affect nutrient removal, but in fact improved effluent quality. The MBR systems produced effluent COD removals of 96% (36mgCOD/ℓ effluent) in comparison to the 95% of the conventional WWTP.

Initially the BSP system was run to assess the feasibility of BEPR in a MBR system and run in a MUCT configuration (Adam *et al.*, 2002). This was followed by retrofitting the BSP to investigate the feasibility of a post-denitification MBR configuration. Following the initial BSP investigations the two pilot scale systems, PP1 and PP2, were run for sludge ages of 26, 22, 8 and 15 days respectively over successive 6 month periods at 12-15 °C. Both pilot systems exhibited similar COD, N-NH_4 and TP removals. Effluent P concentrations in all systems were consistently low (0.5mgP/ℓ), however, due to the presence of calcium and ferric ions in the wastewater, precipitation of P was observed which left doubt as to the extent of biological P-removal performance. Thus in order to assess the biological P removal performance the BSP system was spiked with excess P such that the system would not be P-limited. Taking into account the P precipitation the biological P removal was estimated as 14-19mg P/ℓ in BSP1 and 24-26mgP/ℓ in BSP2. The improved P removal performance in BSP2 can be attributed to the immediate transition of anaerobic to aerobic zones hence preventing anoxic P uptake which often decreases P removal. However only details of the BSP2 system mass fractions were reported, hence it is difficult to fully assess the P removal performance. It was noted that the P content in the sludge was typically 2-3% P/TS in PP1 and PP2, however in the BSP system, where excess P was supplied, 6.4 and 7 % P/TS were observed in BSP1 and BSP2 respectively.

As was expected total N removal was better in PP2 with almost complete N removal, 94% (3.6mgN/ℓ), compared to 82% (11.0mgN/ℓ) N removal in PP1 due to the recycle limitation. This is an advantage of the post-denitrification system. However at short sludge ages the denitrification of the PP2 system became unstable and could not produce consistent N removal, while PP1 could. Vocks *et al.* (2005) investigated denitrification rates in the systems by running batch tests on anoxic sludge. They reported K_1 rates (presumably on influent RBCOD) of up to 3.2mgN/mgVSS.h in the primary anoxic reactor, and noted K_3 rates (presumably on endogenous organics) of 0.2-0.6 mgN/mgVSS.h in the secondary anoxic reactor of PP2 which are faster than those expected for endogenous respiration which is assumed to provide the carbon source in post-denitrification systems. The improved post-denitrification rates were hypothesised by Vocks *et al.* (2005) to be due to stored glycogen in denitrifying organisms.

A major concern of post-denitrification is that slower denitrification rates require a substantially larger anoxic mass fraction than pre-denitrification configurations. Hence there is a need to dose COD to the secondary anoxic reactor in order to decrease the f_{Manx} requirements. It is interesting to note that both systems had effectively denitrified mid-way through the flow through anoxic reactors suggesting that they were underloaded and hence the systems were not optimized in so far as the mass fractions of the different zones were concerned. Thus, from this investigation, it is difficult to gauge the impact of post-denitrification over pre-denitrification in terms of system anoxic mass fractions.

2.7.2 Korea Institute of Science and Technology

Ahn *et al.* (2003) operated two lab scale MBRs, one as a sequencing anaerobic/anoxic membrane bioreactor (SAM) and the other a MLE MBR configuration. System mass fractions were $f_{Man/ax}$ = 40% and f_{Maer} = 60% respectively. The systems were monitored for 35 days after achieving a sludge age of 70 days, and a MLSS concentration of 10 100 – 11 100 mgTSS/ℓ. The feed composition ratio was 61/9.5/1 (mgCOD/TN/TP). P removal was substantially better in the SAM system (93% 0.26mgP/ℓ) than in the MLE system (45% 2.0mgP/ℓ), due to the presence of the anaerobic zone in the SAM. However the BEPR potential of the system was not demonstrated as excess P was not dosed with the influent. TN removal in the SAM system was poor, 60%, due to the reduced anoxic zone mass fraction and hence reduced denitrification. The MLE system achieved 67% TN removal. The authors noted that better TN removal could have been obtained with a larger anoxic mass fraction. The experiments demonstrate that the performance of parallel MLE and BEPR systems cannot be compared because each has a different objective and favours the removal of one nutrient or the other.

2.7.3. University of British Columbia

Monti *et al.* (2006) compared and evaluated the enhanced biological phosphorus removal (EBPR) performance of two 2500ℓ pilot scale BNR systems using membranes and SST's respectively for solid liquid separation. A commendable effort was made in the study to keep the operational and design parameters of both systems identical. The only differences were the method of solid liquid separation and the presence of the SST which effectively increased the system volume of the conventional (C)EBPR system.

Both systems were in UCT configurations with system volume fractions of 0.11, 0.28 and 0.61 for the anaerobic, anoxic and aerobic reactors. Solid liquid separation was effected in the aerobic reactor for both (in the CEBPR system sludge from the SST was recycled back to the aerobic reactor). The systems were operated at sludge ages of 12 days, and HRT of 10h and 7h for different periods of the study. The systems were loaded equally with feed, and wasted according to the total sludge in the system including that in the SST of the conventional system, to achieve a SRT of 12 days. The operational and system parameters are summarised in Table 2.2.

Table 2.2: *System and operational parameters for UBC MBR and Conv. comparison study*

System	Units	MBR	Conv
Reactor vol.	ℓ	2228	2228 (+ 900)
Sludge age	d	12	12 (9.5)
Aerobic TSS	mgTSS/ℓ	3500[1]	2800[1]
f_{Mana}	-	0.04	0.04 (0.03)
f_{Manx}	-	0.21	0.21 (0.37)
f_{Maer}	-	0.75	0.75 (0.60)

[1] = approximate values;
Values in parentheses take into account the influence of the clarifier on the conventional system.

Due to the presence of two large clarifiers (450ℓ each), which contained approximately 20% of the CEBPR system sludge, the MLSS concentrations in the reactors of the CEBPR system were consistently lower, at 80% of those in the membrane (M)EBPR system, 3500 and 2800 mgTSS/ℓ in the MEBPR and CEBPR systems respectively. Hence although the CEBPR and MEBPR systems had proportionally the same mass fractions, the SST in the CEBPR system caused a lower effective aerobic mass fraction and aerobic sludge age (9.5 d vs 12 d in the MEBPR system).

The COD removal of both systems was good with 92 and 90% COD removal in the MEBPR and CEBPR systems respectively. Monti *et al.* (2006) noted that the COD removed via utilization with oxygen in the MEBPR system was substantially higher (27% of COD removal vs 18% in the CEBPR system). This observation was attributed to the higher effective aerobic sludge age and supported by the decreased sludge production in the MEBPR. The CEBPR system produced 15% more sludge than the MEBPR system which is also attributed to a longer aerobic sludge age and the additional degradation capacity of the system. Monti *et al.* (2006) noted that previous literature argue both greater and lesser sludge production for MBR systems, and suggest that sludge production is rather a function of system configuration and operating conditions than merely retention of more solids by membranes. N removal by both systems was good, with superior denitrification in the CEBPR system attributed to denitrification in the SST.

The EBPR performance varied in both systems through the study. Frequent Bio-P failure was attributed to

i) VFA limitation due to changes in temperature, dilution of COD in the influent feed and reduced denitrification capacity of the MEBPR system which resulted in nitrate being recycled to the anaerobic reactor. This limited the VFA's available for sequestration by the PAOs in the anaerobic reactor.
ii) The shorter aerobic sludge age in the CEBPR system resulted in greater sludge production and hence increased P-removal capacity.

The lower sludge yield (due to increased sludge age) and lower denitrification capacity of the MEBPR (due to increased anoxic volume in the CEBPR system) affected the MEBPR system's P removal performance. However Monti *et al.* (2006) suggested that this could be compensated for by carbon addition to ensure P-release is not carbon-limited and by including post-denitrification in the system design to increase denitrification capacity. On average both systems produced comparably low soluble P in the effluent illustrating that EBPR is feasible with membranes. Additionally the MEBPR system retained all solids in the aerobic reactor and hence no P escaped as sludge with the effluent producing a reduced TP concentration compared to the CEBPR system. However the extent of biological P removal could not be determined as the system was P-limited. It must be noted that both f_{Mana} and f_{Manx} were very small thus limiting PAO and denitrification activity respectively.

Prior to concluding the study the CEBPR system was converted to a MEBPR system by the insertion of a membrane module in the aerobic reactor. The system was monitored for four months and the system adapted quickly. This indicated that a smooth upgrade of a MEBPR system is possible.

Monti *et al.* (2006) concluded that under carbon-limited conditions the CEBPR system performed better due to its increased sludge production and additional denitrification capability, though this was at the cost of the additional volume requirements for the SST. The MEBPR system proved to be more robust as it recovered far faster than the CEBPR system after bio-P failure due to its ability to retain all solids.

2.7.4. University of Guelph

Mouthon-Bello and Zhou (2005) conducted a study on a pilot submerged membrane bioreactor with BNR. The pilot scale plant was operated at an average of 18.5°C in an anoxic-anaerobic-aerobic configuration with mass fractions (0.17:0.33:0.50) over two periods for sludge ages of 20 days and 50 days respectively. An average influent feed ratio of 100:17:3 mgCOD:mgN:mgP was fed to the system. Influent unbiodegradable COD fractions of 0.09mgCOD/ℓ and 0.20mgCOD/ℓ for $f_{S,us}$ and $f_{S,up}$ respectively were assumed. At a 20 day sludge age removals of 89% (35mgCOD/ℓ), 82% (11mgTN/ℓ)) and 94% (0.05mgP/ℓ) were reported, compared to removals of 92% (31mgCOD/ℓ), 78% (14mgTN/ℓ) and 90% (0.1mgP/ℓ) at a 50d sludge age.

In order to maintain system mass fractions the volumes of the reactors and the sludge recycle were adjusted for the two sludge ages. Consequently the changed sludge recycle affected the nitrate load (N_{nL}) to the anoxic reactor and the denitrification potential (D_{PP}) was influenced by increased reactor volume and solids concentration without any change to influent COD. Thus there were differences in the N removal performance at the two sludge ages that are system specific. Ferrous chloride was dosed to the influent feed thus providing high P removal through precipitation but no indication of biological P-removal performance. Due to the reactor configuration of having the anoxic reactor upstream of the anaerobic reactor most readily biodegradable COD would have been utilized for denitrification resulting in limited COD for acquisition by POAs and hence limited biological P removal potential. Thus without COD dosing to the anaerobic reactor, which was not reported, little biological P removal would have been possible thus making the anaerobic zone mass fraction redundant.

A significant difference in the aerobic and effluent NO_3 concentrations was reported (8.7mgN-NO_3/ℓ vs 17.5mgN-NO3/ℓ at 50 day sludge age) which could not be readily accounted for despite efforts to minimize biological activity while handling the aerobic sample. Sludge production at a 20 day sludge age was reported as 0.39(mgTSS/d)/(mgCOD/d).

2.7.5. Loudoun County Sanitation Authority

Fleisher *et al.* (2005) conducted a pilot scale study over an 8 month period using MBR technology coupled with BNR activated sludge and chemical treatment systems to achieve very strict effluent nutrient discharge requirements of <3mgN/ℓ and <0.1mgP/ℓ. Three MBR BNR configurations were investigated, namely:

- a 4-stage process with a de-aeration stage between the MBR reactor and the primary anoxic reactor,
- a 4 stage system, and
- a 5-stage system including an anaerobic reactor at the head of the system.

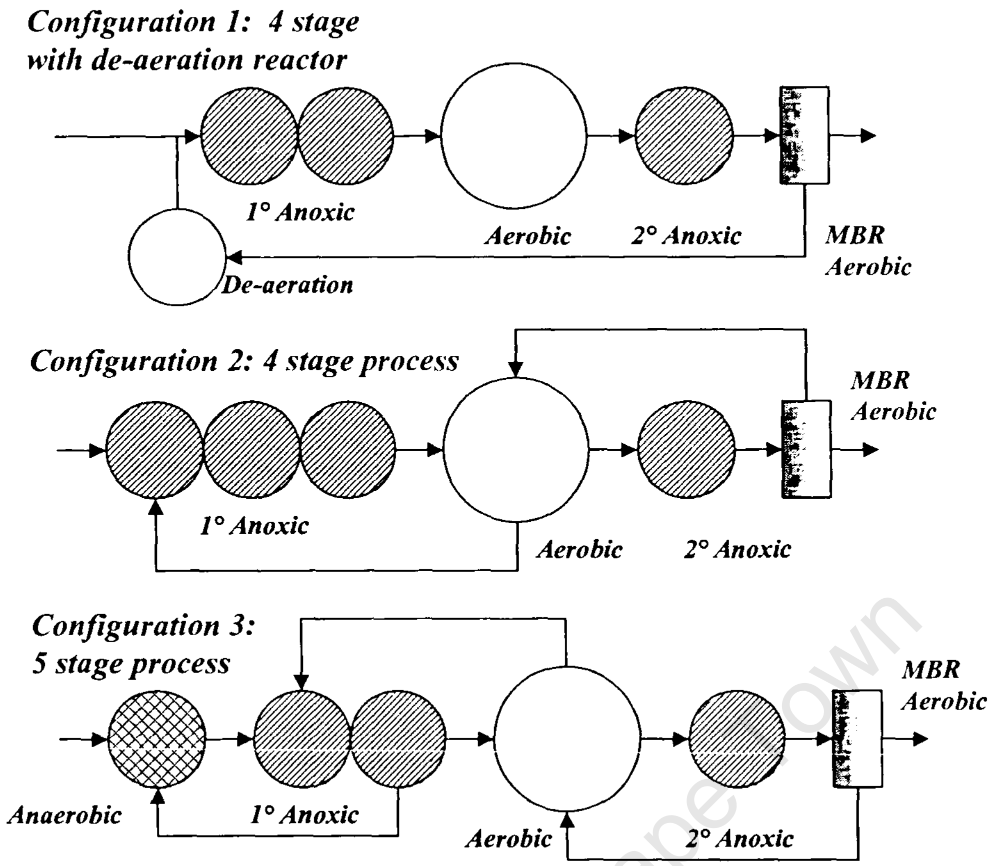

Figure 2.1: *Three BNR configurations were investigated for the Loudoun County MBR study: a 4-stage system with de-aeration reactor, a 4-stage process and a 5-stage process including an upstream anaerobic reactor.*

A schematic of the systems is presented in Fig 2.1. The first two configurations were run in order to ascertain the influence of recycled oxygen from the heavily aerated MBR reactor to the anoxic zones of the system on the BNR performance of the system. Following these investigations the system was run in the third configuration with varied concentrations of methanol dosed to the 2° anoxic reactor and alum dosed to the MBR aerobic reactor in order to observe their effects on N removal and P removal respectively.

Influent wastewater nutrient ratios of 100:13:2 mgCOD/mgN/mgP were reported. The systems were run at sludge ages of between 19-23 days and no indication of the system recycles and mass fractions was given. This omission is unfortunate as these parameters are necessary to assess system N and P removal performance.

System average MLSS concentrations varied through the investigation from 4000 to 9000mgTSS/ℓ with a system average VSS/TSS ratio of 0.80 for BNR performance alone and 0.70 with the additional influence of chemical precipitation due to alum dosing. The alum was dosed in the MBR aerobic reactor in order that as much BEPR as was possible would have taken place prior to chemical precipitation. However de Haas *et* al. (2001) showed that with simultaneous precipitation chemical dosing can progressively displace BEPR, particularly when low P-concentrations (<1.0mgP/ℓ) are required.

The membrane filterability was found to be strongly influenced by the filtration characteristics of the sludge. Fouling was assumed to be a result of colloidal solids not naturally incorporated into the activated sludge flocs. The addition of alum however caused these colloids to be included in the activated sludge flocs and hence improved sludge filterability. The system solids were found to be floc forming despite the turbulent conditions induced by the MBR. Pathogen counts were negligible with e-coli counts of <2cfu/100ml and 5-log virus removal.

Expected nitrification performance, determined from model predictions, was observed with a total N concentration of 3mgN/ℓ obtained with methanol dosing to the 2° anoxic reactor to aid denitrification in the third configuration. When nitrification inhibition occurred the system would recover quickly demonstrating that the MBR system retained a robust nitrifying population. Prior to alum dosing BEPR was observed with P concentrations dropping from 6mgP/ℓ influent to 3mgP/ℓ effluent. With the addition of alum almost complete P removal was possible (<0.1mgP/ℓ). Both N and P removal performances were closely predicted using IWA ASM 2d indicating that ASM 2d could adequately model BNR performance.

Sludge production varied according to the organic load on the system and the chemical dosing of methanol and alum. Prior to chemical dosing an average system sludge production of 0.25(mgVSS/d)/(mgCOD/d) was observed. The sludge was additionally examined for dewatering and sludge handling purposes. In comparison to conventional sludges treated from the same influent wastewaters a higher solids cake could be produced from the MBR sludge (14.7% vs 12.7%). It was concluded that MBR MLSS characteristics were within those expected for a long SRT BNR process.

2.7.6. UCT Water Research Group

Ramphao *et al* (2004) conducted an in depth study of the BNR performance of a MBR system. Two UCT configured systems were run in parallel: the first a MBR BNR system with membranes located in the aeration reactor, and the second a conventional activated sludge system with a secondary settling tank. Both systems were run at their design solids concentration, i.e. the conventional system at low solids (~3500mgTSS/ℓ) and the MBR system at high solids (~18000mg/TSS/ℓ) for effective cross-flow scour. They were fed from the same feed, and design parameters such as the sludge age, zone mass fractions and recycles were kept the same. In order to assess the BNR performance of the systems RBCOD was dosed into the feed in order to accentuate BEPR performance, thus allowing P removal to occur without being P limited. The UCT WRG investigation (Ramphao *et al.*, 2004) forms the basis of this investigation and is referred to as the Phase 1 investigation. The objectives and methodology of this investigation stem directly from the initial work of Ramphao *et al.* (2004) and are described in detail in Chapter 3.

2.7.7. Summary

In summary six investigations were reviewed in which membranes had been used in conjunction with BNR processes, and where nutrient removal had been observed and quantified. Table 2.3 summarises the investigations, their design configurations and operational parameters, and the removals they reported.

Table 2.3: Summary of MBR BNR investigations reviewed

Study	System configuration	Zone mass fractions			Aerobic MLSS	Rs	N-removal	P-removal	modelling
		fmana	fmanx	fmaer	gTSS/l		%	%	-
Ruhleben, Germany (Lesjean *et al.* 2005)	Pre-denitrification	0.1	0.45	0.45	10	26	82 (11.0mgN/l)	99 (ppt[1]) (0.06mgP/l))	no
	Post denitrification	0.1	0.5	0.4	10	26	94 (3.6mgN/l)	99 (ppt[1]) (0.07mgP/l)	no
Korea IST, S Korea (Ahn *et al*. 2004)	SAM	0.4		0.6	10.5	70	60	93 (0.26mgP/l)	no
	MLE	0	0.4	0.6	10.5	70	67	45 (2.0mgP/l)	no
UBC, Canada (Monti *et al*. 2006)	UCT	0.04	0.21	0.75	3.5	12	63.8	97 (bio) (0.2mgP/l)	no
Guelph, Canada (Mouthon & Zhou, 2005)	anaerobic-anoxic-aerobic	0.33	0.17	0.5	15	20	82 (11.0mgN/l)	94 (ppt[1]) (0.05mgP/l)	no
		0.33	0.17	0.5	16	50	78 (14mgN/l)	90 (ppt[1]) (0.1mgP/l)	no
Loudoun County, USA	5-stage bardenpho	n/a	n/a	n/a	9	21	92 (3mgN/l-COD dosed)	99 (bio + ppt[1]) (<0.1mgP/l)	yes ASM 2d
UCT WRG, RSA (Ramphao *et al*. 2004)	UCT	0.13	0.28	0.59	18	20	74 (26.4mgN/l)	BEPR: 26 mgP/l removal	yes UCTPHO

[1] = P precipitated

(COD removal not reported as >90% in all cases regardless of system)

2.8. CONCLUSIONS

Significant amounts of research have been conducted and published on the influence and performance of membranes for solid liquid separation in AS sludge systems. Much of the research has been focused on the membrane performance, to understand the mechanisms of fouling and minimize them thus improving the lifespan of membranes and their cost, or on the membrane performance in removing organic compounds or nitrogen compounds.

With increasingly stringent water quality standards internationally for discharge and reuse (Lesjean *et al.*, 2003, Howell, 2004) there is a need for wastewater treatment plants to provide effluents of a reliable and excellent standard. This can be achieved by combining membrane technology with BNR processes. Despite numerous studies on COD removal and nitrification, little research has been published on the impact of membranes on BNR performance, particularly on biological excess P-removal (BEPR), and on the applicability of current BNR simulation packages to membrane applications.

It is however difficult to compare the performances of the various systems as different configurations will give different results and system performances are specific to operating conditions and influent wastewater characteristics. Systems run in parallel can give an indication of comparative system performance but differences in recycles and mass fractions will occur due to the nature of membranes and SSTs, thus to base performance comparisons on effluent measurements alone is faulted. By running batch tests on the systems and reporting kinetic rates only systems run at the same sludge age and fed the same wastewater can be compared with each other. Thus in order to make general comparisons between different investigations the kinetic constants used for modelling, such as unbiodegradable fractions and specific kinetic rates need to be established. These are generally unavailable thus hindering useful comparisons of different investigations. Such kinetic constants are reported for this investigation in Parco *et al* (2007).

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

As described in Chapters 1 and 2 membranes for solid liquid separation in activated sludge systems offer many advantages over conventional activated sludge (CAS) systems. Membranes can produce a reliable, high quality, solids free effluent which is largely disinfected and very suitable for reuse. Membranes obviate the need for secondary settling tanks (SST's). In addition membranes allow activated sludge plants to run at high mixed liquor concentrations providing a substantial reduction in plant footprint. These advantages make membranes for solid liquid separation an attractive option in cases requiring a guaranteed high quality effluent (e.g. recycling and reuse of wastewater, or discharge to sensitive water bodies), or where space is a priority (e.g. Plant upgrades in dense city areas or areas where land is very valuable). Moreover, membrane activated sludge plants can be run at long sludge ages which together with the high mixed liquor solids concentrations produce a stable, concentrated sludge which reduces sludge thickening and further stabilization processes.

However, as noted in Ramphao *et al.* (2004) the biocoenosis of mixed liquor in membrane systems differs from CAS systems due to unique selection properties; membranes retain all micro-organisms in the system, whereas CAS systems only retain those micro-organisms that flocculate and settle in the SST's; membrane systems run at considerably higher mixed liquor solids concentrations (12000 – 18000mgTSS/ℓ) versus (3000 – 5000mgTSS/ℓ) in CAS systems. The effects of these differences on design and performance of fully aerobic biologically mediated COD removal and nitrification are well established (Brindle and Stephenson, 1996), and have been investigated for denitrification and P-removal (Kaume *et al.*, 2005, Yang *et al.*, 2006). However the optimization of membrane biological reactor (MBR) biological nutrient (nitrogen and/or phosphorus) removal (BNR) systems, the applicability of steady state design models to MBR BNR systems and the impacts of membranes on BEPR remain to be established. The main aim of this research is to address these deficiencies.

In Chapter 1, the first phase (Phase 1) of this investigation was described. Phase 1 aimed to quantitatively establish the impact of membranes on the design, operation and performance of BNR activated sludge systems (Ramphao *et al.*, 2004), and a substantial initial investigation was carried out into the impacts of membranes on design, and steady state and kinetic performance of MBR BNR systems (Ramphao *et al.*, 2004). Hence the objectives of this thesis served to:

- Verify the results obtained in the initial investigation, with particular emphasis on explaining the phenomena of excessive sludge production,
- Gain a better understanding of the operating conditions and considerations of MBR BNR systems,
- Provide a parent system from which further investigations into the kinetics of a MBR BNR system could be performed.

In order to address these objectives two parallel lab-scale conventional (CAS) and membrane (MBR) activated sludge systems were operated under laboratory conditions allowing their behaviour to be monitored and their performance compared. In order to verify the previous results the same original experimental apparatus and operational conditions were adopted and testing continued. This chapter describes the set-up, operation, and monitoring of these systems; behaviour and performances are described in Chapter 4 and 5 for the MBR and CAS BNR systems respectively, and Chapter 6 compares the system performances with each other and previous studies on similar systems.

3.2 RESEARCH APPROACH

With the research approach for Phase 2 adopted from Phase 1, two parallel BNR activated sludge systems were run, at lab scale, under controlled conditions, one a MBR system and the other a CAS system with a SST. The two systems had identical design and operating parameters, such as anaerobic, anoxic and aerobic mass fractions, recycles and sludge ages. The major difference between the two systems was the amount of feed fed to the MBR system, which was fed a little over three times (3.1) the organic load of the CAS system in order to generate the solids concentration required for effective cross-flow scour (greater that 12000 mgTSS/ℓ versus 4000 mgTSS/ℓ). As the same feed was used for both systems, the higher influent flow rate to the MBR system resulted in a decreased hydraulic retention time (13 hours versus 40 hours). The two systems were chosen to run in a UCT configuration with three internal recycles, called:

- a – aerobic mixed liquor to anoxic rector,
- r – anoxic mixed liquor to anaerobic reactor,
- s – return sludge from SST to anoxic reactor.

The MBR system had only two internal recycles as membranes replaced the SST and were located in the aerobic reactor (see Fig. 3.1). Thus the "s" recycle was incorporated into the "a" recycle represented henceforth as the "as" recycle and which was increased accordingly. The UCT configuration was chosen because it allows denitrification and phosphorus removal to act independently of each other; the anaerobic reactor is protected from recycled nitrate from the anoxic reactor – provided the recycles do not overload the anoxic reactor with nitrate.

3.3 ACTIVATED SLUDGE SYSTEMS DESCRIPTION

3.3.1 Activated Sludge Systems Operated

From Section 3.2 above, the steady state activated sludge laboratory-scale systems run for this research were:

- Long sludge age (20d) MBR-UCT system – this configuration was an adaption of the UCT configuration with membranes in the aerobic reactor replacing the function of an SST. Kubota® panel membranes were used (Fig. 3.1).

- Long sludge age (20d) UCT system with SST - this was operated as a control against which to compare the impact of the membranes on the BNR performance of the MBR system (Fig. 3.2).

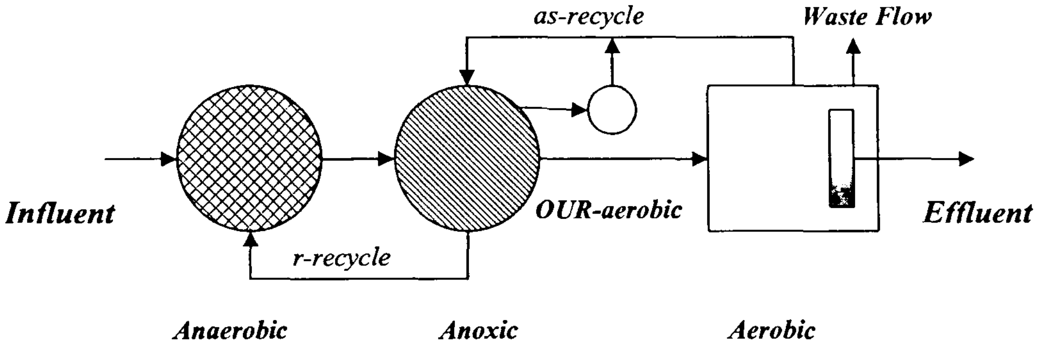

Figure 3.1: *Schematic layout of the MBR UCT system*

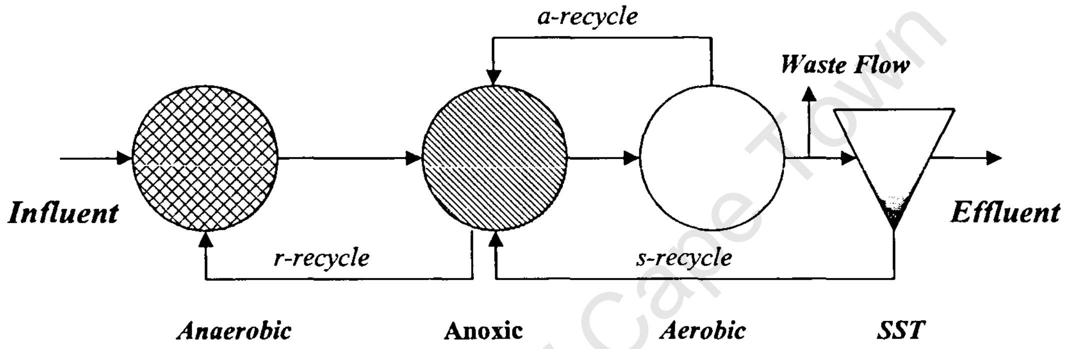

Figure 3.2: *Schematic layout of the conventional UCT system*

Readily biodegradable (RB)COD has a significant impact on nutrient removal in BNR activated sludge, regardless of the solid-liquid separation mechanism (Wentzel *et al.*, 1990). To quantify the RBCOD the technique developed by Ekama *et al.*(1986) was used requiring the following activated sludge system to be operated:

- Short sludge age (2 days) square wave (SQW) fed activated sludge system (Fig. 3.3).

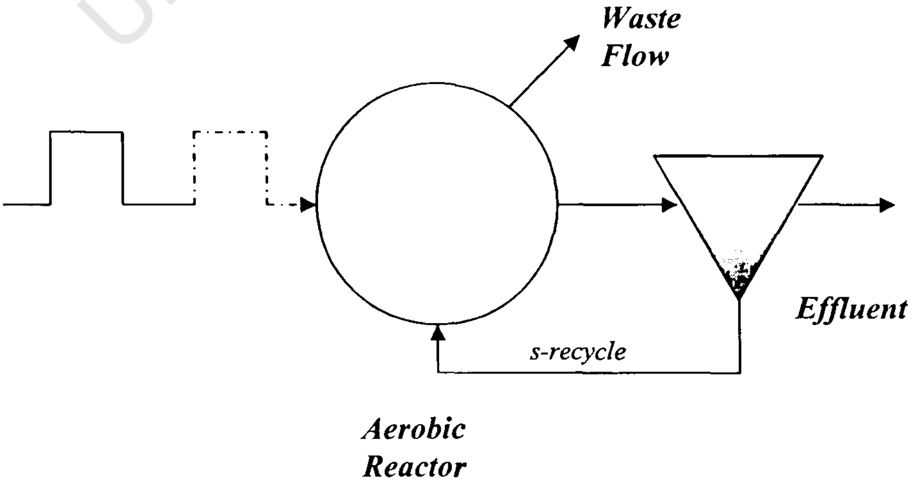

Figure 3.3: *Schematic of the SQW activated sludge system.*

3.3.2 UCT systems design and operating parameters

The two activated sludge systems have, as far as practically possible, identical design parameters, such as anaerobic, anoxic and aerobic mass fractions, recycles and sludge ages. The main difference was to be the influent flow rate (Section 3.2). The volume requirements for the panel membranes used in the research set the size of the MBR aerobic reactor and hence (for the selected anaerobic and anoxic mass fractions) the total system volume. Operating the conventional UCT system with the same volume was not possible due to the large volumes of influent wastewater required. Accordingly the total reactor volume of the MBR system was about 2.96 times larger than that of the conventional system (not including the SST volume).

The influent feed COD concentration was set at 1000mgCOD/ℓ. The influent flow rates of 140ℓ/d and 15ℓ/d for the MBR and conventional UCT systems respectively were calculated to achieve the design reactor mixed liquor concentrations of 18000mgTSS/ℓ and 5000mgTSS/ℓ respectively using the BNR kinetic model UCTPHO (Wentzel *et al.*, 1992). Model inputs used were: a 20 day sludge age, where the sludge production and oxygen demand in the systems per unit COD were the same for both systems: 5.19mgVSS/mgCOD load per day, 6.92 mgTSS/mgCOD load per day and 0.706mgO/d per mgCOD load per day respectively. The South African raw wastewater unbiodegradable particulate ($f_{S,up}$) and soluble ($f_{S,us}$) COD fractions of 0.13 and 0.05 respectively and 20% readily biodegradable COD (RBCOD) with respect to the total influent COD (S_{ti}) and sludge VSS/TSS ratio of 0.75 were used. It was anticipated that the membrane mixed liquor concentrations would be higher still than the design value as the membranes would retain all solids, some of which would naturally flow through the SST of the control system.

The initial MBR and conventional system design operating parameters are listed in Table 3.1.

Table 3.1: *Initial MBR and conventional UCT systems' design and operating parameters.*

SYSTEM PARAMETERS	MBR UCT	CAS UCT
Sludge Age (d)	20	20
Anaerobic (R1) Volume (ℓ)	19	5.6
Anoxic (R2) Volume (ℓ)	21	6.2
Aerobic (R3) Volume (ℓ)	34[1]	13.2
Anaerobic (R1) Mass Fraction (%)	12.6[2]	12.6[2]
Anoxic (R2) Mass Fraction (%)	27.9[2]	27.9[2]
Aerobic (R3) Mass Fraction (%)	59.5[2]	59.5[2]
s-sludge Return Recycle (SST to R2)	-	1:1
a-recycle Return Recycle (R3 to R2)	3:1	2:1
r-recycle Return Recycle (R2 to R1)	1:1	1:1
Hydraulic retention time (d)	0.53	1.67
Aerobic MLVSS conc. (mgVSS/ ℓ)	12 500	3 600
Aerobic MLSS conc. (mgTSS/ ℓ)	18 000	5 000
Influent flow (ℓ /d)	140	15
Feed COD concentration (mg/ ℓ)	1000	1000
Waste flow from Aerobic Reactor (ℓ /d)	2.85	1.1
OUR (mgO/ ℓ)	135	37
Membrane Flux ($m^3/m^2/d$)	0.239	-

[1] effective aerobic volume. MBR UCT Aerobic reactor is in fact 32 ℓ , with a side OUR -aeration reactor for OUR measurement of 2 ℓ .

[2] For the given a, s and r recycle values

3.3.3 MBR UCT System Description

The MBR UCT system reactors were constructed of clear Perspex with cylindrical anaerobic and anoxic reactors with volumes of 28 ℓ each. Though the anaerobic and anoxic reactors were to hold 19 ℓ and 21 ℓ respectively the additional head would aid in unblocking the flow through pipes should they block which would commonly occur with small pipes and sludge of high concentration (Ramphao *et al.*, 2004). Together the design volumes gave a total unaerated mass fraction of approximately 40.5% at the design recycles (as and r).

The aerobic membrane bioreactor used for this study was a rectangular aeration tank with an effective maximum capacity of 40 ℓ , dimensions 185 x 260 x 1720mm. Two additional Perspex walls rising about two-thirds of the liquid height from the base were inserted into the bioreactor, joining between the shorter walls, approximately 100mm in from and parallel to the longer walls; these two walls had 100 x 150mm slots at the base to effectively create an inner riser zone and an outer descender zone.

In the riser zone five panel membrane modules (Kubota®) were submerged. The membrane modules were secured in slots in the shorter walls of the riser zone, and anchored with a stainless steel pin (The membranes were Kubota® polyethylene, pore size 0.4μm, 0.225 x 0.31 rectangular panels 6mm wide with effective filtration area

0.202m x 0.29m x 2 = $0.117m^2$ each). Coarse bubble aeration was provided directly below the membrane modules, by a rigid PVC loop with small holes drilled on the upper surface connected to a low-pressure air supply (100kPa). The air served to supply oxygen to, and mix the activated sludge, and induce a cross flow velocity over the membrane surface to prevent fouling. The air rates were controlled by a Rotameter® 2000 (GEC – Elliott Process Instrument); DO concentrations were regularly monitored (YSI Model 5739) and never fell below 2mgO/ℓ .

The effluent flow through the membranes was collected via flexible silicone tubing connected to the membrane outlets, into a common rigid PVC pipe that exited through the reactor sidewall. This outflow was connected via flexible silicone piping to an adjustable overflow piece. Membrane flux is directly proportional to the pressure head (trans-membrane pressure, TMP) on the membranes, which is the difference between the level inside the reactor and the level of the overflow pipe. The TMP was measured by comparing the level of a standpipe connected to the bottom of the reactor against the level of the outflow. The level of the reactor needed to remain constant and could thus be controlled by adjusting the level of the overflow. This was important so that sudden changes in influent flow due to a blockage or spillage, or gradual changes in TMP could be compensated for while keeping the reactor volume constant at 32ℓ .

Since the aerobic reactor containing the membranes required constant aeration, the oxygen utilization rate (OUR) could not be measured in this reactor. Accordingly a small cylindrical Perspex reactor (3ℓ) was included in the system configuration in which the OUR could be constantly monitored using an automated technique (Randall *et al.* 1991). Initially flow for the reactor was taken directly from the aerobic reactor and recycled back to the aerobic reactor. However this setup yielded lower OUR values than expected and was revised with the reactor fed instead from the anoxic reactor and run at the same hydraulic retention time as the aerobic reactor before being fed back into the as-recycle (Section 3.8.1). This change gave OUR values far closer to those expected from simulations. The 3ℓ OUR reactor had a solids concentration equal to that of the anoxic reactor and so the measured OUR had to be increased by the ratio of the aerobic to anoxic solids concentrations. As the 3ℓ aerobic reactor had a lower solids concentration it is considered to be equivalent to a 2ℓ reactor with the aerobic reactor solids concentration, and is hence-forth referred to as such.

The volume of the aerobic reactors was set at 34ℓ (32ℓ + 2ℓ), yielding a process volume (V_p) of 74ℓ . The system was operated at a sludge age of 20 days (see Table 3.1), by maintaining a wasting rate of 2.85ℓ /d. Waste sludge was removed once per day at the end of the daily feed cycle, after sampling had been completed, taking into account any mixed liquor removed through sampling, cleaning or lost through spillage. The influent flow rate (Q_i) of 140ℓ /d with a target COD concentration (S_{ti}) of 1000mgCOD/ℓ , to give a target mass loading rate of 140 000 mgCOD/d. Pumping of influent and recycle flows (Table 3.1) was by means of a simple peristaltic pump with flow rate controlled by an inverter. Recycle flows were set relative to the influent flow by using the appropriate number of pump channels as multiples of the influent number of channels. Reactors were connected by soft silicone tubing (~5mm to 15mm in diameter). Recycle flow rates were frequently checked with stop watch and measuring cylinder because these flows affect the mass fractions in the MBR system.

3.3.4 Conventional UCT System Description

As with the MBR system, all reactors used in the conventional UCT system were constructed of clear Perspex tube (~5 mm wall) , with approximate dimensions (height x diameter): anaerobic, 410 x 190mm; anoxic, 410 x 190mm; aerobic, 470 x 210mm ; and SST 450 x 60 mm. The tubes were closed by Perspex disks for base plates and lids. The contents of the reactors were completely mixed by means of a motor driven paddle mixer (~100rpm), mounted centrally on the lid of the reactors. To prevent hydraulic short circuiting each reactor was equipped with a pair of vertical side baffles situated opposite each other and extending about 2 cm into the bulk solution. The reactors had two paddles fitted to the mixing shaft, one situated at the bottom and one about 120mm above it. These were positioned to ensure complete suspension of the reactor contents while avoiding turbulence at the liquid surface to minimize air entrapment into the bulk solution. The lid of each of the reactors had a circular opening (~50mm diameter) to allow sampling and for the placement of the DO probe in the case of the aerobic reactor. Each reactor had a single inlet and outlet situated about 100mm apart on its base plate. The process volume was maintained in each reactor by an overflow tube at the desired overflow level on an adjustable vertical slide attached outside of the wall of the reactor. Aeration in the aerobic reactor was provided by low pressure compressed air entering the reactor through a small bore Perspex tube that terminated in a small fish tank bubble diffuser at the bottom of the reactor. The airflow was controlled manually by adjusting a hose clamp on the airline entering the reactor. The dissolved oxygen (DO) in the aerobic reactor was maintained between 2.0 and 5.0 mgO/ℓ and was controlled with an YSI Model 5739 DO probe and Hi-Tech Micro-system OUR meter (Randall et al. 1991).

The SST was a Perspex tube inclined at 60° to the horizontal, fitted with a motor driven (~0.5 rpm) wiper blade rotating a half turn every minute to reduce attached growth on the inside wall and release any nitrogen gas generated from possible denitrification in the settled sludge. Mixed liquor from the aerobic reactor entered the SST at the upper end of the tilted bottom disc to facilitate settling, while clarified effluent overflowed at the top and was collected in an effluent bucket. The s-recycle was drawn from the bottom end of the bottom disc and pumped to the anoxic reactor. Like the MBR system all pumping was by means of a peristaltic pump with the recycles achieved by assigning a proportional number of channels to each recycle relative to the number assigned to feed, only with the conventional UCT system the pump also ran on a timer due to the low flows required. Reactor and SST connections were by means of soft silicone connection piping (~5mm – 15mm in diameter).

The total reactor volume (V_p) for the conventional UCT system totalled 25 ℓ , and was divided into 5.6 ℓ anaerobic, 6.2 ℓ anoxic and 13.2 ℓ aerobic to give an unaerated mass fraction of about 40.5 percent (ie 12.6% anaerobic and 27.9% anoxic). The system was operated at a sludge age of 20 days by maintaining a wasting rate (Q_w) of 1.1 ℓ /d. Waste sludge was removed once per day from the aerobic reactor at the end of the daily feed cycle taking into account any mixed liquor removed for sampling, cleaning or lost through spillages. The influent COD load to the system was set at a flow rate (Q_i) of 15 ℓ /d with target COD concentration (S_{ti}) of 1000mgCOD/ ℓ , to give a target mass loading rate of 15 000 mgCOD/d (Table 3.1).

3.3.5 Square Wave Feed Activated Sludge System

In evaluating BNR it is essential to determine the RBCOD concentration in the influent. The sodium acetate added to the influent (see Section 3.4 below) is all RBCOD, and its contribution to the total RBCOD could be calculated theoretically. However the RBCOD of the sewage component needed to be measured. This was achieved using the short sludge age square wave fed activated sludge system (SQW) method developed by Ekama and Marais (1978) and described by Ekama *et al.* (1986).

A schematic layout of the SQW system is shown in Fig. 3.3. The SQW system comprised a single aerobic reactor and SST constructed and equipped in the same way as for the conventional UCT system above. The reactor dimensions were approximately (height x diameter) 400 x 180 mm, with a total system process volume $V_p = 6.7\,\ell$. A short sludge age of ~ 2 days was maintained by wasting 3.2 ℓ /d from the reactor at the end of each day's feed cycle. (In the original test a sludge age of 2½ days was used. This was shortened to 2 days to ensure no interference by nitrification).

Unlike the UCT systems the SQW system was operated in a 12h - ON/ 12h - OFF feed pattern, hence the square-wave name, with an influent flow rate (Q_i) of 18 ℓ /0.5d = 36 ℓ /d over a 12 hour period. The initial target COD concentration was 500mgCOD/ℓ with a target mass loading of 9 000 mgCOD/d at 18 000mgCOD/d instantaneous loading. However later this was changed to the unaugmented sewage feed of 800mgCOD/ℓ , with a mass loading of ~16 000 mgCOD/d at ~32 000 mgCOD/d instantaneous loading as this could be taken from the feed to the UCT systems prior to augmenting the feed with sodium acetate. The system was operated with an s-recycle ratio of 1:1 with respect to the influent flow, which was terminated when the feed pumping stopped at the end of the 12 hour feed period.

3.3.6 Operating Procedures and Conditions

All activated systems were operated in the Water Research Laboratory at UCT with the temperature controlled at 20 °C (± 1 °C).

The pH in the aerobic reactors of the systems was regularly monitored. Sodium bicarbonate was dosed with the feed to maintain a stable pH between 7.2 and 7.9.

Operating procedures detailed by Burke *et al* (1984) and Clayton *et al* (1989) were followed including *inter alia* regularly brushing reactor walls and intermittent cleaning of reactors and tubing.

3.3.7 System Seeding

In Phase 1 both systems were seeded from SST underflow mixed liquor (~9 000 mgTSS/l) from the Potsdam WWTP (Milnerton, South Africa), which operates in the UCT configuration for BNR. This mixed liquor was diluted 1:1 prior to addition to the conventional UCT system, but allowed to settle further to ~12 000 mgTSS/ℓ prior to addition to the MBR UCT system. The writer continued to use the sludge that had developed in the reactors during Phase 1 for the Phase 2 investigation. The SQW system was started up with wasted sludge from a laboratory ND system because BEPR sludge cannot be used for influent RBCOD measurement.

3.4 INFLUENT FEED

3.4.1 Wastewater Collection and Storage

The influent wastewater used in the study was raw (unsettled) sewage from the Mitchells Plain Wastewater Treatment Plant (MPWWTP) in Cape Town, South Africa. This wastewater is mainly domestic with a small (less than 10 percent) industrial component. The wastewater was collected in approximately 2 m^3 batches from the main outlet channel at the head of the works, just upstream of the influent screw lift pumps and before screening (coarse and fine) and grit removal. The collected wastewater was brought to the laboratory by tanker-truck and, while being agitated with high pressure air, was dispensed by gravity through an in-line macerator into individual 400 ℓ stainless steel tanks in the laboratory's 4 °C cold room. The sewage was stored in this way for about 12 to 14 days after which it was discarded and a new sewage batch collected. Experience has shown that the storage of sewage in the cold room tanks longer than three weeks leads to septicity (hydrogen sulphide accumulation) and non-representative changes in sewage characteristics. Immediately after storage in the cold room, a COD test was done on the new sewage to determine the necessary dilution for feed preparation for experimental systems operated in the laboratory. Typically, undiluted raw sewage COD from the MPWWTP ranges between 1000 and 1600 mgCOD/ℓ, though during periods of water restrictions in Cape Town the concentrations closer to 2000mgCOD/ℓ were observed.

3.4.2 Feed Preparation

The target total influent COD's for both the conventional and MBR UCT systems were the same at 1000mgCOD/ℓ of which 800mgCOD/ℓ was the raw sewage and 200mgCOD/ℓ was acetate. From the raw wastewater batch the daily feed batches were prepared by diluting the raw sewage with tap water to the targeted influent sewage COD concentration to 800mgCOD/ℓ. Since the total daily volumes for the MBR, conventional UCT and SQW systems were 140 ℓ, 15 ℓ and 20 ℓ respectively, and all three systems were fed the same mixture of sewage to water, prior to dosing, a combined feed of 175 ℓ was prepared. The raw sewage in stainless steel tanks was thoroughly mixed, then withdrawn via a valve outlet pipe at the bottom of each tank through a 1mm stainless steel mesh (to minimize the blockages in the lab systems). The appropriate volume of screened sewage was then poured into a 200 ℓ plastic drum where the volume was made up with the required amount of tap water. The SQW feed would be removed leaving 155 ℓ. The remaining wastewater, for the MBR and conventional UCT systems was further supplemented with artificial organic (sodium acetate) and inorganic (ammonium chloride and di-hydrogen potassium orthophosphate) compounds (composition developed earlier in BNR research) to increase the COD, TKN and phosphorus to 1000mgCOD/l, 100mg-N/ℓ and 40mgP/ℓ. Sodium acetate was selected to augment the sewage organics by 200mgCOD/ℓ in order to enhance the biological P removal processes (Wentzel *et al.*, 1988), thereby to accentuate potential effects of the membranes on these processes. The additional di-hydrogen potassium orthophosphate was added to the influent to ensure the system was not P-limited, allowing BEPR to be observed.

3.5 SAMPLING AND TESTING

3.5.1 UCT Activated Sludge Systems

To evaluate the process performance of the MBR and conventional UCT systems, the following routine samples were taken (shown schematically in Fig. 3.4).

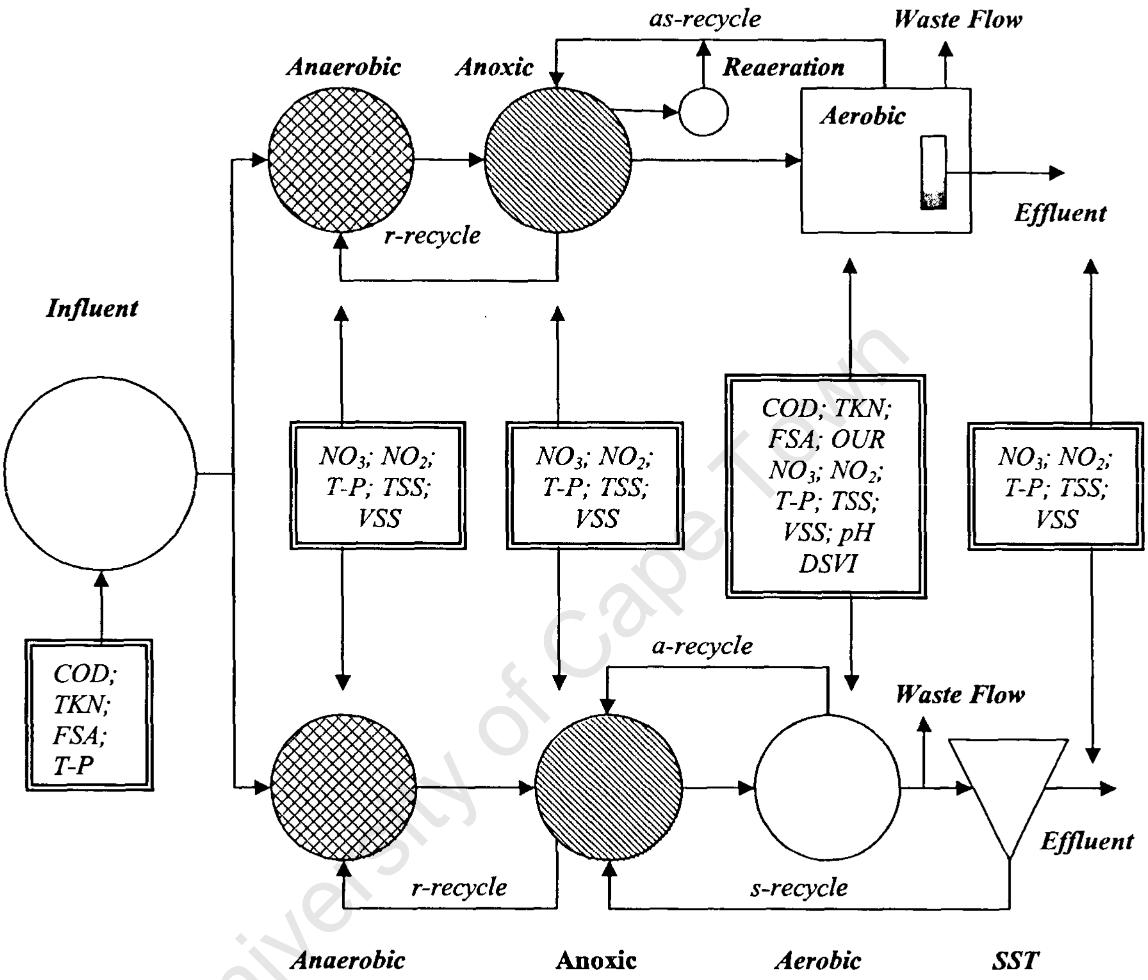

Fig 3.4: *Schematic representation of routine sampling for the MBR and conventional UCT systems.*

Influent Feed Sample

Following the feed preparation of the diluted raw wastewater and augmentations, about 200ml was drawn out before feeding the systems and immediately preserved with one drop of mercuric chloride solution (8.6g/ℓ $HgCl_2$), and then placed in the 4°C cold room for later analysis, see Table 3.2.

Reactor Mixed-Liquor Samples

Near the end of each day's feed cycle, 100ml samples were drawn from the anaerobic, anoxic and aerobic reactors respectively of each system, and an additional 50ml sample was also drawn out of the OUR-aeration reactor of the MBR UCT system. As with the influent samples one drop of mercuric chloride solution (8.6g/ℓ $HgCl_2$) was added to the samples immediately after sampling to prevent any further biological activity. The samples were then placed in 50ml centrifuge tubes and centrifuged at 3500rpm or 10minutes. A drop of polyelectrolyte flocculent (1g/ℓ) was also added to the MBR UCT samples to make subsequent filtering easier (the high MLSS concentrations proved difficult to filter at times; tests in Phase 1 showed that polyelectrolyte had negligible effect on subsequent analysis). The centrifuged supernatants were filtered through 0.45 μm membrane filters and stored for later total phosphorus, nitrate and nitrite analysis. The centrifuged solids were flushed into measuring crucibles with distilled water and tested for total settleable solids (TSS) and volatile settleable solids (VSS). During the analysis period it was noted that rapid denitrification in the MBR reactor samples compromised the nitrate measurements if samples were allowed to sit for any length of time. Hence samples were taken, poisoned and centrifuged as quickly as possible to prevent the occurrence of denitrification in the samples. The phenomenon of rapid denitrification was attributed to the high solids concentrations in the MBR system and is discussed further in Chapter 4, Section 4.7.

Additional 50ml and 25ml samples were drawn from the aerobic compartments of the conventional and MBR UCT systems respectively, then placed in 500ml and 1000ml volumetric flasks respectively, and then made up to volume with distilled water, to give respective dilutions 10 times (50 in 500ml) and 40 times (25 in 1000ml) for the conventional and MBR systems respectively. The diluted mixture was thoroughly mixed manually and then analysed for unfiltered COD and TKN (see Table 3.2).

Additionally 50ml and 300ml samples were drawn from the respective aerobic compartments of the MBR and conventional UCT systems, and diluted with secondary effluent from the respective systems in separate 1 ℓ graduated cylinders to measure the diluted sludge volume index (DSVI, Ekama and Marais 1984b): The contents of the cylinder were shaken up and allowed to settle for 30 minutes, after which the settled volume was recorded. This value (DSV_{30}) was divided by the TSS concentration of the mixed liquor in the measuring cylinder to give the system DSVI in ml/gTSS; i.e. an estimation of the volume occupied by 1gTSS of sludge in a SST (See Table 3.2).

Effluent Samples

At the end of each days feed cycle, a sample of the secondary effluent was drawn from the effluent bucket of each system. Conventional UCT samples were filtered through a 0.45 μm membrane filter. There was no need to filter effluent samples from the MBR as the membrane pore sizes were smaller than those of the 0.45 μm filter paper. These samples were filtered for COD, TKN, FSA, NO_2, NO_3, and TP (see Table 3.2). Effluent unfiltered samples for both systems were taken from the supernatant of the DSVI test described above. These samples were analysed for COD and TKN (See Table 3.2).

Microbiological and Batch Test Samples

Periodic sampling was performed on both the conventional and MBR systems for microbial analysis. All sampling was taken into consideration in calculating the daily sludge wasted and samples were prepared appropriately for their respective tests.

Once monthly and fortnightly from March 2006 samples were analysed by a microbiologist for filament identification and floc morphology. Additionally from August 2006 samples were sent fortnightly to the Durban Institute of Technology for FISH analysis. Results are presented in Maharaj *et al.* (2006). All samples for microbial analyses were prepared appropriately with autoclaved equipment.

In-situ Measurements

The oxygen utilization rates (OUR) of the MBR and conventional UCT, and the SQW systems were measured continually and automatically using the technique detailed by Randall *et al.* (1991): A dissolved oxygen (DO) probe (YSI Model 5739) was placed in the aerobic activated sludge mixed liquor and connected to an automated DO meter/OUR data logger (HiTech Microsystems), which controlled reactor aeration between high and low DO set points via a solenoid valve on the air line. When the DO concentration in the mixed liquor reached the low set point (≤ 2mgO/l), the solenoid valve was opened and the reactor contents aerated until the DO concentration reached the high set point (≥ 5mgO/l) and the air was switched off automatically. The decrease in DO with time was monitored until the DO reached the low setpoint again, when aeration recommenced and the cycle repeated. During each air off period in the cycle the slope of the DO-time data was automatically calculated by linear regression to give the OUR at that time, which together with the correlation coefficient, temperature and time, was stored by the meter. The OUR results for each day's feed cycle were downloaded from the DO meter to the PC the following day. The data was imported into a spreadsheet program where it was plotted and the average OUR for the day calculated. The DO meter and probe were routinely calibrated.

Daily the pH in the anoxic and aerobic reactor was measured by means of a pH probe connected to a pH meter.

In the MBR UCT system, the hydraulic head required to achieve the specific flux was measured daily, as the difference between the levels of the reactor contents (monitored by the standpipe) and the effluent (permeate) overflow weir, see Section 3.3.4.

Summary

Table 3.2 summarizes analyses routinely performed on the various system samples. Although all analyses refer to Standard Methods (1985), some have been adapted to suit the requirements in the UCT Wastewater Research Laboratory (WRL).

Table 3.2: Sampling position and parameter measurement

TEST	COD 1	TKN 2	FSA 3	NO_3 4	NO_2 5	T-P 6	TSS 7	VSS 8	OUR 9	DSVI 10	pH 11
Influent	U	F; U	F			U					
Anaerobic				F	F	F	U	U			
Anoxic				F	F	F	U	U			
Aerobic	U	U		F	F	F	U	U	*	*	*
Final Effluent	F; U	F; U	F	F	F	F					

F = Filtered through Schleicher & Schull ME 25/21 0.45 µm membrane filters.
U = Unfiltered samples
* = Direct measurement taken (filtering not applicable)

The numbers on the test methods below refer to Standard Methods (1985), though some have been adapted to suit the requirements of the UCT wastewater research laboratory (WRL).

1. COD	Chemical Oxygen Demand, open reflux method; 5220 (B)
2. TKN	Total Kjeldahl Nitrogen, micro-kjeldahl method; 4500 – Norg (C)
3. FSA	Free and Saline ammonia, titrimetric method; 4500 – NH_3 (B), (E)
4. NO_3	Hydrazine reduction (Technicon Auto-Analyzer); 4500 – NO_3 (H)
5. NO_2	Hydrazine reduction (Technicon Auto-Analyzer); 4500 – NO_2 (H)
6. T-P	Total Phosphorus; Sulphuric acid/Persulphate digestion at 100°C followed by molybdate-vanadate colour development for ortho-phosphate (Standard Methods, 1985 – Method 424C III)
7. TSS	Total suspended solids dried at 103 - 105°C; 2540 (D)
8. VSS	Volatile suspended solids ignited at 600 °C; 2450 (E)
9. DSVI	Dilute Sludge Volume Index; (Ekama and Marais, 1984b), 271 (D)
10. OUR	Oxygen Utilization Rate; automated (Randall, *et al.*, 1991), 271 (B)
11. pH	pH meter, Hanna Instruments model HI9023; 4500 – H^+ (B)

3.5.2 Square Wave Feed Activated Sludge System

The unfiltered influent sample for the SQW system was analysed for total COD, as described above. Also, OUR was monitored continually in-situ and reactor pH measured regularly, as described above.

3.6 INITIAL TESTING

3.6.1 Initial Flux Testing

In April 2005 new membranes were acquired for the investigation and the potential flux of the new membranes was evaluated to test whether the membranes could achieve the flux required for the MBR setup, and whether the physical design of the aerobic membrane bioreactor could accommodate the required head (TMP). Both the "old" and the "new" membranes were tested to allow a comparison of their performance.

The tests required timing the effluent flow from the aerobic reactor. The effluent would flow directly into an Imhoff cone and the TMP at the start and end of the test was measured with the mean TMP calculated for the test. Thus the flux through the membranes for a set TMP could be calculated and a relationship between flux and TMP developed. The tests were run using both distilled water and activated sludge mixed liquor.

Continued Flux testing

It was expected that over time the TMP of the membranes would increase, initially due to the establishment of a dynamic gel layer and over time due to progressive fouling. In order to track changes in the TMP over time the TMP was measured daily. Initially this was simply done by measuring the difference between the level in the reactor and the level of the effluent overflow weir. However, over time the results varied significantly due to fluctuations in the flow through the aerobic reactor. These fluctuations were due to a number of factors – primarily the pump speed which would vary throughout the day within its set range due to the liquid level of the feed tanks, and minor blockages in the feed lines. Additionally blockages, not obvious to the operator in the recycle piping would cause a build up of mixed liquor in one reactor and upon clearing surgeto the next reactor. In order to compensate for these fluctuations flux tests were adjusted whereby the TMP would be taken at the beginning and the end of the flux test and averaged. The TMP would then be adjusted by the quotient of the average daily flux divided by the measured flux. This method gave more consistent results, with the result that TMP could be monitored carefully in times of dynamic change – for instance during and after power failures when aeration had been off causing fouling to occur.

3.6.2 Oxygen Transfer Rates

To prevent fouling, scour across the membrane surface was provided by coarse bubble aeration installed directly below the membrane assembly. This aeration unit also had to provide sufficient oxygen to satisfy the biological oxygen demand (carbonaceous and nitrification), estimated at ~135 mgO/ℓ /hr. Accordingly the oxygen transfer rate of the aeration assembly installed in the MBR UCT system aerobic reactor was experimentally determined in Phase 1 of the project using the unsteady state aeration of deoxygenated water. The results showed that the aeration supplied to the system was adequate and this was confirmed in Phase 2 by a DO concentration in the aerobic reactor consistently between 2 – 5 mgO/ℓ .

3.6.3 Residence Time Distribution

To determine that the aerobic reactor containing the membranes was completely mixed in the MBR UCT system, despite the presence of the riser and descender zones, a residence-time distribution (RTD) test was carried out in Phase 1 by salt addition and conductivity measurements. The rate of appearance of conductivity in the effluent following a NaCl dose to the influent gives an indication of how well the reactor is mixed. The results of the tests in Phase 1 one indicated excellent mixing in the aerobic reactor (Ramphao *et al.*, 2004).

3.7 OXYGEN TRANSFER TESTING

3.7.1 Oxygen Transfer Theory

Aeration is one of the most important considerations in designing wastewater treatment plants and together with sludge handling is one of the primary costs in running a plant. Hence having a good understanding of oxygen transfer and providing an efficient aeration system will not only ensure that the plant works effectively but will reduce operation costs.

There are a number of factors which influence Oxygen Transfer Efficiency (OTE), which is the measure of how much oxygen introduced to the system is in fact transferred to the solution (Equation 3.1). These factors include temperature, pressure, geometry of the reactor and sludge concentration. The ability of the MBR to concentrate sludge allowed a study of the effect of concentration on the rate of oxygen transfer (OTR) and OTE to be conducted.

Typically in aeration tests concentration is taken into account through the Alpha (α) value. Alpha is derived as the quotient of the mass transfer coefficient K_{LA}' through the sludge divided by the K_{LA} though tap water, Equation (3.1). Values vary considerably but are generally inversely proportional to the sludge concentration.

$$\alpha = \frac{K_L a'}{K_L a} \tag{3.1}$$

In order to calculate Alpha two sets of tests need to be carried out. The first test is an Unsteady State (USS) test which would give the relationship between K_{LA} (water) and the air flow rate as measured by a calibrated rotameter. The second test is a Steady State (SS) test conducted on the system while in operation. This would give K_{LA}' (mixed liquor) values in relation to a set airflow rate and a MLSS concentration. Thus Alpha values could be determined for a range of MLSS values by interpolating the K_{LA} vs airflow relationship so that the K_{LA} and K_{LA}' could be found for a particular MLSS value. The basis of both of these tests is Equation (3.2).

$$\frac{dC}{dt} = K_L a(C_S - C_L) - OUR \tag{3.2}$$

Where:

$\frac{dC}{dt}$ = change in DO concentration with time

C_S = saturated concentration of DO under site conditions (mgO/l)

C_L = DO concentration in the reactor

OUR = oxygen utilization rate in the reactor

With the K_{LA} of the solution known the OTR and subsequently the OTE of the system can be calculated using Equations (3.3) – (3.5).

$$OTR = K_L a . C_S . V \tag{3.3}$$

$$OTE = {}^{OTR}\!/_{OSR} . 100 \qquad (\%) \tag{3.4}$$

Where:

V = Volume of the system aeration reactor

OSR = Oxygen supply rate

$= Co_2.Q_{air}$ (3.5)

Co_2 = Oxygen content of air (kgO/m^3)

Q_{air} = Air flow rate (m^3/h)

3.7.2 Unsteady State (USS) Test

This test was conducted in the aerobic reactor which was drained of activated sludge, dismantled and thoroughly cleaned to remove all impurities which may impact the oxygen transfer in the reactor. Once clean the reactor was reassembled with "dummy" membranes in order to protect the system membranes from potentially aggressive salts used in the USS testing. The reactor was filled with distilled water to the operational volume of 32 ℓ . The system is then aerated for an hour in order to saturate the water completely with oxygen. A DO probe, calibrated the same morning was suspended upside down in the aerobic reactor to prevent bubbles collecting on the probes' membrane which would affect the DO readings. The expected saturated DO concentration (C_S) from Equation (3.6) was checked with the saturated DO value to confirm correct calibration of the probe.

$$Cs_{(site)} = Cs_{(std)}\left[\left(\frac{P_{(site)} - p_{(site)}}{P_{(std)} - p_{(std)}}\right)\times\left(\frac{P_{(site)} + 76.13\times h\times f - p_{(site)}}{P_{(site)} - p_{(site)}}\right)\times\left(\frac{51.6}{31.6+T}\right)\right] \qquad (3.6)$$

Where: $P_{(site)}$ = Pressure at site (mmHg)

$P_{(std)}$ = Pressure at 1 atm (760 mmHg)

$p_{(site)}$ = Saturated vapour pressure at site (mmHg)

$p_{(std)}$ = Saturated vapour pressure at standard temperature (mmHg)

$76.13\times h$ = pressure of h m of water (mmHg)

f = fraction of submerged depth (from suface) at which pressure corresponds to the average concentration. Accepted 0.325.

T = Temperature in °C.

The temperature of the water in the reactor was checked before and after each iteration of the USS test, in order to take its influence into account. As the test was run in the Water Research Laboratory, in Cape Town at sea level the site pressure was assumed to be equal to the standard pressure. No correction was applied to C_S to account for the effect of concentration of dissolved salts in the mixed liquor (Baker *et al.,* 1975).

Each iteration of the test proceeded as follows: The air flow rotameter would be set at a value and the system aerated to saturation. A solution of Sodium Sulphate (±150 mgNa_2SO_3/ ℓ) with Cobalt Chloride (0.05 mgCo^{2+}/ ℓ) as a catalyst was added to the aeration reactor in order to deoxygenate the reactor completely. Once all the sulphate has been utilised the DO will be retained in the water again. The DO was monitored with time as it increased from 0mgO/ ℓ to saturation. This process is repeated for a number of airflow rates.

From Equation (3.2), and assuming that due to the lack of any impurities in the water the OUR is 0, the K_{LA} of a airflow rate is calculated by plotting the DO deficit, $C_S - C_L$, on a log scale versus time, the slope of which is K_{LA} (Baker *et al.,* 1975). Similarly K_{LA} was calculated in this study from the plot of Log(C_S-C_L) as in Equation (3.7). K_{LA} is considered to increase with an increase in temperature due to lower viscosity and increased diffusivity (Baker *et al.,* 1975). In order to adjust $K_{LA\,(T)}$ to standard conditions Equation (3.5) was applied

$$K_{La(T)} = \left[gradient.Log(Cs - C_L) \big/ 2.303 \right] \tag{3.7}$$

$$K_{La(20)} = K_{La(20)} \big/ \theta^{(T-20)} \tag{3.8}$$

Where:

θ = 1.024

With a series of $K_{LA\,(water\ 20)}$ values a curve relating airflow rate to $K_{LA\,(20)}$ could be plotted.

3.7.3 Steady State Testing

In wastewater systems the DO concentrations in the activated mixed liquor is continually being depleted by microbial metabolism (Baker *et al.,* 1975). Hence under steady state conditions an equilibrium is reached between the oxygen supplied and the oxygen used in the mixed liquor and the DO concentration in the reactor remains generally unchanged. Thus Equation (3.2) can be modified to Equation (3.9) and the $K_{LA}'_{(T)}$ of the activated sludge can be calculated by measuring the DO concentration in the reactor and the OUR of the activated sludge. $K_{LA}'_{(20)}$ is calculated using equation (3.8).

$$K_{La(T)} = \frac{OUR}{(\beta \times Cs - C_L)} \tag{3.9}$$

Where:

β = effect of impurities on Cs

In order to run the test at constant OUR conditions the sludge was aerated without feed for 24 hours prior to testing to achieve endogenous conditions. This also served to concentrate the activated sludge. At the start of a test a portion of the activated sludge (2-3 ℓ) was removed for OUR testing in a separated batch reactor leaving the operating volume of approximately 32 ℓ in the aerobic reactor. A number of average DO concentrations were measured at different air flow rates. MLSS samples were taken from both the aerobic reactor and the OUR batch reactor to determine the MLSS concentration during testing. Temperature was measured throughout. Once sufficient readings had been taken, all sludge was returned to the aerobic reactor and diluted. The excess activated sludge would be stored and the testing repeated at the new MLSS concentration.

Additionally mixed liquor samples at various concentrations were exported for analysis by the Flow Process Research Centre (FPRC) at the Cape Peninsula University of Technology for rheological analysis to determine the viscosity of the mixed liquor.

Previous studies had indicated that there is a liner relationship between viscosity and Alpha values.

3.7.4 Beta Testing (β)

Beta represents the effect of impurities in the sludge on C_S and is calculated using Equation (3.10). In order to assess the effect of impurities in the sludge β was calculated by poisoning a (3 ℓ) sample of activated sludge with 100ml Mercuric Chloride (HgCl) and measuring the saturated DO concentration achieved in the mixed liquor.

$$\beta = {Cs_{(sludge)}}\Big/{Cs_{(water)}} \qquad (3.10)$$

3.8 SYSTEM AND OPERATIONAL MODIFICATIONS

3.8.1 MBR System Operation

The main system operational problems experienced in the MBR system in Phase 2 are summarised in Table 3.3.

Table 3.3: *Membrane system operational problems and actions taken.*

Sewage Batch #	Event (day) action taken;
2	Foaming (26) brushed down foaming; Spills (31, 35) ML[1] filtered and returned
3	
4	Foaming (throughout) Foam wasted (56); Spills (66-69;74) ML[1] filtered and returned - reduced wasting on subsequent days to recover lost ML
5	anaerobic motor seized (92) motor repaired; small spill (94) ML[1] lost incorporated in waste sludge
6	Backlogs in Feed (100; 102)
7	Excessive foaming (111) in anoxic reactor - installation of wire foam mixer
8	New OUR setup installed (d 133)
9	Minor spill (140) ML[1] lost incorporated in waste sludge
10	Minor Spills (149, 153,162) ML[1] lost incorporated in waste sludge
11	Power failure (176) washed membranes;
12	Pipes ruptured on feed pump - Spills(191, 198, 200, 203) Changed feed piping regularly
13	
14	Cold room off (d 219) sewage batch monitored for deterioration of waste water; Spill (224)
15	Spills (237, 241) ML[1] filtered and returned
16	Spill (254) ML[1] filtered and returned
17	System feeding irregularly (d 260) feed pump serviced and piping checked
18	Spill (275) ML[1] filtered and returned; Anoxic reactor outflow blocked draining aerobic reactor exposing membranes (271) washed membranes; re-aeration reactor mixer broken (274) repaired
19	Spills (294, 298, 305) ML[1] filtered and returned
20	Writer on leave
21	Writer on leave
22	Spills (344-346; 348) ML[1] filtered and returned
23	Spills (359-360; 365) ML[1] filtered and returned; a-recycle blocked (366) recycle cleared
24	Power failures (374, 377-8; 383) washed membranes; anaerobic and anoxic motors seized (374) replaced motors
25	Power failure/Spill (386) washed membranes, ML filtered and returned
26	Spills (394, 405) ML[1]filtered and returned
27	Spills (409, 411) ML[1] filtered and returned
28	Rapid deterioration in membrane permeability (from 407) Ran chemical clean (431)
29	

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[1] *Mixed Liquor (ML)*

Foaming

Excessive foaming by N_2 gas generation in the anoxic reactor was noticed early in the investigation (from day 26). Initially foam was brushed down into the mixed liquor on a daily basis, however this proved ineffective resulting in the development of a substantial foam layer which was physically removed from the surface of the anoxic reactor on day 56. The foam constituted a significant mass of sludge and its removal was accommodated as best as possible into the mass of sludge wasted. However a foam layer developed again shortly thereafter and floating balls were inserted into the anoxic reactor to prevent the development of foam with little success. Finally the foaming was remedied by inserting a wire stirrer slightly above the surface (10mm) of the anoxic reactor (day 111). The stirrer disturbed the development of any further foam layer by incorporating foam back into the mixed liquor solution before it could consolidate. In order to prevent the aeration of the anoxic mixed liquor by the stirrer the anoxic reactor was lightly sealed by capping the sampling port, such that nitrogen gas could escape, but oxygen would not enter the reactor headspace. The reasons proposed for excessive foaming in the MBR anoxic reactor are discussed in Chapter 4, Section 4.6.2.

OUR Measurement

Due to the requirement of the membranes for constant aeration for cross-flow velocity scour, OUR in the aerobic reactor could not be measured by the method developed by Randall *et al.* (1991). Instead in Phase 1 a separate 3 ℓ aerobic reactor (OUR-aeration reactor) was employed to measure OUR (Fig. 3.4). However in Phase 2 the OUR readings from this setup were found to be very low and attributed to the longer aerobic retention imposed on the re-aeration mixed liquor due to it being recycled from and returned to the aerobic reactor. Instead it was proposed to run the re-aeration reactor in a parallel configuration to the aerobic reactor, fed from the anoxic reactor and recycling back to the as-recycle with the same aerobic hydraulic residence time as in the aerobic reactor, Fig. 3.5.

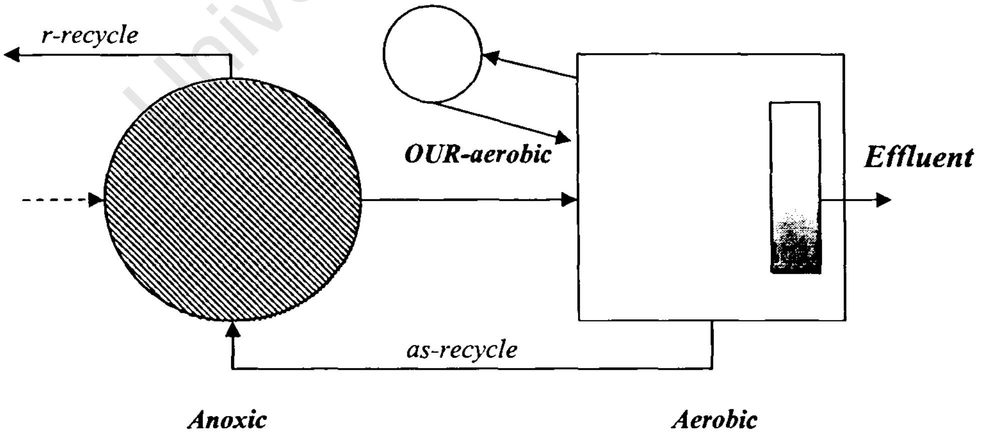


Figure 3.4: *The original OUR setup, with re-aeration recycling mixed liquor directly from the aerobic reactor.*

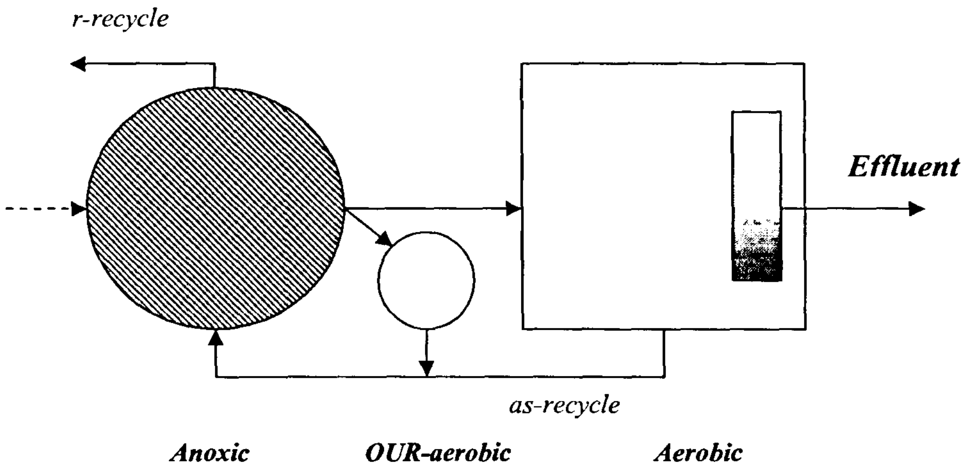


Figure 3.5: *The modified OUR setup implemented on day 133 whereby the re-aeration reactor ran in parallel to the anoxic reactor drawing mixed liquor from the anoxic reactor and feeding mixed liquor directly back into the as-recycle.*

Due to the absence of the membrane concentration effect in the OUR-aeration reactor the mixed liquor solids concentration was effectively that of the anoxic reactor and needed to be adjusted to represent the OUR in the aerobic reactor. The OUR was simply increased proportionally with the MLSS concentration difference of the two reactors as in Equation 3.11. which gave OUR readings close to those calculated for the UCT system using UCTPHO.

$$OUR_{aer} = OUR_{re\_aer} . \frac{MLSS_{aer}}{MLSS_{re\_aer}} \tag{3.11}$$

Power Failures

On day 176 and from days 374 to 386 the Water Research Laboratory experienced several electrical power failures due to city wide power outages. The power failures resulted in membrane fouling, and backlogs in the feed volume due to no aeration, no reactor mixing and no feeding or recycling flows between reactors. Once power had been restored the TMP of the membranes would be checked, as in Section 3.6. If the TMP of the system had increased, indicating fouling on the membranes, the membranes would be removed and washed down with water only to remove mixed liquor caking on their surface. Additionally the sludge from the aerobic reactor would be drained and filtered through a 2mm mesh screen to prevent potential pipe blockages from mixed liquor "clots". When a backlog in the feed had occurred the feed pump would be sped up appropriately and testing would only resume once a normal steady state flow was re-established. On day 374 power failures caused the anaerobic and anoxic reactor mixers to seize resulting in them having to be replaced with similar motors.

Mixed Liquor Blockages and Spills

Regular blockages occurred in the system due to the high concentration of the MBR mixed liquor. Blockages would typically occur in the piping connecting reactors. These could be reduced by massaging the piping on a daily basis to remove any minor blockages and discourage wall growths. However sporadic major blockages resulting in spills from the system reactors occurred. Mixed liquor lost through spillages could usually be recovered from drip trays inserted underneath the MBR system and was filtered through a 2mm mesh to ensure removal of large foreign particles that could damage the membranes and large mixed liquor clots that could block piping before returning mixed liquor to the system.

Silicon piping, used for the peristaltic pump feeding the MBR system and the recycles, was replaced on a weekly basis. However from sewage batches 12 to 19 the silicon piping would occasionally rupture prematurely. Buckets were placed under the pump in order to catch any spillages resulting from ruptured piping and the mixed liquor returned directly to the MBR system.

Reactor Motor Failures

Due to the increased MLSS concentration and continuous operation the mixing motors overheated and seized on days 92, 174 and 274 requiring them to be replaced. In these cases if possible the reactors would be mixed manually using a brush periodically until the motor was repaired.

3.8.2 Conventional UCT Operation

The conventional UCT system remained essentially unmodified throughout the investigation. Occasional failures of the SST resulted in sludge overflows to the effluent collector bucket in which mixed liquor would settle and could be returned to the system. In the event that sludge was lost, either through spillages, or while cleaning the system, the lost sludge would be estimated and incorporated into the sludge wasted on that day, and if necessary on subsequent days.

3.8.3 Operation of MBR system at a longer sludge age (40d)

Following the parallel investigation the MBR UCT system was run by Mahimba *et al.* (2006) at a longer sludge age of 40 days in order to properly investigate the phenomenon of increased sludge production and high $f_{S,up}$ in the system. In order to facilitate this transition certain design and operating parameters were changed, namely the feed volume was decreased from 140 to 80 ℓ /d and the volume wasted was similarly decreased to 1.45 ℓ /d from 2.85 ℓ . The operation changes were determined in order to achieve an aerobic MLSS concentration of 18000mgTSS/ ℓ , the same as in Phase 1 and 2 of the investigation. The system was run for two full sludge ages prior to the commencement of testing in order for the sludge to reach a steady state condition. No other significant changes were made to the system.

All the testing procedures from Phase 2 were retained in order to monitor the BNR performance of the 40 day slid

3.9 CLOSURE

In this chapter the experimental methodology for the SQW, MBR UCT and conventional UCT systems run in this investigation is set out. The results from the experimental Phase 2 of the investigation are presented in Chapters 4 (SQW and MBR UCT system) and 5 (conventional UCT system).

CHAPTER 4

SQW and MBR SYSTEMS EXPERIMENTAL RESULTS AND ANALYSIS

4.1 INTRODUCTION

In Chapter 3, the methodology of the project to investigate the impact of membranes for solid liquid separation on BNR behaviour and performance was described. This methodology was adopted and modified where necessary from Phase 1 of the project reported in Ramphao *et al.* (2004) in order to confirm and verify the results observed in Phase 1 and to expand on these. This required that operation of the three laboratory scale systems from Phase 1 be continued:

1. A square wave (SQW) activated sludge system in order to determine the RBCOD component of the influent waste water. This is an important parameter for evaluation of the BNR performance of activated sludge systems.
2. A MBR UCT system. This system, run in a UCT configuration, used membranes in the aerobic reactor for solid liquid separation. It allowed the BNR performance of a MBR system to be observed and studied.
3. A conventional UCT system with a SST. This system, also in a UCT configuration, acted as a control against which to compare the performance of the MBR system.

In this chapter, the experimental results from the SQW and MBR systems will be presented and analysed in detail.

4.2 SYSTEM CONDITIONS AND STEADY STATE PERIODS

4.2.1 System Operating Conditions

All three systems listed above were run continuously in the controlled conditions of the water research laboratory (WRL), which was kept at approximately 20 °C (± 1 °C). The two UCT systems were run continuously with close monitoring and control of the engineering and operational parameters. At least every two days samples were drawn from the systems and analysed in order to quantify and elucidate the BNR performance of the systems, see Chapter 3.

As described in Chapter 3 wastewater was collected in batches from the Mitchells Plain WasteWater Treatment Plant (MPWWTP, Cape Town, South Africa) and stored in an in-house cold room (4°C). Each sewage batch served as influent feed for up to a maximum of three weeks, before being discarded and replaced with a new batch of sewage. The sewage batches were accepted to represent steady state periods, and thus the system results are divided into sewage batch periods, see Table 4.1. The investigation extended over 449 days, which included a total of 29 sewage batch periods.

Table 4.1: *Sewage batch periods and dates of operation of the three activated sludge systems.*

Sewage Batch No	Date		Day number	
	From	To	From	To
2	5-Mar-05	18-Mar-05	21	36
3	19-Mar-05	4-Apr-05	37	53
4	5-Apr-05	26-Apr-05	54	75
5	27-Apr-05	15-May-05	76	94
6	16-May-05	31-May-05	95	110
7	1-Jun-05	14-Jun-05	111	124
8	15-Jun-05	23-Jun-05	125	132
9	24-Jun-05	7-Jul-05	133	147
10	8-Jul-05	27-Jul-05	148	167
11	28-Jul-05	17-Aug-05	168	188
12	18-Aug-05	2-Sep-05	189	204
13	3-Sep-05	16-Sep-05	205	218
14	17-Sep-05	3-Oct-05	219	335
15	4-Oct-05	12-Oct-05	236	244
16	13-Oct-05	27-Oct-05	245	259
17	28-Oct-05	10-Nov-05	260	273
18	11-Nov-05	28-Nov-05	274	291
19	29-Nov-05	19-Dec-05	292	312
20	20-Dec-05	2-Jan-06	313	326
21	3-Jan-06	17-Jan-06	327	341
22	18-Jan-06	30-Jan-06	342	354
23	31-Jan-06	14-Feb-06	355	369
24	15-Feb-06	28-Feb-06	370	383
25	1-Mar-06	8-Mar-06	384	391
26	9-Mar-06	23-Mar-06	392	406
27	24-Mar-06	7-Apr-06	407	421
28	8-Apr-06	22-Apr-06	422	436
29	23-Apr-06	5-May-06	437	449

Since this research followed on from a previous investigation, all three systems had been operated from May 2003 (Ramphao *et al.*, 2004). The writer assumed responsibility for operation and monitoring of the MBR and SQW systems in March 2005 and operated and monitored these two systems over the entire Phase 2 investigation. However, until sewage batch 15 the conventional UCT system was fed and monitored by laboratory staff. After this period, the writer took over control of operation, maintenance and monitoring of all three systems. During periods of extended absence by the writer (sewage batches 20 and 21) the systems were maintained by fellow post-graduate students and laboratory staff; however, no testing was conducted during these periods. Also, during sewage batch 1 analyses were incomplete because the writer was still learning and mastering the testing procedures.

4.2.2 Steady State Periods

Daily results for the MBR and conventional UCT systems are presented in Appendices A and B respectively and results for the SQW system included in Appendix A-1. The routine sampling and measurements taken from the two UCT systems were quantified and averaged as follows: Sewage batches were taken as steady state periods based on the assumption that no significant accumulation (±) would occur within the sewage batch and observations largely confirmed this.

Within a sewage batch, the first few days were allowed for the transition between steady state conditions and hence no testing was done on these days. Results recorded during a sewage batch period were analysed for consistency using a 95% confidence interval, whereby any results that fell outside this range (mean $\pm$ 1.96 $\times$ sample standard deviation) were considered non-representative of the steady state and excluded (for a more detailed description of the statistical analysis see Appendix D). The remaining values were considered valid and averaged to generate an average response for the sewage batch. The average responses for each sewage batch (steady state period) were used for subsequent analysis of the performance of the systems. These averages are reported in Appendices A and B.

4.3 SQW ACTIVATED SLUDGE SYSTEM

The short sludge age square-wave (SQW) fed system used in this investigation was based on the conventional "standard" method to measure the RBCOD developed by Ekama and Marais (1978) and Ekama *et al.* (1986). As described in Chapter 3, in this investigation the system was operated at a short sludge age of 2 days. The OUR was measured continually and automatically using the technique detailed by Randall *et al.* (1991).

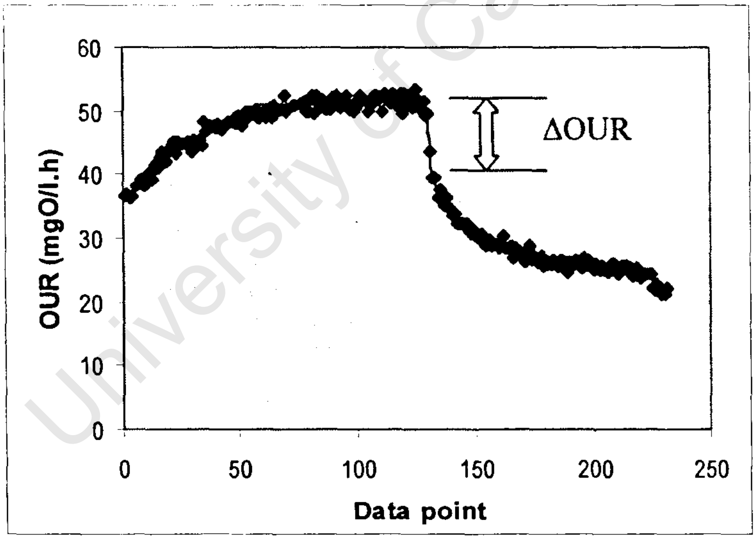


Figure 4.1: *A typical OUR profile in the short sludge age SQW fed activated sludge system run in this investigation.*

A typical OUR profile is shown in Fig 4.1. To calculate the RBCOD from the observed "drop" in OUR after feed termination (ΔOUR) Equation (4.1) was used (Ekama *et al.*, 1986):

$$S_{bsi} = \frac{\{1/(1-f_{cv}Y_H)\}.\Delta OUR.V_P.24}{Q} \qquad (4.1)$$

Where: S_{bsi} = the RBCOD concentration of the wastewater (mgCOD/ℓ)
f_{cv} = the COD to VSS ratio of the sludge (mgCOD/mgVSS)

Y_H = the heterotrophic yield coefficient (mgVSS/mgCOD)
ΔOUR = the "drop" in OUR readings as the feed to the system ends, indicating the change from RBCOD and SBCOD utilization to only the remaining SBCOD (mgO/ℓ/h).
V_P = the volume of the reactor (6.7 ℓ)
Q = the equivalent daily flow just prior to feed termination (36 ℓ/d)

The influent wastewater RBCOD fraction with respect to the total COD ($f_{ts,S}$) is given by Equation 4.2:

$$f_{ts,S} = S_{bsi}/S_{ti} \tag{4.2}$$

Using Equation (4.1) the daily RBCOD fractions for the sewage were calculated from the measured ΔOUR and S_{ti} values, using the commonly accepted constants Y_H = 0.45 and f_{cv} = 1.48 (WRC, 1984, Ekama *et al.*, 1986). The daily RBCOD fractions ($f_{ts,S}$) from the SQW system are plotted in a linearized probability graph (see Appendix D) to check for normality, Fig. 4.2.

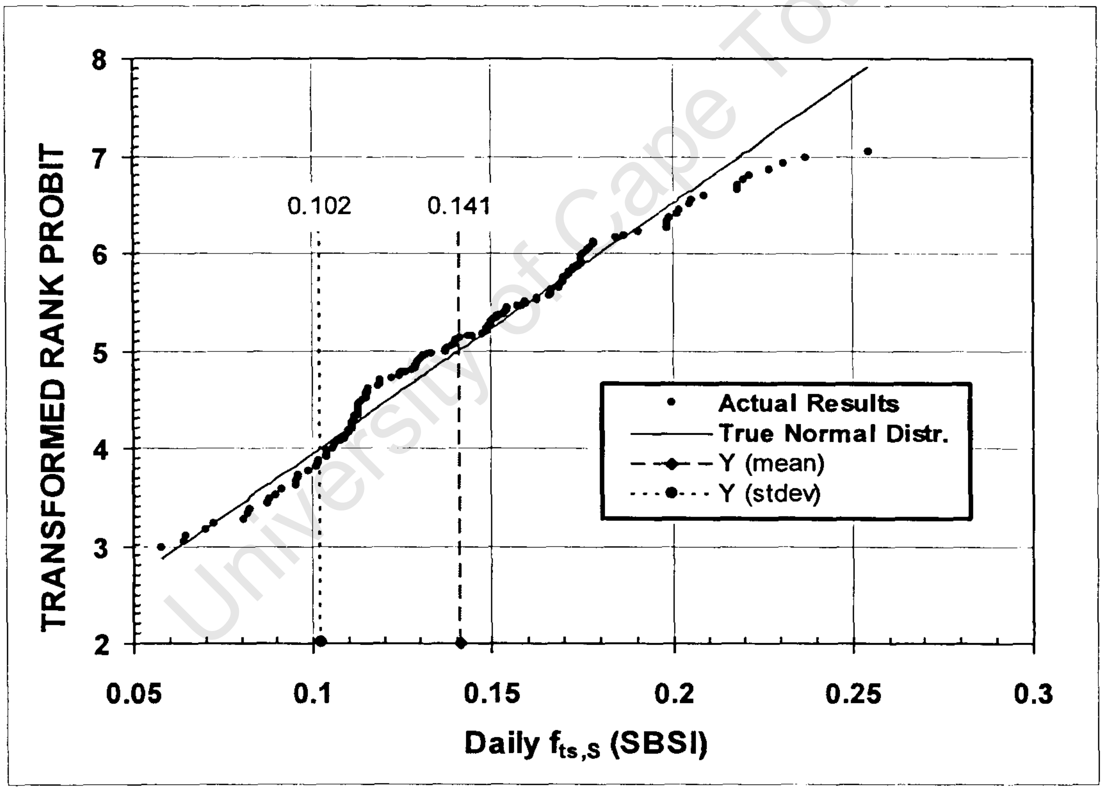


Figure 4.2: *Statistical plot of the daily RBCOD as a fraction of the total influent COD ($f_{ts,S}$) feed in the SQW influent feed.*

The daily data, except for the few largest values, lie close to the normal distribution line, indicating a normal distribution. The mean $f_{ts,S}$ of 0.141 is very close to that observed in the Phase 1 investigation of 0.145 (Ramphao *et al.*, 2004), and falls within the range of previous $f_{ts,S}$ values observed on sewage from the same source: 0.14 observed by Muller *et al.* (2003) and 0.16 by Ekama and Marais (1978). The sample standard deviation was 0.039 compared with 0.020 in Phase 1 (Rampaho *et al.*, 2004).

With the investigation average mean $f_{ts,S}$ value of the sewage determined above and knowing that the sewage was augmented with 200mgCOD/ℓ sodium acetate which is readily biodegradable, the total RBCOD content of the influent sewage feed ($f_{ts,T}$) could be calculated using Equation (4.3):

$$f_{t,T} = \frac{\{f_{ts,S}.(S_{ti,T} - 200) + 200\}}{S_{ti,T}} \qquad (4.3)$$

Where $S_{ti,T}$ = the total measured influent COD of the feed (mgCOD/ℓ)

Hence, the influent readily biodegradable component of the biodegradable COD ($f_{bs,T}$) could be calculated:

$$f_{bs,T} = \frac{f_{ts,T}}{(1 - f_{S,us} - f_{S,up})} \qquad (4.4)$$

Where: $f_{S,us}$ = unbiodegradable soluble fraction of the total influent COD
$f_{S,up}$ = unbiodegradable particulate fraction of the total influent COD

Following the procedures above the sewage batch average $f_{ts,T}$ and $f_{bs,T}$ values were calculated using the unbiodegradable particulate and soluble components of the influent ($f_{S,up}$ and $f_{S,us}$ respectively) calculated in sections 4.8.1 and 4.8.2 respectively. Table 4.2 lists the average $f_{ts,T}$ and $f_{bs,T}$ values for the various sewage batches.

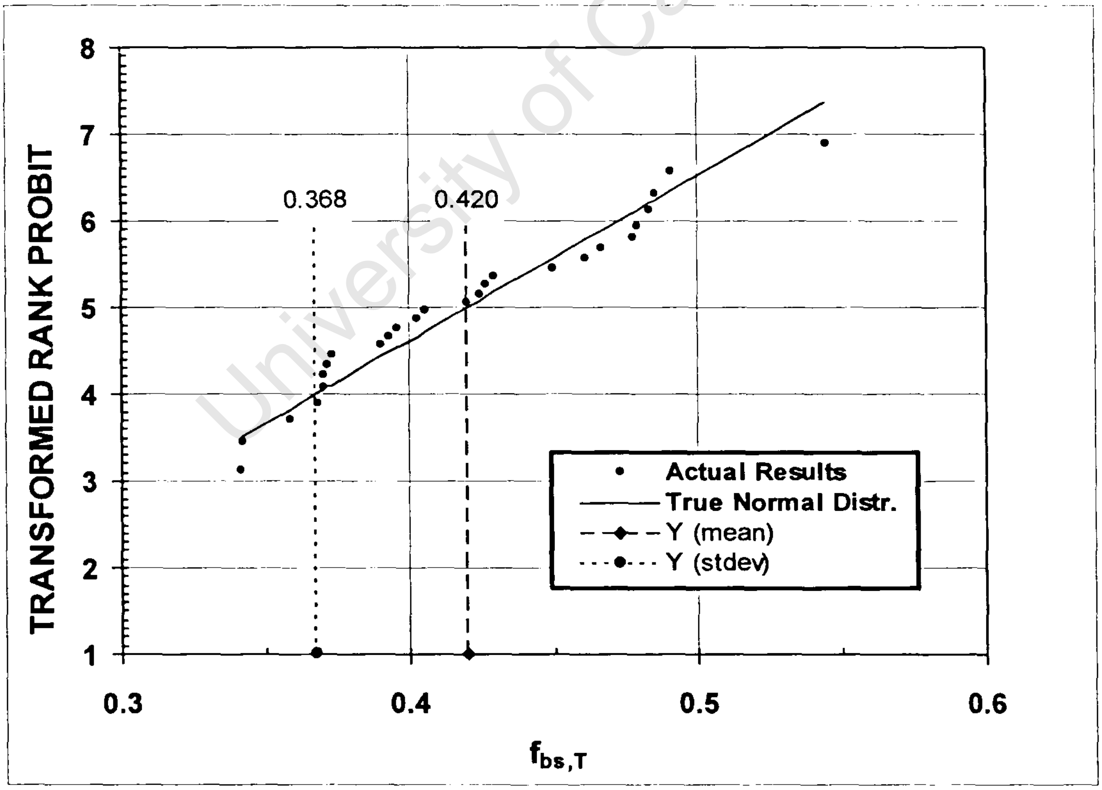


Figure 4.3: *Statistical plot of $f_{bs,T}$ for sewage batch periods using $f_{S,up}$ and $f_{S,us}$ values generated with the MBR data.*

A statistical plot of the sewage batch $f_{bs,T}$ data (Fig 4.3) indicates only minor deviation from the normal line. The mean is 0.420, with a sample standard deviation of 0.052, which is very close to that observed in Phase 1 of the project, mean = 0.431 (Ramphao *et al.*, 2004). The very high mean $f_{bs,T}$ value is due to the addition of sodium acetate to the feed to augment BEPR.

Table 4.2: *Sewage Batch RBCOD as a fraction of total and biodegradable influent COD ($f_{st,T}$ and $f_{sb,T}$)*

Batch Number	$f_{ts,T}$	$f_{bs,T}$
2		
3	0.317	0.360
4	0.297	0.341
5	0.352	0.431
6	0.323	0.461
7	0.336	0.483
8	0.368	0.569
9	0.328	0.424
10	0.322	0.404
11	0.302	0.390
12	0.290	0.393
13	0.358	0.479
14	0.285	0.376
15	0.258	0.351
16	0.285	0.371
17	0.237	0.320
18	0.325	0.482
19	0.286	0.378
20		
21		
22	0.291	0.356
23	0.303	0.372
24	0.336	0.562
25	0.375	0.485
26	0.339	0.435
27	0.319	0.403
28	0.258	0.367
29	0.333	0.450
Average	0.313	0.420

4.4 MBR SYSTEM ANALYSIS AND RESULTS

In this section the experimental results and analysis for the MBR system are presented. As far as possible all system operation, sampling and testing were performed by the writer, in order to maintain consistency and a full understanding of the system and factors that may affect it.

4.4.1 System Recycles and Mass Fractions

From sewage batch 6 system recycle flow rates were measured on a weekly basis and found to vary considerably. Two possible causes for this variation are:

i) the level of the feed tanks at the time of measurement affected the differential head pressure, particularly for the feed line, which would affect the recycle ratio, and

ii) undetected blockages in pipes (which were not always obvious) were suspected of affecting the flows through the recycle pipes. Hence, recycle values were checked by calculating the recycle ratios from total solids mass balances around the reactors, using Equations (4.5 a & b) developed for the MBR system by Ramphao *et al.* (2004):

$$r = \frac{X_{Vana}}{(X_{Vanx} - X_{Vana})} \quad \text{and} \quad as = \frac{X_{Vanx}}{(X_{Vaer} - X_{Vanx})} \qquad (4.5\ a\&b)$$

Where: $X_{Vana,\ anx,\ aer}$ = the VSS concentration of the anaerobic, anoxic an aerobic reactors respectively.

For most sewage batches the calculated and measured recycle ratio values corresponded closely, but as in Phase 1 these differed significantly from the expected (design) values (Ramphao *et al.*, 2004). Thus, for analysis of system behaviour, the recycles used for sewage batch periods were the average of the measured and calculated values, see Table 4.3. For the early sewage batches (2-5) where recycle flows were not measured, the as-recycle had been incorrectly configured in a 4:1 ratio, hence a recycle of 4:1 is assumed as the measured value for these sewage batches.

The mass fractions (f_{Mana}, f_{Manx}, f_{Maer}, for anaerobic, anoxic and aerobic reactors respectively) were calculated for each reactor from the average sewage batch recycles above using Equation (4.6) and corresponded closely with those calculated from the measured reactor mixed liquor concentrations and volumes (Table 4.3).

$$f_{Mana} = \frac{V_{ana}.X_{ana}}{(V_{ana}.X_{ana} + V_{anx}.X_{anx} + V_{aer}.X_{aer})} \qquad (4.6)$$

Where: V = the measured reactor volume

$X_{ana} = X_{anx}.r / (1+r)$

$X_{anx} = 1$

$X_{aer} = (1+a) / X_{anx}.a$

(f_{Manx} and f_{Maer} can similarly be calculated by substituting the values on the numerator of Equation (4.6) respectively)

Table 4.3: *Recycles and mass fractions for each sewage batch period*

SB no.	r-recycle				a-recycle				mass fractions		
	design	measured	calculated	average	design	measured	calculated	average	fm_{ana}	fm_{anx}	fm_{aer}
2	1	1.00	1.39	1.19	3.00	4.00	4.37	4.19	0.141	0.285	0.574
3	1	1.00	1.46	1.23	3.00	4.00	4.93	4.47	0.143	0.287	0.570
4	1	1.00	1.53	1.26	3.00	4.00	2.67	3.33	0.140	0.277	0.583
5	1	1.00	1.20	1.10	3.00	4.00	1.99	3.00	0.130	0.275	0.594
6	1	1.29	1.25	1.27	3.00	3.11	2.92	3.01	0.138	0.273	0.589
7	1	1.14	1.06	1.10	3.00	2.96	4.05	3.50	0.133	0.281	0.585
8	1	1.28	1.28	1.28	3.00	2.99	4.93	3.96	0.144	0.283	0.573
9	1	1.22	1.19	1.20	3.00	3.08	2.85	2.97	0.135	0.273	0.592
10	1	1.15	1.08	1.12	3.00	3.17	4.34	3.75	0.135	0.283	0.581
11	1	1.43	1.08	1.25	3.00	3.40	4.20	3.80	0.142	0.282	0.576
12	1	1.44	1.29	1.36	3.00	3.31	4.74	4.02	0.147	0.282	0.571
13	1	1.27	1.18	1.22	3.00	3.32	4.04	3.68	0.137	0.279	0.583
14	1	1.14	1.60	1.37	3.00	2.96	3.83	3.40	0.142	0.271	0.587
15	1	1.20	1.46	1.33	3.00	3.06	3.43	3.24	0.140	0.272	0.589
16	1	1.07	1.24	1.15	3.00	2.84	3.11	2.97	0.132	0.273	0.608
17	1	1.00	1.23	1.12	3.00	3.00	3.02	3.01	0.131	0.276	0.606
18	1	1.27	1.39	1.33	3.00	3.38	3.08	3.23	0.140	0.271	0.600
19	1	1.13	0.99	1.06	3.00	3.23	3.31	3.27	0.129	0.278	0.605
20											
21											
22	1	1.15	1.29	1.22	3.00	3.32	4.19	3.75	0.141	0.282	0.588
23	1	1.18	1.08	1.13	3.00	3.57	3.16	3.37	0.136	0.273	0.602
24	1	1.23	1.16	1.20	3.00	3.13	3.62	3.37	0.136	0.278	0.599
25	1	1.17	1.29	1.23	3.00	3.45	3.59	3.52	0.139	0.274	0.599
26	1	1.23	1.23	1.23	3.00	3.91	2.95	3.43	0.139	0.276	0.598
27	1	1.12	1.24	1.18	3.00	3.52	3.19	3.36	0.135	0.276	0.603
28	1	1.10	1.26	1.18	3.00	3.15	3.35	3.25	0.133	0.271	0.610
29	1	1.20	1.18	1.19	3.00	3.21	2.73	2.97	0.130	0.275	0.610
Ave	1	1.17	1.25	**1.21**	3.00	3.35	3.56	**3.45**	0.137	0.277	0.591
Ramphao *et al* (2004)	1	1.47	1.51	1.52	3.00	3.29	2.92	3.01	0.142	0.264	0.594

4.4.2 Membrane and Bioreactor Testing

4.4.2.1 Initial Membrane and Bioreactor Testing

In Phase 1 the bioreactor was tested for adequate mixing with a residence time distribution (RTD) test and adequate aeration using aeration of deoxygenated tap water (Ramphao *et al.*, 2004). The RTD and aeration tests were not repeated in Phase 2, though the dissolved oxygen (DO) concentration in the aeration reactor was checked regularly and consistently found to be between 2 and 5 mgO/ℓ, which was adequate for the biological demand of the system. Air flow into the aerobic reactor was consistently in the range of $2.5m^3/h$ with a Specific Air Transfer Rate of $78m^3/(m^3.h)$.

In April 2005 new membrane panels were received for installation into the membrane bioreactor. The old membranes had been in operation since the beginning of the investigation in April 2003 and had not been chemically cleaned. Flux tests were performed on the new and old membranes and are presented in Fig. 4.4. After Günder and Krauth (1999) the permeability of membranes is calculated by the quotient of the flux ($m^3/m^2.d$) divided by the TMP (m). Thus according to the initial flux tests, the permeability of the new and old membranes was determined as 5.68 and 2.09 $m^3/m^2.m.d$, demonstrating that the new membranes were almost 3 times as permeable as the old membranes.

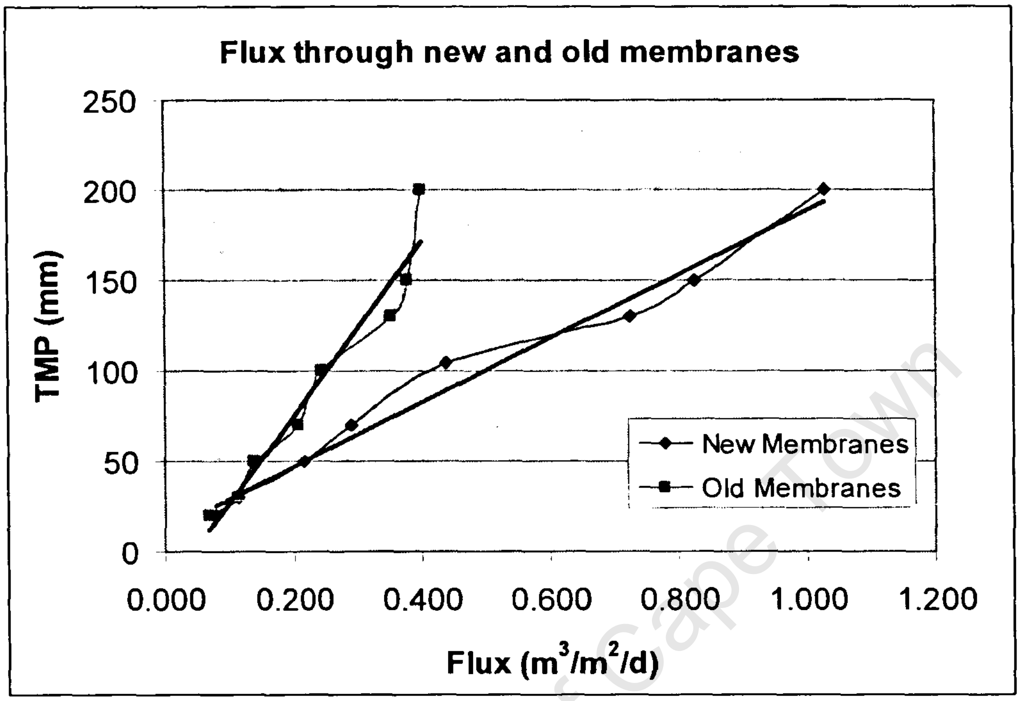


Figure 4.4: *Results from flux tests on the old membranes and new membranes installed in April 2005.*

4.4.2.2. Oxygen Transfer Rate Testing

Once the intensive study on BNR performance in the MBR system had been completed after sewage batch 29, (May 2006), the oxygen transfer rate (OTR) and oxygen transfer efficiencies (OTE) of the activated sludge at high MLSS concentrations were determined by performing tests on the sludge in the aerobic reactor. Details of the tests and methodology can be found in Chapter 3, Section 3.7.

Unsteady State Testing

Oxygen mass transfer co-efficient (K_{LA}) values were determined for a number of air flow rates in the operating range of the aeration system (Appendix F-2). In Fig. 4.5 the curves representing the airflow rate-vs- K_{LA} are presented for tests with membranes in the reactor, and tests with the membranes absent. The similarities of the curves suggest that the different geometry, and particularly the additional shear induced by the membranes had little impact on the oxygen transfer in the aerobic reactor.

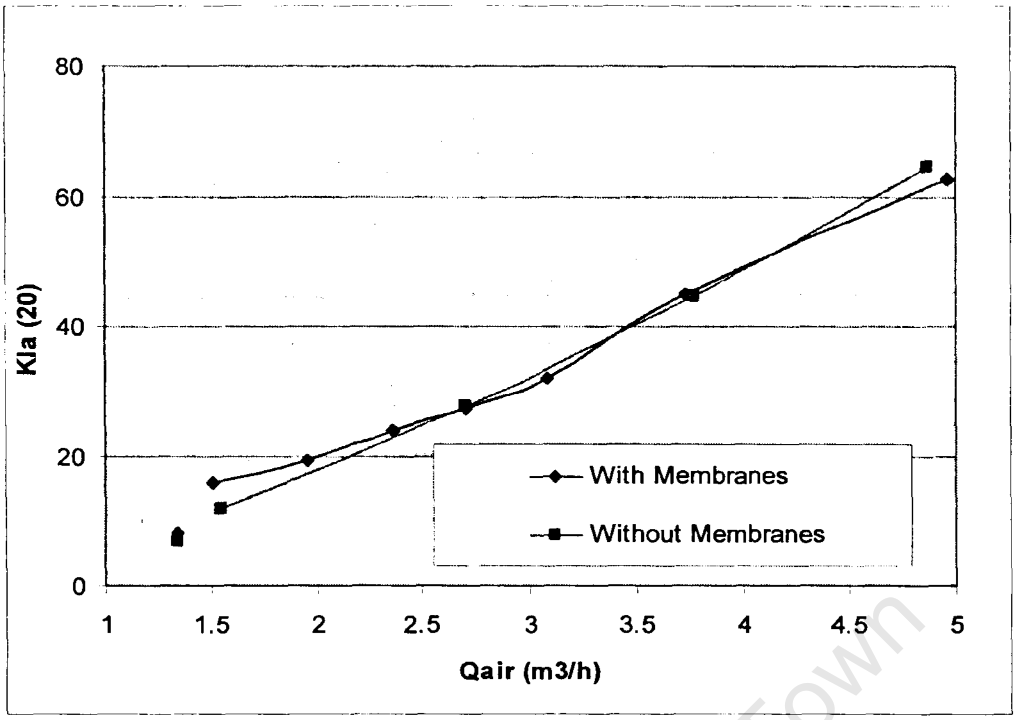


***Figure 4.5*:** *Reference curves for* K$_{LA\ (20)}$ *at various airflow rates* (Q_{air}) *for testing with and without membranes installed in the reactor.*

Steady State Testing

As described in Chapter 3, Section 3.7, steady state tests were carried out on the activated sludge once it had reached endogenous conditions to reduce the interference of differences caused by variations in feed (Appendix F-1). For a single MLSS concentration a number of readings were taken at different airflow rates (Fig. 4.6) and the Alpha values observed were averaged to give Fig. 4.7.

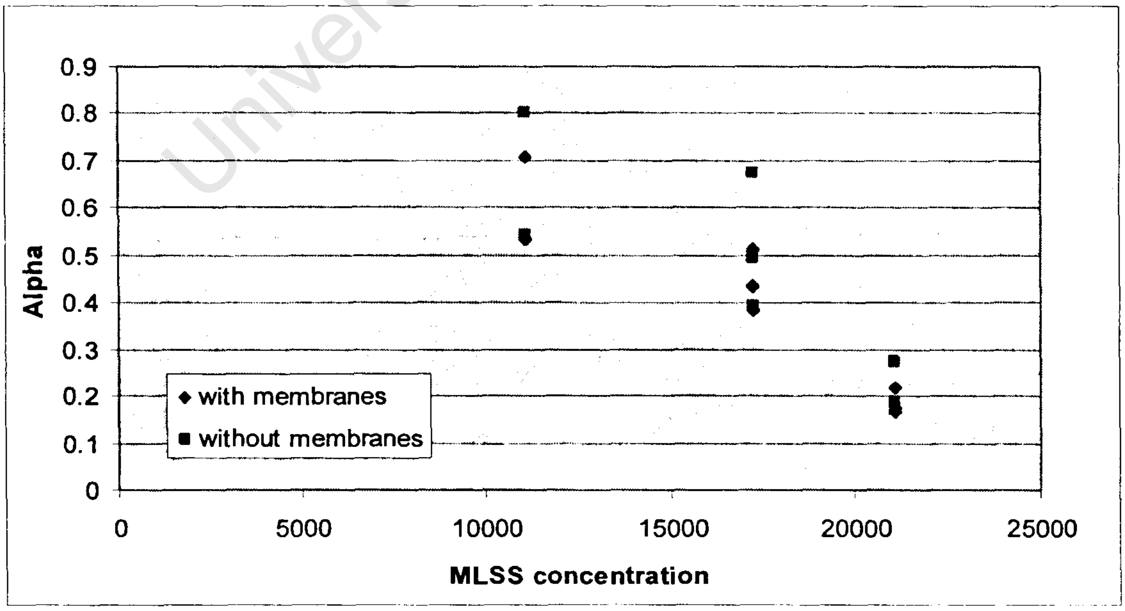


***Figure 4.6.*:** *The range of Alpha values observed at set MLSS values for the system with and without membranes respectively.*

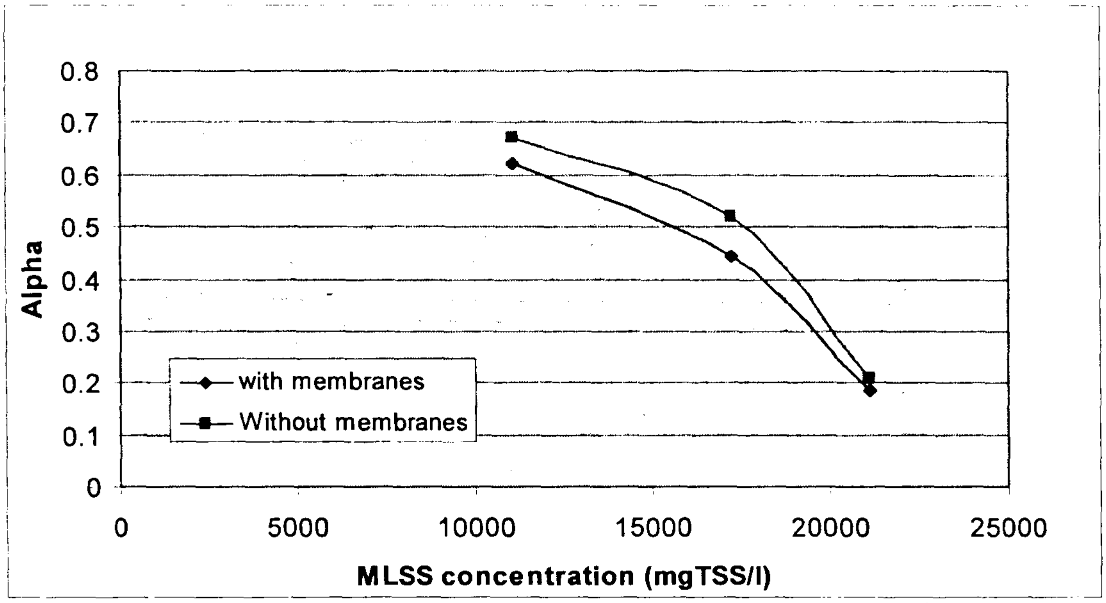


Figure 4.7: *Averaged Alpha values at set MLSS concentrations for conditions with membranes and without membranes respectively.*

The wide range of Alpha values observed is a concern. It was concluded that the predominant reason for the variations in observed Alpha values was the sensitivity of Equation (3.2) to variations in the measured OUR and C_L values, and fluctuations in the airflow readings. As the system was run under endogenous conditions, limited OUR activity meant that OUR readings were typically very low and C_L readings very high, hence minor differences in readings translated into major changes in calculated results. In order to compensate for high C_L values only low airflows could be run, at which the rotameter was less accurate. It was hoped that by averaging a number of readings at the same MLSS concentration a more accurate Alpha value could be determined for that MLSS concentration. In conclusion it is recommended that future Alpha tests are run on sludge with a far shorter sludge age, thus providing a greater active fraction in the activated sludge, and hence an increased OUR at endogenous respiration. Additionally very sensitive airflow rate instrumentation is required to accurately monitor the airflow into the aerobic reactor.

Measurement of OTR and OTE in the system

Having established K_{LA} and K_{LA}' values for clean water and mixed liquor respectively the OTR and OTE for the system were calculated using Equations (3.3) and (3.4). The same difficulties in measurement, noted above, also affected these calculations. Fig. 4.8a presents the OTR at various mixed liquor solids concentrations and in tap water against the specific air flow rate (SAFR) which is the volume of air per volume of liquid per hour. In this investigation the SAFR is very high in comparison to other studies (Cornel *et al.*, 2003 investigated systems with SAFR in the range of 0 – 4 $m^3/(m^3.h)$) but this is attributed to the small volume of the aerobic reactor (32 ℓ) in this study and the requirement of substantial aeration for cross-flow velocity membrane scouring. The OTE values calculated for various mixed liquor solids concentrations are presented in Fig. 4.8b. The OTE values were very low but comparable to OTE values reported by Cornel *et al.* (2003) for coarse bubble aeration in mixed liquor at high solids concentrations. OTE values remained relatively constant at increasing SAFR rates, indicating that OTE is dependant on solids concentration, not flow rate.

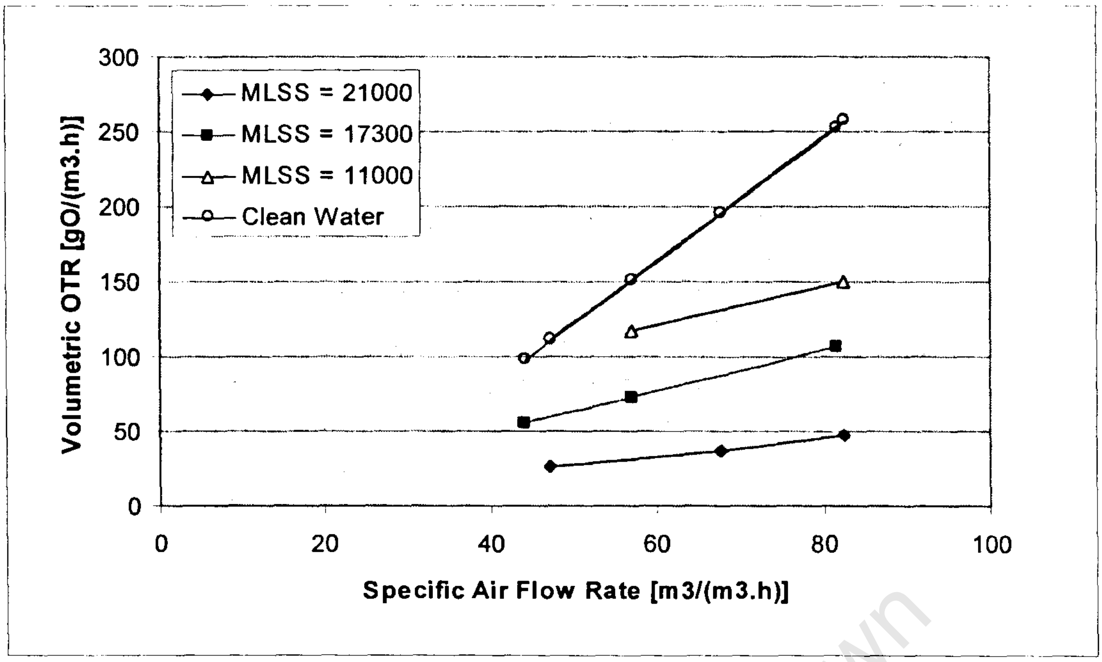


Figure 4.8a: *Oxygen transfer rates (OTR) in clean water and various MLSS concentrations.*

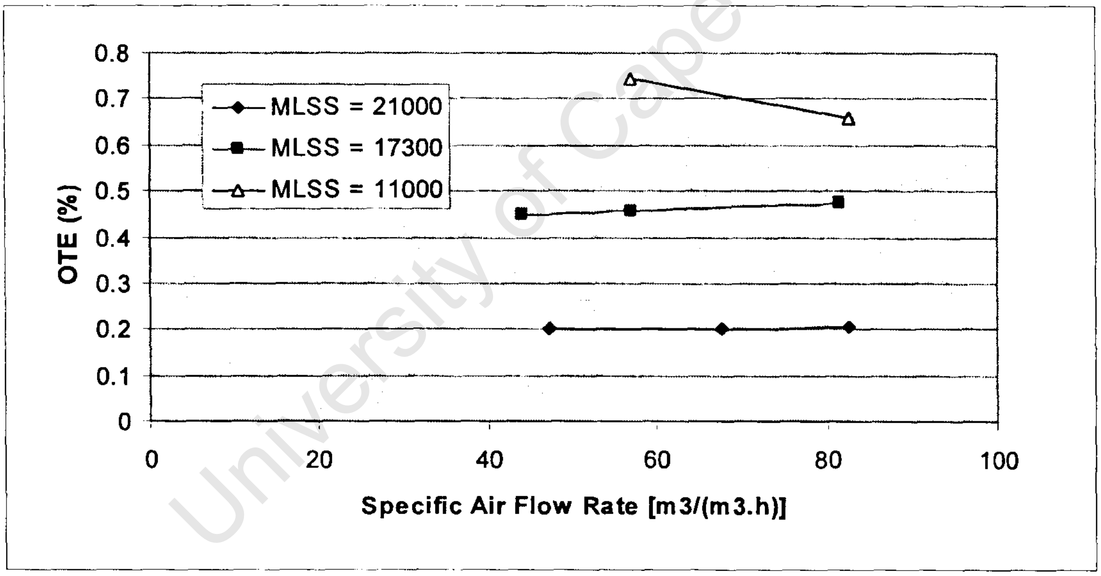


Figure 4.8b: *Oxygen transfer efficiency (OTE) for various MLSS concentrations).*

Rheometric testing

Baker *et al.* (1975) and Krampe J. and Krauth K. (2003), citing Rosenberger *et al.* 2002b and Günder *et al.* (2001), indicated that there was a linear relationship between viscosity and Alpha, thus the relationship between the measured viscosity and Alpha values was investigated. Rheometric testing was conducted on the various mixed liquor concentrations to determine the viscosity of the mixed liquor at these concentrations (Appendix F-3). Figs. 4.9a and b present MLSS versus Alpha and viscosity, and the plot of Alpha versus the viscosity of the sludge at various shear rates of 58/s, 78/s, 148/s and 280/s respectively. Although only three Alpha values were established there appears to be a linear regression suggesting that there is indeed a linear relationship between viscosity and Alpha. This relationship should be explored further in future investigations as it may allow a more accurate method of predicting Alpha in high concentration mixed liquor sludges. However such an investigation is dependant on the accurate measurement of Alpha in a high concentration sludge for which the writer experienced numerous difficulties as are described above.

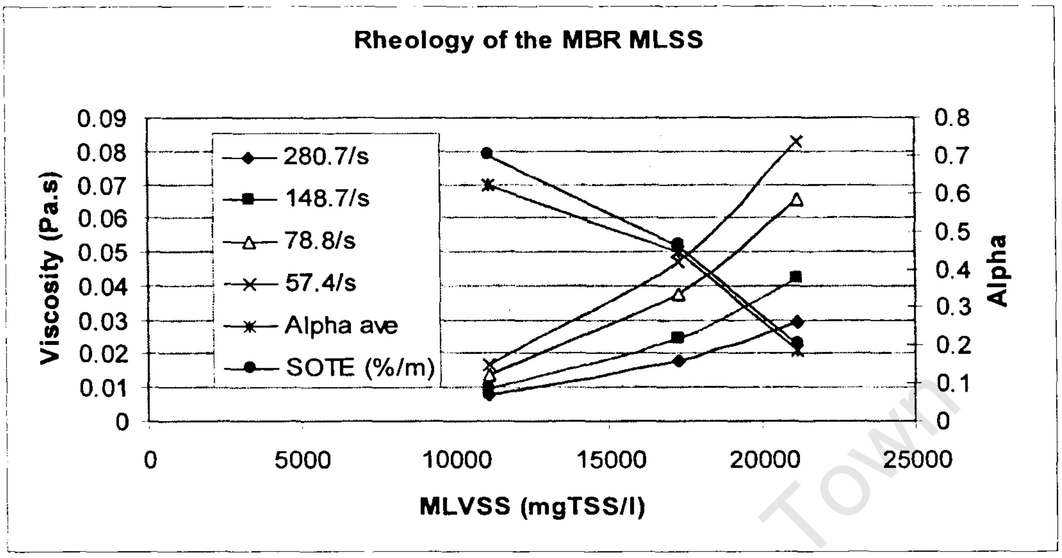


Figure 4.9a: *Changes in viscosity and Alpha at various high concentration sludges.*

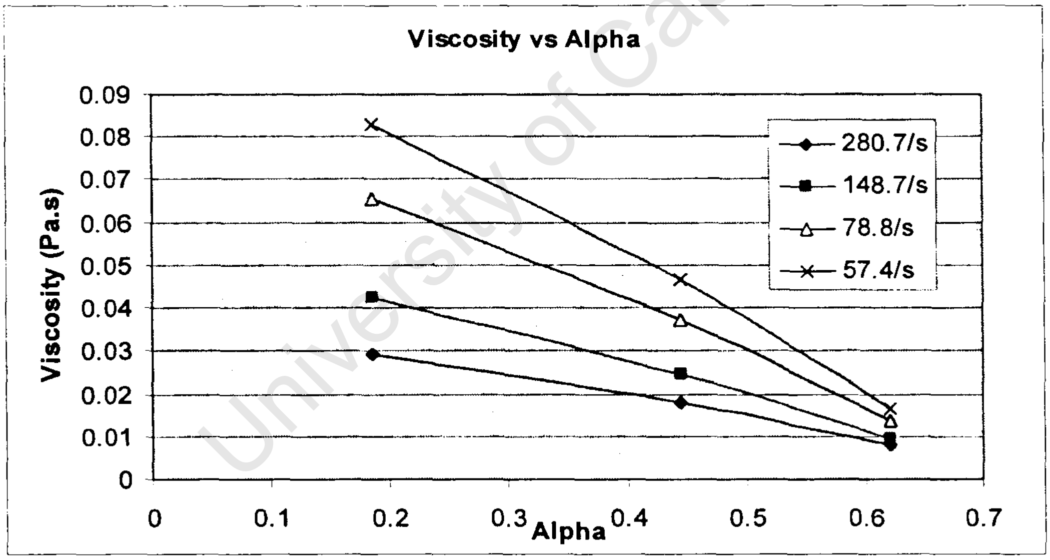


Figure 4.9b: *A linear relationship between Alpha and viscosity was observed.*

Beta Testing

Beta tests were conducted on the MBR sludge as described in Chapter 3, Section 3.7.4. It was found that the C_S achieved in distilled water after aeration for an hour was the same as that observed in the sludge after substantial HgCl dosing had halted all biological activity. Thus a Beta value of 1.0 was assumed.

4.5. MEMBRANE PERFORMANCE

The objective of this research was to investigate the BNR performance in a submerged MBR system. Hence, the performance of the membranes was not a research priority. However, membrane performance was monitored throughout the investigation by measuring trans-membrane pressure (TMP) and is reported in this section.

During the investigation, essentially a constant flux was selected (since the influent flowrate was constant) and the TMP varied to maintain this flux. Also the volume of the aerobic reactor needed to remain constant throughout the investigation. Accordingly the height of the effluent overflow pipe (Chapter 3, Section 3.6.2) was varied to maintain the constant flux and reactor volume. The TMP in mm water is the difference in height between the reactor liquid level and effluent overflow weir level. For the duration of Phase 1 TMP was monitored closely and a continual small increase of 0.12mm/d in the TMP of the membranes was noted. Similarly from the beginning of Phase 2 the TMP was continually monitored.

TMP is directly proportional to the flux passing through the membranes and hence to consistently monitor TMP required that the instantaneous flux be measured also. As the initial membrane tests indicated, the relationship between flux and TMP is linear. Thus, the measured TMP and instantaneous flux could be referenced back to the equivalent TMP at the expected steady state flux. This proved important late in the investigation as there were small but noticeable variations in the flux through the membranes induced by factors such as irregular pumping speeds and minor blockages in the piping connecting the reactors.

Until day 349 only the TMP was measured which, due to only minor fluctuations in the pump speeds and minor blockages, can be accepted as normally distributed and representative. However, from day 359 difficulties due to large mixed liquor spillages and intermittent power outages caused irregular pumping, and the effect of flux on TMP needed to be taken into account. Thus from day 371, an adjusted TMP_{adj} is reported (Equation 4.7).

$$TMP_{adj} = \frac{TMP.Q_i}{Q_e} \tag{4.7}$$

Where: Q_i = the design influent flow of 140 ℓ /day/24hrs

Q_e = the effluent flow measured during the TMP test (ℓ /hr)

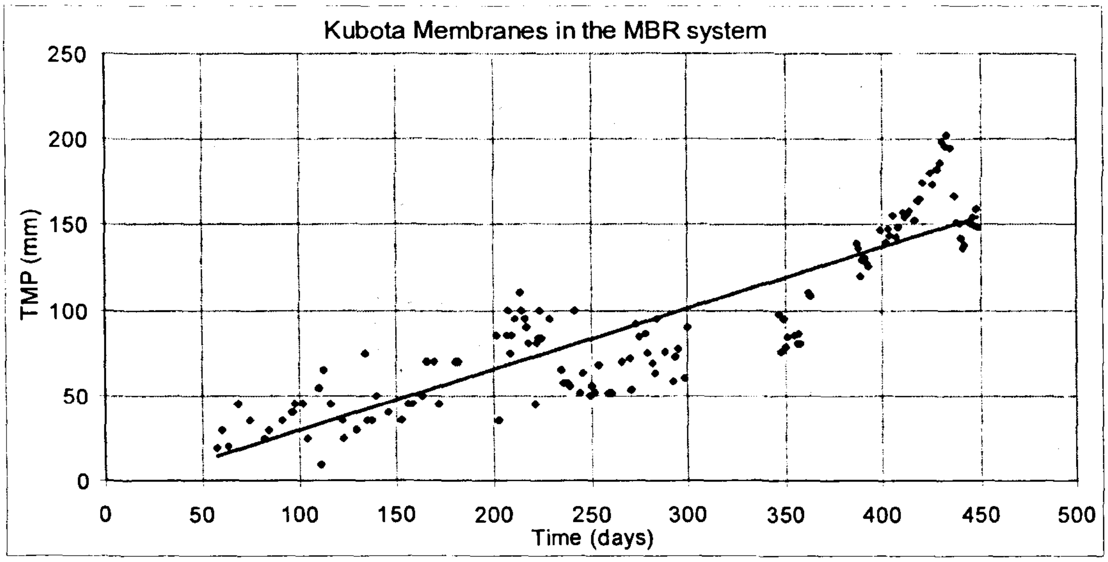


Figure 4.10: *TMP changes in the MBR system were observed for the duration of the project. A steady increase was observed with time though specific events like inorganic colloidal solids in the influent had a marked impact on the TMP.*

The measured TMP with time over the investigation is shown in Fig. 4.10. Although the measured TMP shows considerable scatter due to variations at the time the measurements were taken, a consistent increase in the TMP over time was observed of about 0.29mm/d. This is significantly larger than the increase noted in Phase 1 of 0.115mm/d, and would have a significant influence on membrane life; over 20 years the increase in TMP would be ~ 2.1m. Every two to three weeks the membranes were sprayed down with water, during regular system cleaning. However as with the Phase 1 investigation, no chemical cleans were performed on the membranes until the later stages of the investigation (sewage batch 28) in order to monitor the increase in TMP over time. No definitive explanation for this greater increase in TMP with time in Phase 2 compared to Phase 1 could be identified.

From day 374 to day 386 sporadic power failures were experienced in the lab, often at night, resulting in the membranes fouling due to discontinued or irregular aeration (no aeration results in no cross flow scouring). This resulted in an increased TMP. The fouling was in the form of a thin (2mm), compact cake of sludge. In cases where the power failure had been brief, less than a half hour, the subsequent aeration of the membranes would remove much of the caking formed on the membranes. When the power failure had been longer than a half hour the caking that formed on the membranes was more resilient to the aeration and required manual cleaning by removal of the membranes from the system and water spraying. After water cleaning the TMP would return to levels shortly before the blockage. In full scale plants the potential of fouling due to power failures is circumvented by installing a stop valve on the permeate line which closes when power fails (Kennedy, *pers. com.*).

During sewage batches 27 and 28 (days 407 to 436) following the power failures, the TMP increased sharply from 142mm (day 407) to 202mm (day 433). Simultaneously, the filtration of the mixed liquor from the MBR reactors became increasingly difficult. An ISS test was performed on the sewage and a very high inorganic suspended solids (ISS) content, 0.162mgISS/mgCOD was measured compared with averaged ISS concentrations of 0.041-0.050mgISS/mgCOD from 48 studies reported for sewage from the same wastewater source (Ekama and Wentzel, 2004). On investigation it was found that construction at the Mitchells Plain WWTP could have been the cause of additional fine ISS particles entering the sewage and could potentially have caused the increased TMP. Similar observations were reported by Fleischer *et al.* (2005) whereby the filterability of the sludge was significantly decreased by increased colloidal inorganics accumulating in the mixed liquor.

Up to this point in the study no chemical cleans had been performed on the membranes in order to allow the writer assess the deterioration of the membranes with time from biological factors. However the sudden increase in TMP necessitated that the membranes be thoroughly cleaned. Hence chemical and biological cleans using a 1.0% citric acid solution and 0.5% hypochlorite solution respectively as recommended by the manufacturer (Kennedy, *pers. com.*) were performed on the membranes on day 433. Prior to the chemical clean the system TMP was 202mm. Once the cleaning process had been performed the membranes were returned to the system and a TMP of 118mm was measured in tap water. This improvement was substantially less than expected, which put in doubt the effectiveness of the chemical clean, and there was little improvement in TMP when the sludge was returned to the system, from 202mm (day 433) to 194mm (day 434). Only when the next sewage batch (29, day 437) was introduced, with ISS = 0.050mgISS/mgCOD, did the TMP drop rapidly to previous levels. Thus it appears that the TMP-flux relationship can be significantly influenced by fine colloidal ISS in the influent sewage. The rapid recovery suggested that the colloidal ISS is assimilated into the sludge over a period of only a few days. Thus this phenomenon should affect MBR systems with short and long sludge ages equally.

Kennedy (*pers. com.*) reported that on full scale membrane plants, chemical and biological cleans on membranes return the membrane TMP to original levels. Hence subsequent cleans were performed on the system membranes in October 2006. The membranes were thoroughly sprayed down with water and inserted into a 1% hypochlorite solution for an hour. However a slight suction was placed on the effluent outflow pipes of the membranes to circulate hypochlorite through the membranes. On removal the membranes which prior to cleaning had a light brown colouring had essentially been bleached and came out white. The initial TMP in the system was high, 460mm, but within 24 hours the TMP had dropped to 55mm, roughly the TMP observed when the new membranes had been installed in May 2005. The initial high TMP is explained by the progressive flushing of the soapy hypochlorite layer that had formed on the membranes. Additionally the failure of initial chemical cleans on day 433 is attributed to the old stock of hypochlorite used which may have degraded to the point of being ineffective.

4.6 MIXED LIQUOR SOLIDS

For all the MBR system reactors the mixed liquor solids parameters, MLSS, MLVSS, COD and TKN were monitored regularly from the beginning of the investigation. The information on the variation of mixed liquor concentrations with time was necessary in order to interpret the BNR performance of the system.

4.6.1 Sludge Age (Rs)

As far as possible the sludge age of the system was maintained constant at 20 days by wasting 2.85ℓ/d mixed liquor volume from the aerobic reactor (approximately 1/20th of the system sludge mass). In the event of an unintentional mixed liquor loss from the system due to i) a spill from the reactors, ii) a burst interconnecting pipe, or iii) foam removal, knowledge of the total solids content of the system allowed the mass of mixed liquor lost to be determined and the approximate mixed liquor mass to be wasted was reduced accordingly over the following days.

4.6.2 MLSS and MLVSS Concentrations

After Phase 1 the mixed liquor in the systems was retained and the Phase 2 investigation commenced with the same sludge. Throughout the investigation there were minor unintended mixed liquor losses typically through spillages or while cleaning the system. Most of these were contained in drip trays below the reactors and the spilled mixed liquor was filtered through a 2mm screen to avoid sludge "clots" forming which could cause blockages in the system, and to ensure that foreign objects weren't accidentally returned with the mixed liquor.

On a few occasions substantial amounts of mixed liquor were lost, Table 4.4. On each occasion the total mixed liquor lost was calculated as the difference in solids concentration from the day prior to the spill, and the loss was compensated by not wasting for the equivalent number of days following the spill.

Table 4.4: *Sludge loss events in Phase 2*

Day	Event
48 - 56	Foaming: Steady solids accumulation in foam.
66,67, 69 and 74	Spillages: Extensive spillages resulting in substantial loss of solids and no wasting until day 88.
359 and 360	Spillages: Recurrent spillages resulted in low solids and no wasting until solids returned to 18 000mgTSS/ℓ on day 370.
374 – 378, 383 and 386	Power failure: Regular power failures resulted in numerous minor spillages as the membranes would foul overnight.

Foaming, exclusively in the anoxic reactor, was common and expected due to the high sludge concentration and thus the high volume of N_2 gas released through denitrification. The foam generated was trapped on the reactor which did not allow for surface flow through. This was dealt with by brushing down the foam into the reactor liquid daily. However over one period (Days 48-56, Table 4.4) substantial foaming was observed, and when repeated brushing down did not help, it was physically removed from the system. In this case the mass of foam removed was taken into account when wasting sludge over the next few days. Between days 374 and 386 the laboratory experienced recurrent power failures which resulted in the systems not being fed and consequently mixed liquor was not wasted either. Hence longer sludge ages were measured for this batch period.

Apart from the periods noted above, the MLSS concentration in the aerobic reactor remained within the range of 16 000 - 19 000 mgTSS/ℓ and the anoxic and anaerobic concentrations were within the ranges of 12000 – 14000 mgTSS/ℓ and 6000 – 8000 mgTSS/ℓ respectively. These ranges are substantially less than those reported by

Ramphao *et al.* (2004) in Phase 1. These differences are attributed to both to a lower S_{ti} for Phase 2 (Section 4.9.1) and lower influent unbiodegradable particulate COD fraction ($f_{S,up}$, Section 4.8.2).

For assessment, the sewage batch average TSS and VSS concentrations in the three reactors are shown in Figs. 4.11. to 4.13. The TSS concentration of the 3 ℓ re-aeration reactor is also shown in Fig. 4.12. Reactor concentrations were consistent over the investigation.

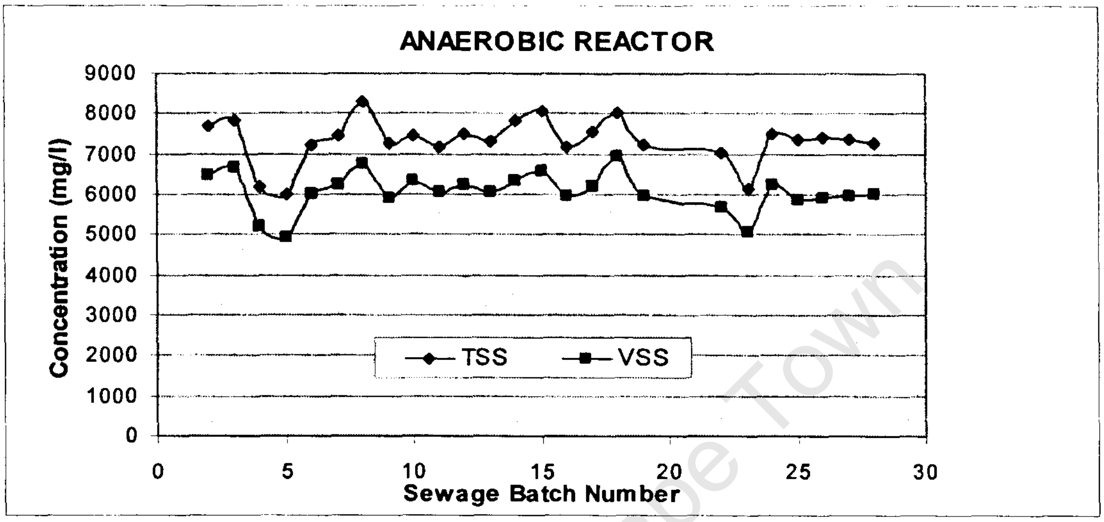


Figure 4.11.: *Development of the mixed liquor total suspended solids (TSS) and the volatile suspended solids (VSS) concentrations in the anaerobic reactor.*

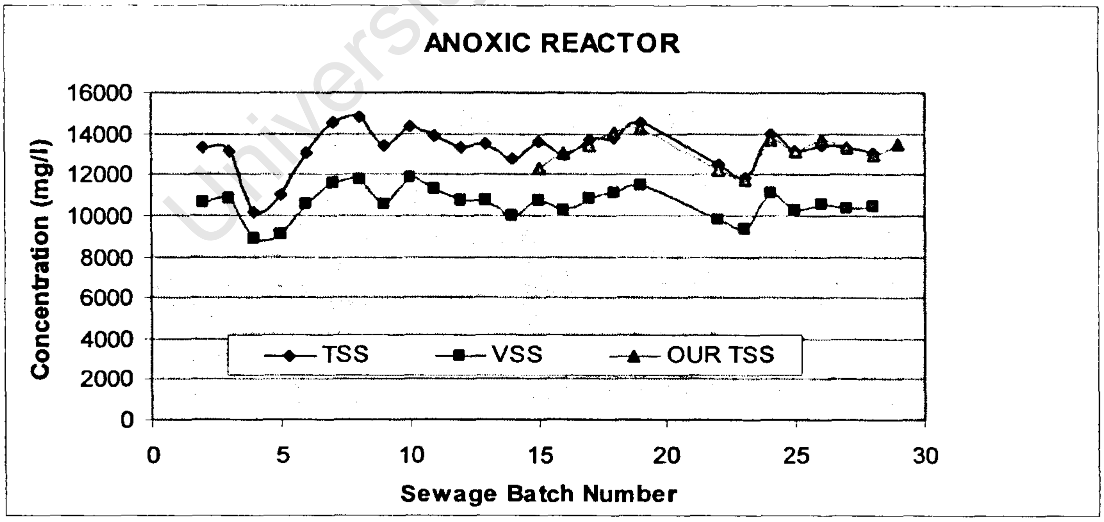


Figure 4.12.: *Development of the mixed liquor total suspended solids (TSS) and the volatile suspended solids (VSS) concentrations in the anoxic and re-aerobic reactors.*

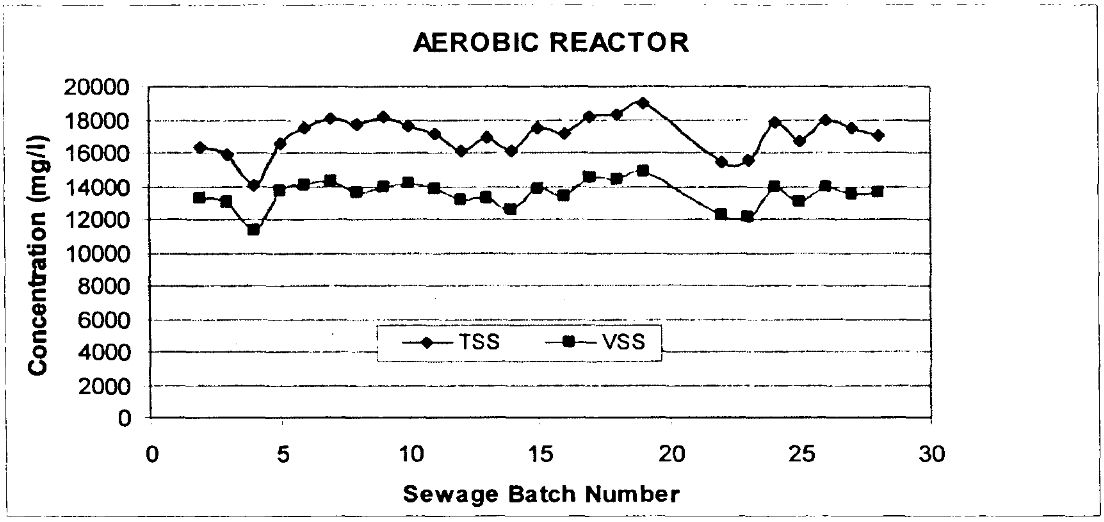


Figure 4.13.: *Development of the mixed liquor total suspended solids (TSS) and the volatile suspended solids (VSS) concentrations in the aerobic reactor.*

In an MBR system, mixed liquor distribution within the reactors is influenced directly by the recycles between reactors. In conventional systems the concentrations in the anoxic and aerobic reactors are very similar as the mixed liquor is concentrated after the aerobic reactor in the SST and then recycled to the anoxic reactor. In the MBR system, this concentration effect occurs within the biological reactor and thus there is a difference in concentration between the two reactors. This concentration difference is dependant on the a-recycle (Ramphao *et al.*, 2004). The a-recycle measured in Phase 1 was marginally less than in Phase 2 (3.0 vs 3.5) and as a consequence the ratio between the TSS concentrations in the anaerobic and anoxic reactors was marginally less in Phase 2.

4.6.3 COD/VSS Ratios

The COD/VSS ratio (f_{CV}) was regularly measured for the aerobic reactor mixed liquor. The sewage batch average f_{CV} values are plotted statistically in Fig. 4.14 giving a mean average of 1.40 (SSD = 0.059. This f_{CV} value is close to the theoretically estimated f_{CV} of 1.42 (WRC, 1984) and is within the range of values (1.3 – 1.5) previously found in laboratory experiments in the Water Research Laboratory (WRL), (e.g. 1.37 Lee *et al.*, 2002a; 1.42 Sneyders *et al.*, 1998; 1.45 Mellin *et al.*, 1998) for conventional systems. Further, the value is close to that measured in Phase 1, of 1.35 (Ramphao *et al.*, 2004), and confirms that the membranes do not significantly influence this value.

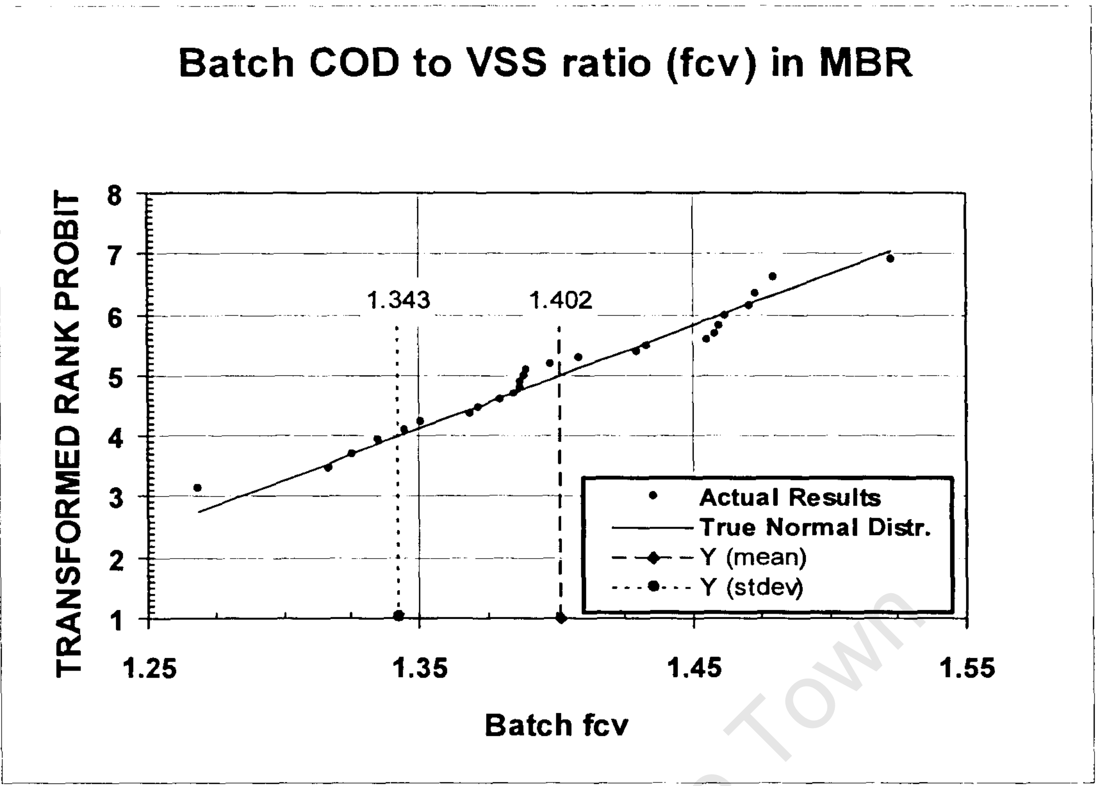


Figure 4.14.: Statistical plot of the sewage batch average COD to VSS ratio (f_{CV}) in the MBR system

4.6.4 System VSS/TSS Ratios

The possibility that the membranes influence the VSS/TSS ratio (f_i) of the mixed liquor through non-selective retention of all ISS was investigated. The ratio of VSS to TSS was measured in all three reactors giving investigation averages of 0.82 (anaerobic), 0.81 (anoxic) and 0.79 (aerobic). The difference in values for this ratio between reactors is expected and attributed to the release of inorganic phosphate and cations by PAO's in the anaerobic reactor, decreasing the inorganic content of the mixed liquor in that reactor (high f_i) and the uptake of phosphate and cations in the anoxic (marginal) and aerobic reactors which reincorporate inorganics in the mixed liquor (lower f_i). Throughout the investigation the VSS values in all three reactors tracked the TSS values consistently, Fig. 4.15.

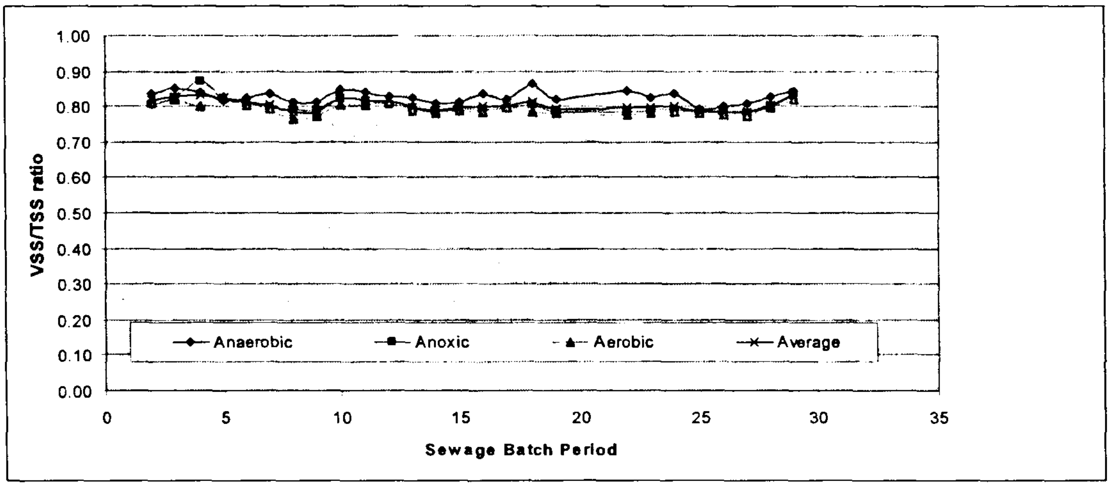


Figure 4.15: Comparison of the VSS/TSS ratios (f_i) of the sludge in the anaerobic, anoxic and aerobic reactors.

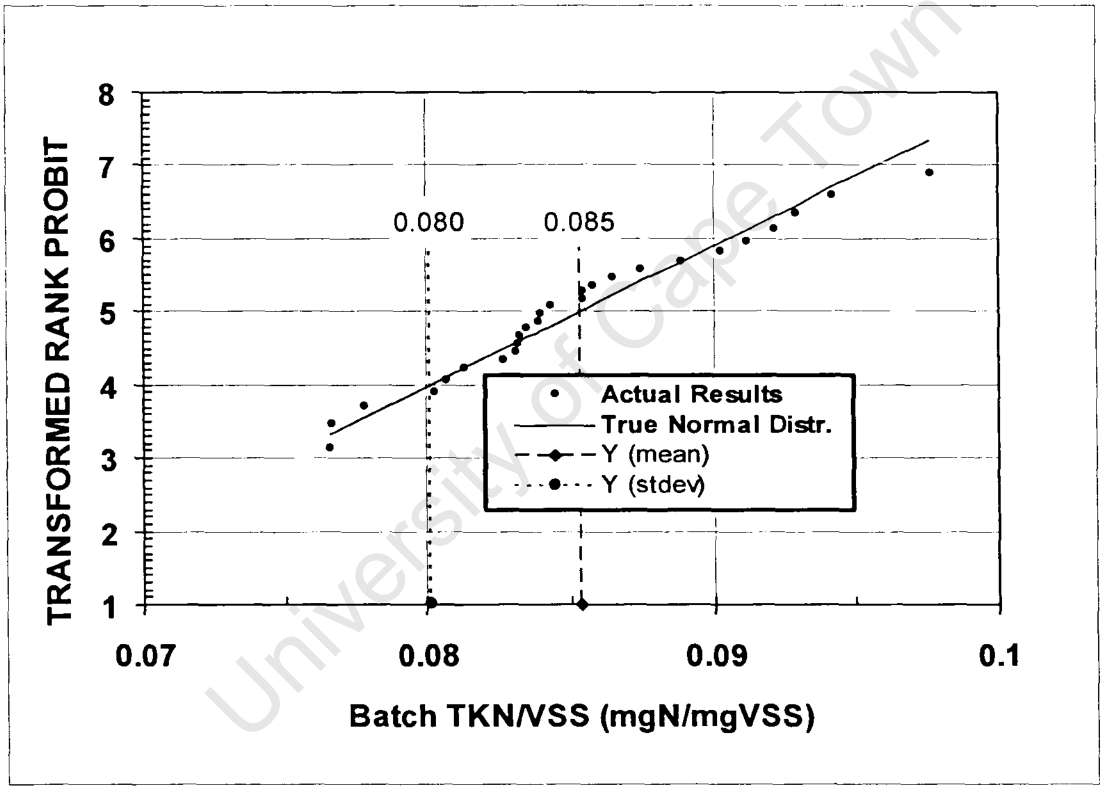


Figure 4.16: The statistical distribution of the daily VSS/TSS ratio (fi) in the MBR system.

The daily weighted average f_i ratios of the three reactors are normally distributed (Fig. 4.16) with the mean 0.809 (SSD = 0.028), which is close to the value determined in Phase 1 (mean = 0.791). These values are higher than that expected (~0.75) for a BNR system accumulating significant biomass ISS through the intracellular storage of polyphosphate and associated counter ions. As noted in Phase 1 (Ramphao *et al.*, 2004), this suggests that the membranes do not promote selective accumulation of ISS but rather may promote selective accumulation of organics as VSS. This will be examined later in the chapter.

4.6.5 System TKN/VSS Ratios

The nitrogen content of the sludge was measured by the TKN/VSS ratio of the aerobic reactor mixed liquor. The results were fairly consistent throughout the test period and were normally distributed with a mean of 0.085 (SSD = 0.005) mgN/mgVSS, Fig. 4.17, which is close to the mean of 0.079 measured in Phase 1, (Ramphao *et al.*, 2004). The mean does differ from the value of 0.10mgTKN/mgVSS/ℓ typically accepted for activated sludge mixed liquor (WRC,1984, Henze et al, 1987). However, as noted in Ramphao *et al.* (2004) the mean is very close to values of 0.086. 0.086 and 0.083 obtained by Beeharry *et al.* (2001), Sneyders *et al.* (1998) and *et al.* (2002a) respectively for mixed liquor treating wastewaters from the same source (Mitchells Plain WWTP).

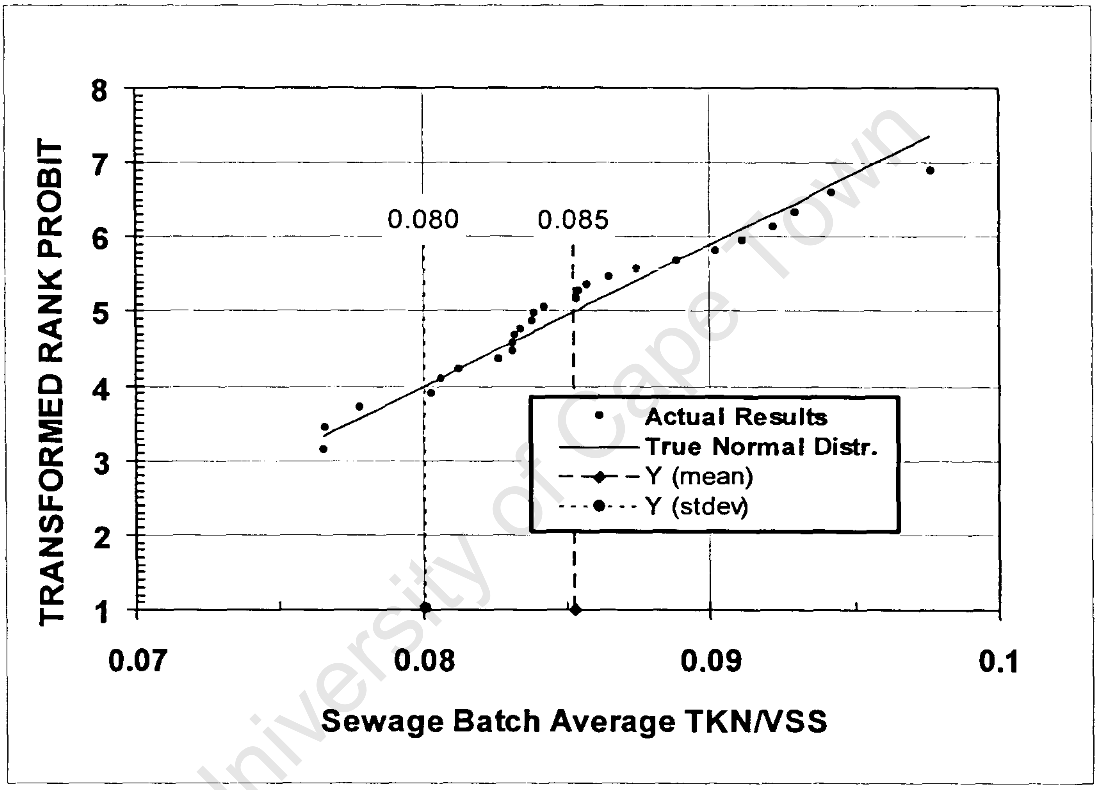


Figure 4.17: *TKN/VSS ratio in the aerobic reactor.*

The system mixed liquor solids were measured with three independent techniques, the VSS, COD and TKN. That the ratios between these measurements conform reasonably closely to theoretical and previously determined values provides substantive support that the mixed liquor solids have been accurately quantified.

4.6.6 Sludge Production

Sludge production is measured as the mass of MLVSS produced per unit influent COD load per day. Two methods were used to determine the sludge production, differing only in the method of calculating the sludge produced: the first calculated the sludge produced by the mass of sludge measured in the system divided by the sludge age, the second measured sludge produced by the mass of sludge wasted daily (Equations 4.8 and 4.9). The results from both methods were very close for the average of the sewage batches averages. The sludge production in the MBR UCT system varied over the study with a range of 0.24 – 0.39 and a mean of 0.311mgVSS/mgCOD (SSD = 0.035mgVSS/mgCOD) as shown in Fig. 4.18. This is very close to the sludge production observed in Phase 1 (Ramphao *et al.* 2004) of 0.32mgVSS/mgCOD, and indicates that the lower MLSS concentrations observed in Phase 2 were indeed due to lower influent COD in the system in Phase 2.

$$ML_{(production)} = \frac{MX_v}{R_s.(MS_{ti} - MS_{te})} \quad \text{or,} \tag{4.8}$$

$$ML_{(production)} = \frac{MX_{v(waste)}}{(MS_{ti} - MS_{te})} \tag{4.9}$$

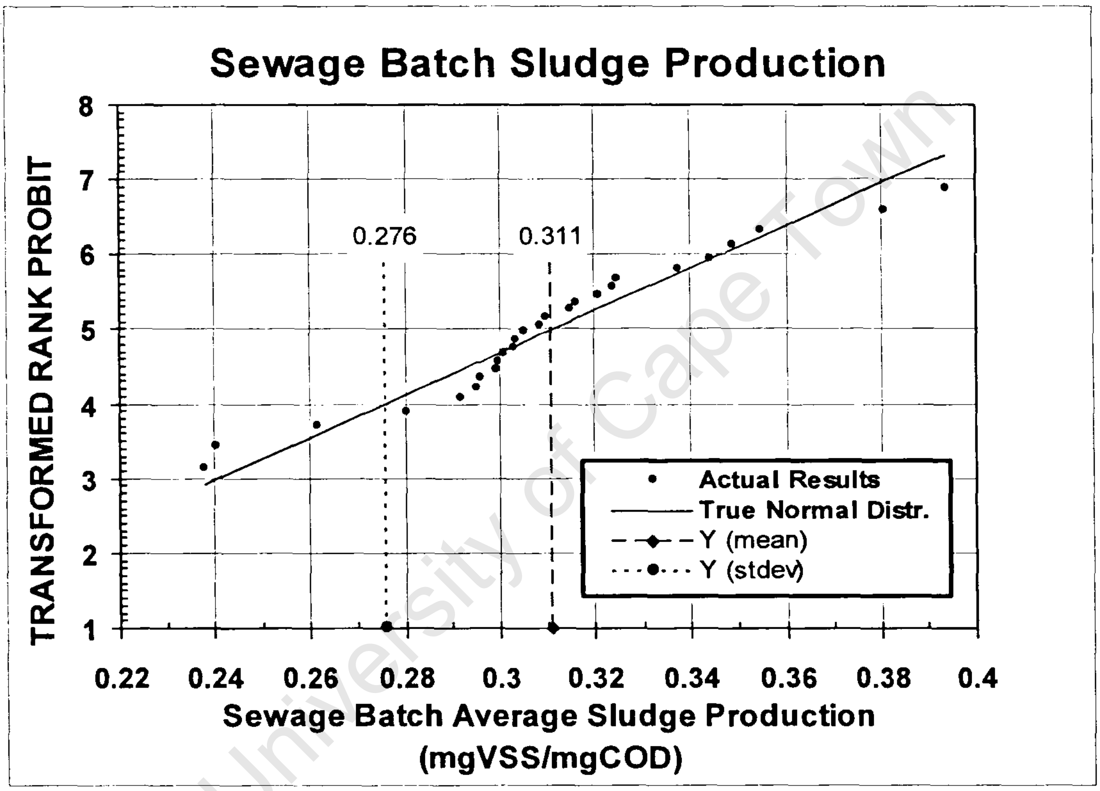


Figure 4.18: *Statistical plot of the sewage batch average sludge production in the MBR system.*

4.6.7 System Mixed Liquor Settleability and Microbial Analysis

MBR systems do not require mixed liquor to settle well due to the solid-liquid separation process occurring via membranes. However, in order to compare the settleability of the mixed liquor in the MBR system with the mixed liquor generated in the parallel conventional activated sludge system, diluted sludge volume index (DSVI) tests were conducted on the aerobic reactor mixed liquor in accordance to the method described in Chapter 3, Section 3.5.1.

Throughout the investigation the DSVI ranged consistently between 80 and 125 ml/gTSS (Fig 4.19). The only exception to this trend was a higher DSVI of

142ml/gTSS which was measured on day 429. No event could be identified to account for this high value.

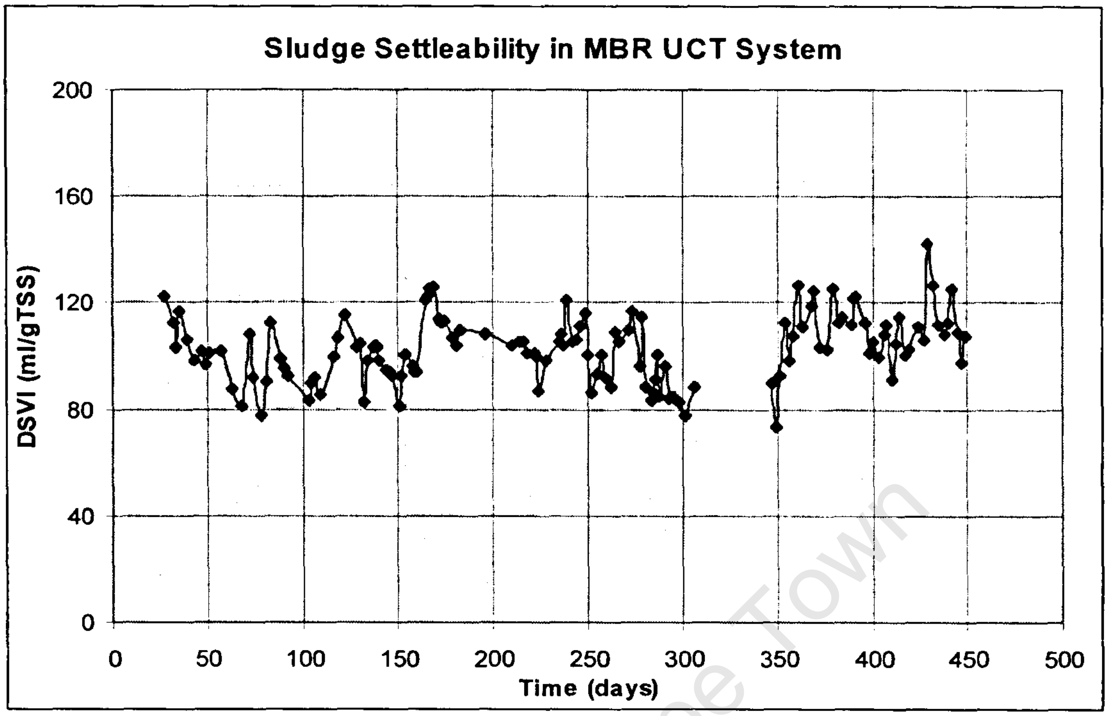


Figure: 4.19: *General trend of diluted sludge volume index (DSVI for the MBR system)*

During the investigation anoxic-aerobic (AA) filaments (*M. Parvicella* and *Type 0092*) were commonly found in the wastewater. As was noted in Phase 1 (Ramphao *et al.*, 2004) these filaments relative abundance appeared to be linked to variations in the sludge settleability. A summary of the monthly, and from March 2006 fortnightly microbiological analyses for the MBR system is presented in Table 4.5. The microbial analysis was compared with the measured DSVI and although the DSVI remained relatively stable (80 – 120 ml/gTSS) there is an apparent trend for compact flocs to give lower DSVI (<100ml/gTSS) and diffuse flocs a marginally higher DSVI (>100ml/gTSS) as would be expected. It is important to note that in a lab scale MBR such as the one run in this investigation the aerobic reactor is very turbulent due to the membrane configuration and coarse bubble aeration, thus shear conditions are not conducive to large flocs forming as was observed in the microbiological analysis.

From August 2005 fortnightly samples were sent to the Microbiological laboratories at the Durban Institute of Technology for quantification of bacteria using Fluorescence *In Situ* Hybridization (FISH) and confocal laser scanning microscopy (CLSM). The microbial investigation, reported in Maharaj *et al.* (2006), concluded from the experiments that the membrane separation itself does not influence the nitrifying community composition. The composition and heterogeneity of the ammonia-oxidizing bacteria (AOB) population and its associated process stability appear to be dependent on other factors like wastewater composition and sludge age. Nitrite oxidizing bacteria (NOB) were in very low numbers, suggesting that they possibly had a higher affinity for metabolism rather than reproduction. It is hypothesized by Maharaj *et al.* (2006) that this function could also be assigned to other groups within the activated sludge population.

Table 4.5: *MBR system microbiological analyses recorded with system observations and DSVI.*

MBR system									
Date	Day #	Sewage Batch	Morfology floc	diameter (µm)	Filamentous microrg			DSVI	observations
						Rank	Abundance		
2005/03/24	42	3	round, compact	<150	M.Parvicella	1	2	122	foaming in AX reactor
2005/04/21	70	4	firm, round, compact	<150	Type 0092	1	4	90	foaming in AX, low solids due to spills
2005/05/23	102	6	firm, round, compact	150-500	Type 0092	1	3	84	n
2005/06/22	132	8	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	2 4	83	n
2005/07/22	162	10	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	3 4	94	spills, low solids conc.
2005/08/15	186	11	weak, irregular, diffuse	<150	M.Parvicella Type 0092	2 1	2 3	108	n
2005/09/19	221	14	weak, irregular, diffuse	<150	M.Parvicella Type 0092	2 1	2 2	100	n
2005/10/17	249	16	irregular, diffuse	150-500	M.Parvicella Type 0092	1 2	4 1	116	n
2005/11/29	292	18	weak, irregular, diffuse	<150	M.Parvicella Type 0092	2 1	2 3	90	n
2006/01/24	348	22	weak, irregular, diffuse	150-500	M.Parvicella Type 0092	1 1	2 2	81	n
2006/02/07	362	23	weak, irregular, diffuse	<150	M.Parvicella Type 0092	1 2	3 3	118	major spills and loss of solids
2006/02/28	383	24	weak, irregular, diffuse	<150	M.Parvicella Type 0092	1 1	2 2	113	foaming in AX, power failures
2006/03/15	398	26	round, compact	<150	M.Parvicella Type 0092	2 1	2 3	101	n
2006/03/28	411	27	round, compact	<150	M.Parvicella Type 0092	2 1	2 3	97	n
2006/04/11	425	28	irregular, diffuse	<150	M.Parvicella Type 0092	1 2	3 3	110	n
2006/04/25	439	29	weak, irregular, diffuse	<150	M.Parvicella Type 0092	1 2	2 2	110	n

4.7 MASS BALANCES

Nitrogen and COD mass balances were performed for each sewage batch period in order to verify the accuracy and reliability of the analytical data, and to provide an early warning sign for data collection error. The mass balance procedure is described in Appendix C and attempts to account for all N or COD entering and exiting the system, based on the assumption that at steady state the measured N and COD entering the system in the influent should equal the measured N and COD exiting the system through the effluent stream, sludge wasted, oxygen utilised and nitrogen denitrified. As above, sewage batches were accepted as steady state periods, and the sewage batch averages used to calculate the N and COD mass balances. The COD and N mass balances obtained are listed in Table 4.6.

A mass balance should fall within the range of 90% - 110% to indicate accurate measurements. Mass balances outside this range do not imply that all the data is poor, but simply indicate that one or more of the parameters measured is incorrect and needs to be interpreted with caution. In this study it was not possible to close the mass balances for the system for a number of sewage batches due to two main problems:

- Errors with the OUR measurement were detected early in the investigation but only solved during sewage batch 8. Thus, the COD mass balance could not be performed for sewage batches 2 to 8. The changed measurement procedure of OUR is described in detail in Chapter 3, Section 3.8.1.

- Analytical nitrate (NO_3) and nitrite (NO_2) measurements appeared to be very low during the first sewage batches. It was suspected that a problem lay with the in-house Technicon auto-analyser used for these measurements. While this was being investigated and repaired, samples were processed on an external high pressure liquid chromatograph (HPLC), until accurate NO_3 values were again obtained with the in-house Technicon auto-analyser. This meant that for sewage batches 2 to 8 inaccurate low NO_3 values were probably the cause for low N mass balances. This would have implications for the COD balance, but as noted above COD mass balances could not be performed until sewage batch 8.

Table 4.6: *Nitrogen and COD mass balances for the MBR system*

Sewage Batch Period	% Nitrogen Balance	%COD Balance
2	152.3%	*No OUR Measurement*
3	112.1%	*No OUR Measurement*
4	72.5%	*No OUR Measurement*
5	74.4%	*No OUR Measurement*
6	75.4%	*No OUR Measurement*
7	93.4%	*No OUR Measurement*
8	86.8%	*No OUR Measurement*
9	76.8%	107.6%
10	101.4%	98.3%
11	105.0%	98.0%
12	96.4%	107.4%
13	82.0%	125.7%
14	96.6%	113.4%
15	95.2%	106.6%
16	91.7%	108.4%
17	79.7%	102.4%
18	88.3%	112.4%
19	74.5%	103.7%
20	*No testing*	*No testing*
21	*No testing*	*No testing*
22	102.1%	93.0%
23	89.5%	93.1%
24	118.5%	123.8%
25	148.2%	103.6%
26	96.1%	93.5%
27	108.8%	89.1%
28	113.0%	84.9%
29	83.2%	93.5%
Average	**96.5%**	**103.1%**

Additionally it was observed that regularly the concentration of NO_3 in the aerobic reactor was substantially lower than that of the effluent, whereas these should be the same. Kinetic studies indicated that the rate of denitrification in the concentrated mixed liquor was substantially faster than that in a conventional activated sludge system suggesting that denitrification was occurring between the sampling of the mixed liquor and its filtration. Hence, for the purposes of mass balances the effluent

NO_3 concentration has been used in place of the aerobic NO_3 concentration measured. Mouthon-Bello and Zhou (2005) reported the same phenomena of significant differences in NO_3 concentration between the aerobic supernatant and membrane permeate. They attributed this difference to the dynamic biological layer that forms on the membrane surface, but suggested that handling times prior to centrifuging could also be responsible for the differences.

4.7.1 Nitrogen Mass Balance

Nitrogen Mass balances for each sewage batch are listed in Table 4.6 and shown graphically in Fig. 4.17. Values ranged from 72.5 to 152% with an average of 96.5%. Throughout the investigation the N-mass balance varied with the majority (~60%) falling outside the acceptable 90 – 110% range. Early on in the study the large variance in N-mass balances caused concern and subsequent efforts were made to identify reasons for the poor N-mass balances. However despite continued efforts the variance continued. A number of reasons for the poor N-mass balances are suggested in order of likelihood of taking place in this investigation:

- The N-balance is very sensitive to the a-recycle value. These recycles were measured on a weekly basis, but at different times to when samples were taken. The recycles could vary greatly throughout a day depending on the condition of piping, occurrence of minor blockages and the pressure head difference between the level of the feed tanks and the anaerobic reactor. For example changing the a-recycle by 0.5 from say 3:1 to 3.5:1 would increase the N-balance by 6 – 10%. Such a variation in the a-recycle is possible as is suggested by the differences between measured and calculated a-recycles in a number of batches (see Table 4.3).
- Sewage batches were shorter than the sludge age of the system, which could have caused brief periods where the system was not at steady state and may have influenced results.
- At high MLSS concentrations (>15000mgTSS/ℓ) other researchers have reported the incidence of anoxic micro-zones forming in the aerobic reactor (Kraume *et al.*, 2005), whereby dissolved oxygen does not distribute to all flocs forming small anoxic zones where denitrification can occur. This would result in loss of nitrogen in the aerobic reactor and a drop in the N-balance.

The variation in the N-balance results is very scattered on either side of 100% suggesting that the error in measurement was not a systematic one. The overall N-mass balance is 96.5% and as a consequence, for overall analysis, the whole investigation average will be used.

Sewage batch periods in which specific conditions can explain poor mass balances are as follows: Sewage batch 2 is very high and is attributed to the familiarization of the writer with the testing regime. As noted above, the results in sewage batches 2 to 8 were subject to poor NO_3 values and appear to bring down the mass of nitrogen leaving the system suggesting that problems in measuring NO_3 remained unresolved throughout that testing period. Sewage batches 24 and 25 were characterised by intermittent power failures in the laboratory which interrupted aeration, and may have influenced nitrification resulting in a higher effluent TKN concentration than usual which would increase the mass balance.

Of the N entering the system approximately 57.0% exited the system through denitrification, 24.6% through sludge wasting, 1.5% via effluent TKN and 17.2% through NO_3 in the effluent (Fig. 4.20).

In Phase 1 Ramphao *et al.* (2004) reported mass balances consistently in the 90% to 110% range giving an average of 103.5% with a resulting breakdown of denitrification (51%), effluent TKN (3.1%), effluent nitrate/nitrite (21.8%) and waste sludge (24.4%). The difference between the two phases, particularly in denitrification and effluent nitrate/nitrite, is attributed directly to a different a-recycle (3.0 in Phase 1 versus 3.45 in Phase 2), thus more nitrate was loaded on the anoxic reactor for denitrification in Phase 2.

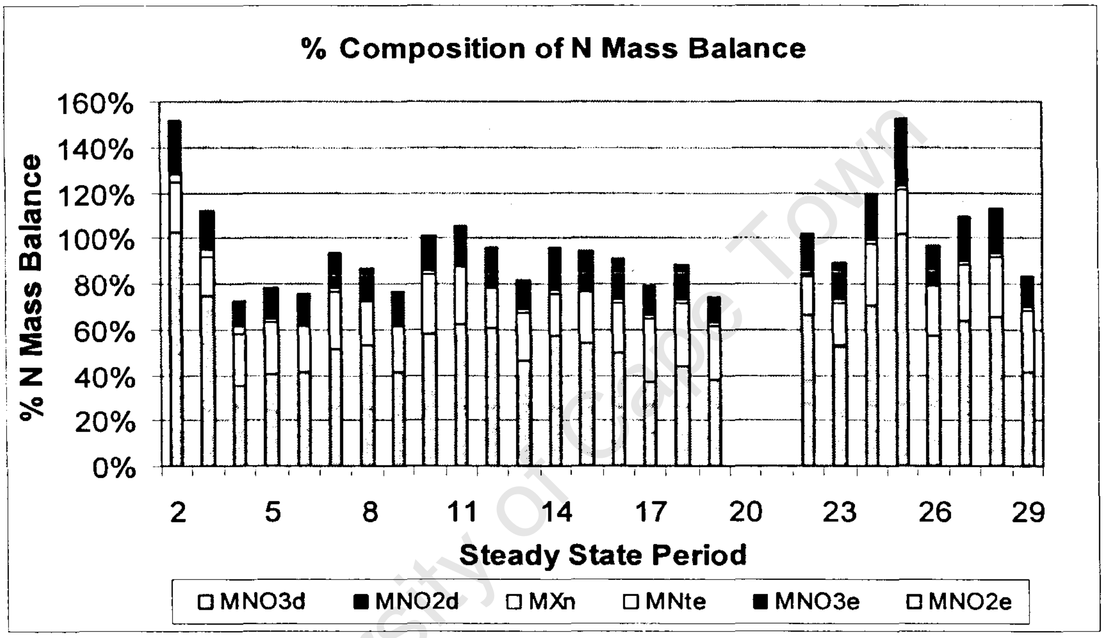


Figure 4.20: *Percent composition of the Nitrogen Mass balance.*

4.7.2 COD Mass Balance

As was noted earlier the COD mass balance could not be closed until sewage batch 8 due to difficulties in obtaining accurate readings for OUR in the aerobic reactor. COD mass balances for the duration of testing are listed in Table 4.6. Values from 85% to 126% were observed with 6 out of the 19 mass balances falling outside the 90% to 110% range. The average was 103.1%.

Of these outliers all but sewage batches 13 and 24 fall close to the 90% to 110% range. Sewage batch 24 was affected by the power failures due to which spillages, and irregular feeding led to an unsteady state condition. The COD mass balance in sewage batch 13 is high due to a very high oxygen demand for Nitrogen linked to high NO_3 values which also affect the N-balance. No reasons for these high values can be put forward.

From Fig. 4.21, of the COD entering the system approximately 37.8% exited the system as oxygen consumed, 17.3% via denitrification, 40.4% was removed with the mixed liquor wasted and 4.5% exited the system via the effluent stream. In Phase 1

Ramphao *et al.* (2004) achieved a lower COD mass balance with an investigation average of 90.5%. In Phase 1, of the COD exiting the system approximately 33.6% was consumed with oxygen, 15.8% was consumed with denitrification, 46.8% was removed with mixed liquor wasted and 3.8% left the system via the effluent stream. The system COD-removal composition is comparable for both Phases 1 and 2 of the investigation.

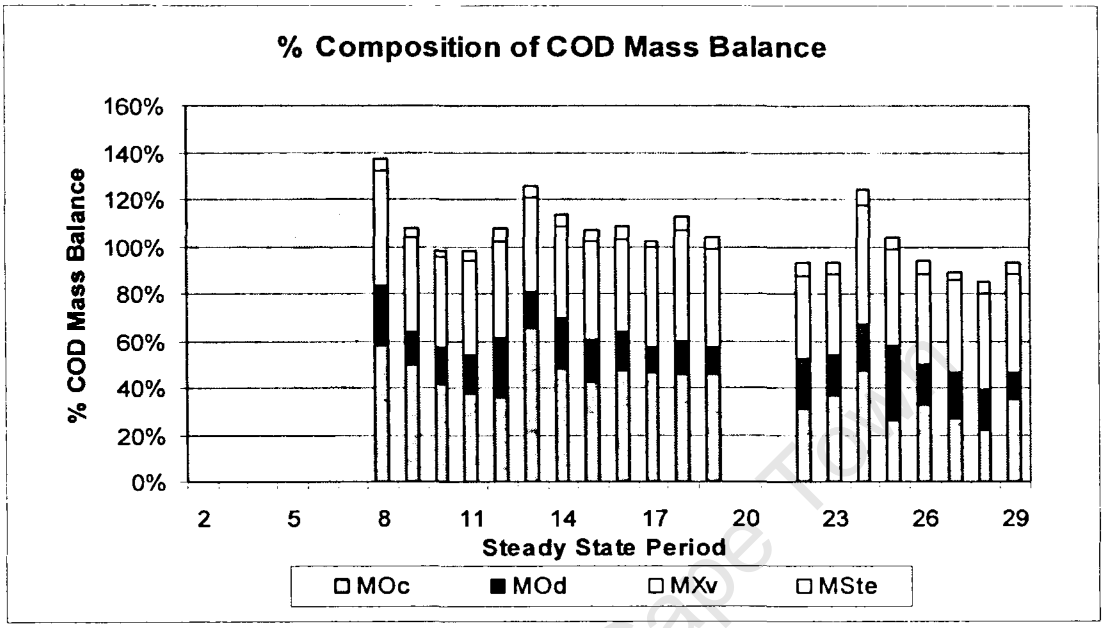


Figure 4.21: *Percent composition of the COD- mass balance.*

4.8. INFLUENT UNBIODEGRADABLE COD FRACTIONS

In Phase 1, measured MLVSS concentrations, higher than predicted with UCTPHO simulations, prompted an investigation into the unbiodegradable soluble and particulate COD fractions of the influent feed. In order to simulate BNR systems the influent sewage needs to be characterised and values for the unbiodegradable soluble ($f_{S,us}$) and particulate ($f_{S,up}$) COD fractions determined. In Phase 1 a much higher $f_{S,up}$ value was required to accurately simulate the system response. In order to substantiate the results from Phase 1, this exercise was repeated with the Phase 2 results.

4.8.1 Unbiodegradable Soluble COD Fraction ($f_{S,us}$)

It is assumed that all biodegradable soluble COD (S_{bs}) is utilised in the activated sludge system and thus any soluble COD that remains in the effluent (S_{te}) must be unbiodegradable soluble (S_{us}). Hence, Equation (4.8) can be used to determine S_{us} as a fraction of the influent total COD (S_{ti}), ($f_{S,us}$):

$$f_{S,us} = S_{te} / S_{ti} \tag{4.8}$$

Batch averages of measured influent total COD (S_{ti}) and membrane filtered effluent COD (S_{te}) were used with Equation 4.8 to calculate $f_{S,us}$. The sewage batch averages were plotted in a linearized probability graph (Fig. 4.22), giving an average $f_{S,us}$ of 0.044, (SSD = 0.009) (Table 4.6). This investigation average $f_{S,us}$ is slightly higher than that reported in Phase 1 (0.036), Ramphao *et al.* (2004). The influent feed (average S_{ti} = 951.8mgCOD/ℓ) was augmented with 200mgCOD/ℓ sodium acetate, which is readily biodegradable. Thus, if the additional RBCOD is accounted for then the raw sewage from the Mitchells Plain WWTP would have a $f_{S,us}$ of 0.056. This value lies in the lower limit of the range of typical values expected from South African wastewaters (WRC 1984). Also, it is well below other reported values from the same wastewater treatment plant cited in Ramphao *et al.* (2004): 0.085, Cronje et al (2000; 0.09, Ubisi et al (1997); 0.09, Mbewe et al (1995), and 0.096 Muller et al (2003).

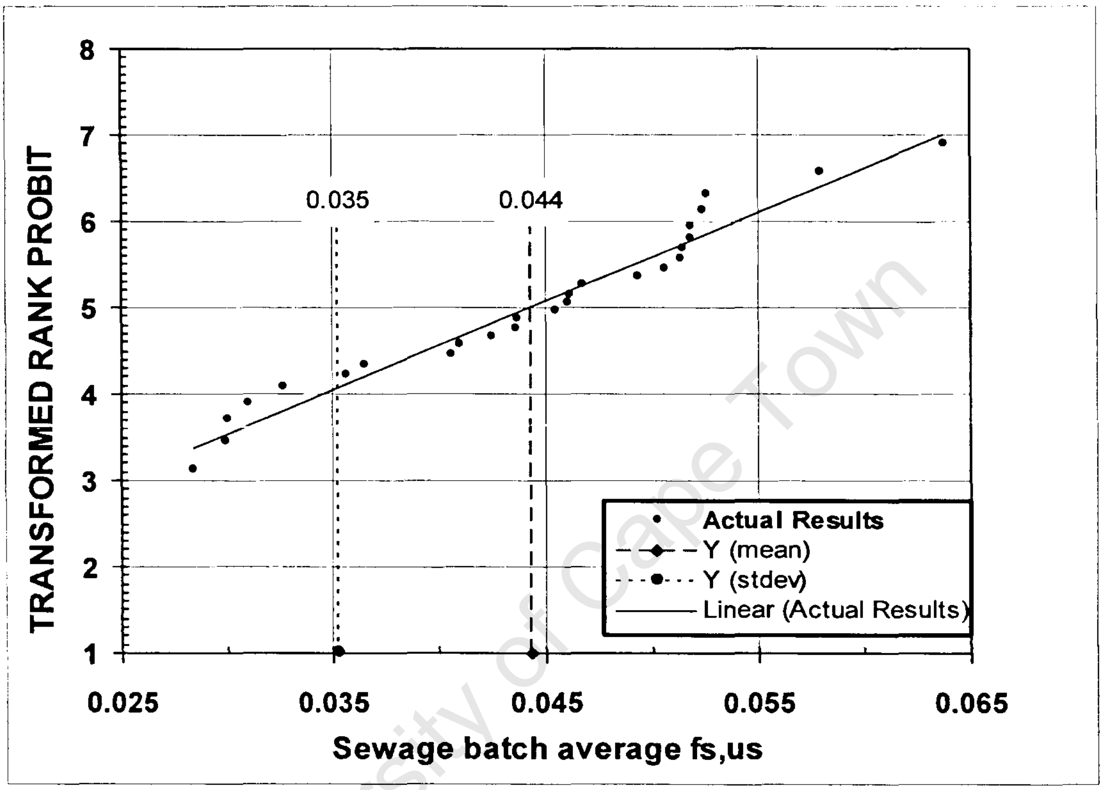


Figure 4.22: *A statistical plot of the sewage batch average unbiodegradable COD fraction ($f_{S,us}$) of the influent feed.*

Table 4.7: *Sewage batch unbiodegradable soluble ($f_{S,us}$) and particulate ($f_{S,up}$) fractions in the MBR UCT system.*

Batch Number	$f_{S,us}$	$f_{S,up}$
2	0.036	0.174
3	0.029	0.087
4	0.031	0.098
5	0.039	0.144
6	0.047	0.252
7	0.037	0.269
8	0.051	0.315
9	0.042	0.184
10	0.028	0.174
11	0.041	0.185
12	0.054	0.210
13	0.046	0.208
14	0.045	0.192
15	0.042	0.218
16	0.052	0.180
17	0.030	0.222
18	0.051	0.274
19	0.051	0.195
20		
21		
22	0.058	0.127
23	0.050	0.135
24	0.064	0.340
25	0.046	0.181
26	0.049	0.168
27	0.034	0.173
28	0.046	0.236
29	0.050	0.207
Average	0.044	0.198

The lower $f_{S,us}$ determined here can be attributed to the finer pore size of the membranes which would retain colloidal and particulate COD that may otherwise have passed through the standard 0.45μm filter paper used to determine S_{us} in conventional systems with SSTs. Hence, as noted in Phase 1 (Ramphao *et al.*, 2004) the MBR system can be expected to attain a lower effluent COD concentration than the corresponding conventional system. Furthermore, in addition to retaining all suspended solids, the MBR system would retain organics considered "soluble" in a conventional system with SSTs, and these will probably reflect in the unbiodegradable particulate COD fraction ($f_{S,up}$); this aspect is examined in more detail below.

4.8.2 Unbiodegradable Particulate COD Fraction ($f_{S,up}$)

The total mass of volatile (organic) suspended solids (MX_v) in a BNR activated sludge system receiving a specific waste water is given by Equation (4.9) (Ramphao *et al.*, 2004). Equation (4.9) is modified from that of the WRC (1984) and Ekama *et al.* (1986) models for ND systems and takes into account the phosphate accumulating organisms (PAO's) which contribute more to the MLVSS mass per COD mass utilized than the ordinary heterotrophs (OHOs) (Wentzel *et al.*, 1990; Ramphao *et al.*, 2004).

$$\frac{MX_V}{MS_{ti}} = (1 - f_{S,us} - f_{S,up})[(1 - \frac{\%}{100} f_{Sb's}) \frac{Y_H R_s}{(1 + b_{HT} R_s)} (1 + f_{EH} b_{HT} R_s) + \frac{\%}{100} f_{Sb's} \frac{Y_G R_s}{(1 + b_{GT} R_s)} (1 + f_{EH} b_{HT} R_s) + \frac{f_{S,up}}{f_{CV}} R_s \qquad (4.9)$$

Where:

MX_V = VSS mass in biological reactor (kgVSS)
= $V_{ana} X_{V,ana} + V_{anx} X_{V,anx} + V_{aer} X_{V,aer} + V_{OUR} X_{V,OUR}$
V_{ana} ; V_{axx} ; V_{aer} ; V_{OUR}
= Volume of anaerobic, anoxic, aerobic and OUR-aeration reactors (ℓ)
$X_{V,ana}$; $X_{V,anx}$; $X_{V,aer}$ and $X_{V,OUR}$
= VSS concentrations in anaerobic, anoxic, aerobic and OUR-aeration reactors (mgVSS/ ℓ)
MS_{ti} = COD mass load on system (kgCOD/ ℓ)
= $Q_i.S_{ti}$
Q_i = influent feed flow (ADWF, ℓ /d)
$f_{S,up}$ = unbiodegradable particulate COD fraction
$f_{S,us}$ = unbiodegradable soluble COD fraction
$f_{Sb's}$ = influent readily biodegradable (RB) COD fraction with respect to biodegradable COD
% = percentage influent RBCOD taken up by phosphate accumulating organisms (PAOs);
= 0 if system is nitrification-denitrification (ND) N removal, i.e. no PAO's, >0 if system is ND biological excess phosphorus removal (NDBEPR), increasing with increasing BEPR (70-90%).
Y_H, Y_G = yield coefficient for ordinary heterotrophic organisms (OHOs) and PAOs
= 0.45 mgVSS/mgCOD for both
b_{HT}, b_{GT} = endogenous respiration rate for OHOs and PAOs at T°C
= 0.24/d and 0.04/d respectively at 20°C ($\theta_b = 1.029$ for both)
θ_b = temperature sensitivity coefficient for endogenous respiration
Rs = system sludge age (days)
f_{EH}, f_{EG} = endogenous residue fraction of the OHOs and PAOs
= 0.20 and 0.25 respectively
f_{CV} = COD/VSS ratio of organics (mgCOD/mgVSS)
= sewage batch measured value

In Equation (4.9), values are available for the kinetic (b_{HT}, b_{GT}, θ_b) and stoichiometric (Y_H, Y_G, f_{EH}, f_{EG}) constants. Operational (Q_{ADWF}, V_{ANA}, V_{ANX}, V_{AER} and R_S) parameters varied slightly from sewage batch to sewage batch and accordingly were averaged for each sewage batch along with measured reactor VSS concentrations ($X_{V,ANA}$, $X_{V,ANX}$ and $X_{V,AER}$), wastewater characteristics (S_{ti}, $f_{Sb,s}$ and $f_{S,us}$) and mixed liquor (f_{CV}) characteristics. The percentage influent RBCOD taken up by polyphosphate accumulating organisms (%) was assumed to be 90% based on literature (Wentzel *et al.*, 1990). This leaves $f_{S,up}$ as the only unknown. Thus Equation

(4.9) was solved for each sewage batch by successive substitution of $f_{S,up}$ until the calculated system VSS mass matches that measured. The resultant sewage batch $f_{S,up}$ are listed in Table 4.6 and plotted in Fig. 4.23. It must, however, be noted that as $f_{S,up}$ is the only unknown it becomes a "catch all" variable for any other values in the equation that may not be correct. Hence, the $f_{S,up}$ values calculated must be interpreted with care.

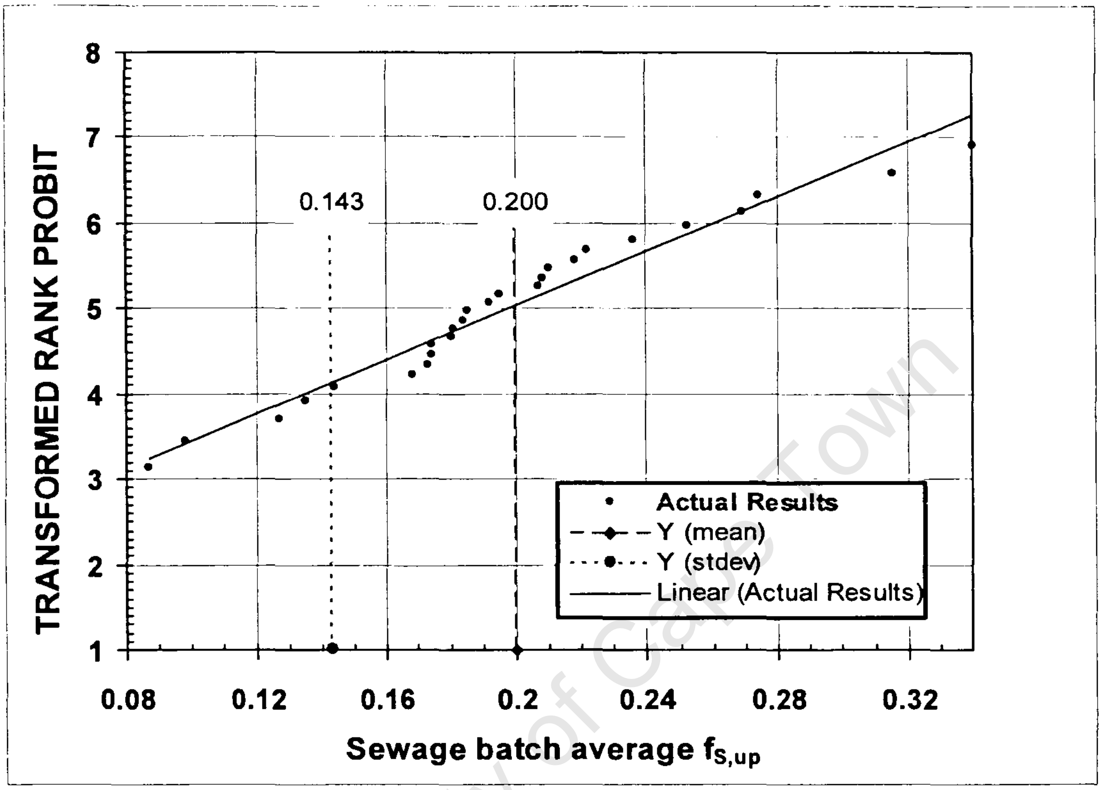


Figure 4.23: Statistical plot of batch average $f_{S,up}$ for the MBR UCT system.

From Fig. 4.23, the $f_{S,up}$ values exhibit a normal distribution, with mean 0.200 (SSD = 0.057). This mean is only slightly lower than that reported in Phase 1, of 0.216 (Ramphao *et al.*, 2004). Again, realising that 200mgCOD/ℓ in the influent is Sodium Acetate and hence completely biodegradable, and that the overall average total is 952mgCOD/ℓ, the sewage $f_{S,up}$ = 0.251. This value is significantly higher than values reported in previous literature cited in Ramphao *et al.* (2004) for aerobic (0.108, Mbewe *et al.*, 1995) and MLE (0.135, Warburton *et al.*, 1991; 0.120, Ubisi *et al.*, 1997; 0.160, Beeharry *et al.*, 2001; 0.150, Lee et al 2002a) systems which used wastewater from the same source. However, the value does fall within the range measured for BEPR systems receiving wastewater from the same source (0.06 – 0.32, Ekama and Wentzel, 1999).

The total unbiodegradable COD fraction ($f_{S,u}$) is calculated as the sum of the soluble ($f_{S,us}$) and particulate ($f_{S,up}$) unbiodegradable fractions. For Phase 1 and 2 of the investigation, the $f_{S,u}$ values are very similar, 0.252 and 0.242 respectively.

4.9 SYSTEM PERFORMANCE

It was expected that the MBR system with its superior solids separation ability would provide a solids free effluent and hence improved effluent TKN and COD concentrations.

4.9.1 COD Removal

COD removal is one of the primary parameters on which wastewaters are monitored due to the detrimental effects of de-oxygenation within receiving water bodies. The COD conversion mechanism is primarily through synthesis where the carbonaceous material is either included in new cell mass and accumulates in the sludge, or is oxidised during the metabolism processes as CO_2 with the electrons passed to oxygen to form water. Thus, COD is removed from the waste water through the wasted sludge or through oxygen utilization in the system.

The improved COD removal by the membranes could be seen in the very low $f_{S,us}$ fraction achieved which suggested that more COD was retained in the system than would have been expected in a conventional system.

In the investigation three categories of effluent COD were measured (Chapter 3, Section 3.5.1): Membrane filtered effluent which was collected from the biological reactors' membrane outflow; 0.45 μm filtered effluent which was the filtered supernatant from the centrifuged aerobic reactor mixed liquor sample; and an unfiltered "effluent" sample which was the supernatant from the DSVI settling test on the MBR sludge. The different effluent samples were intended to determine the difference in quality of the effluent in the absence of membranes.

Sewage batch average total influent and membrane filtered effluent COD concentrations are plotted in Fig. 4.24. Throughout the investigation reasonably consistent effluent values around 40mgCOD/ℓ were obtained.

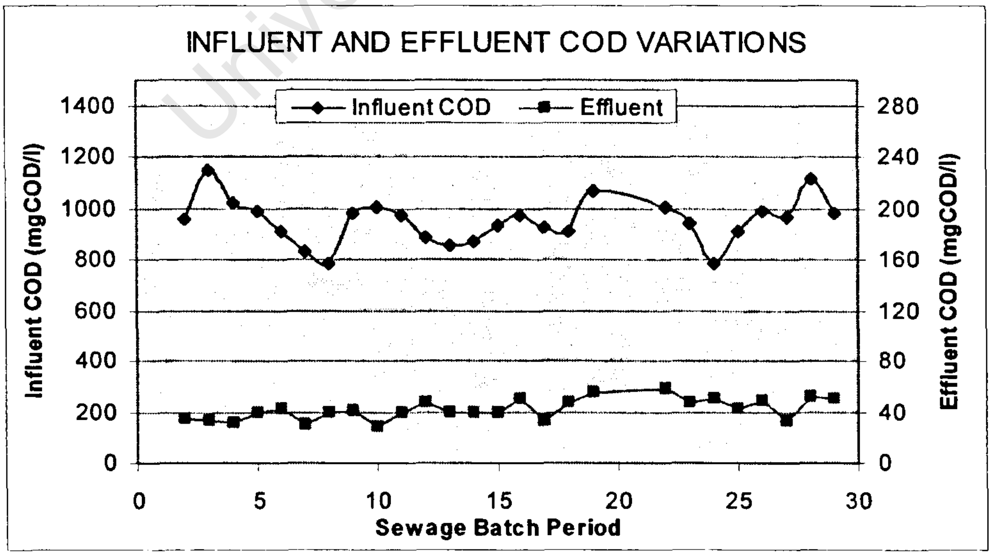
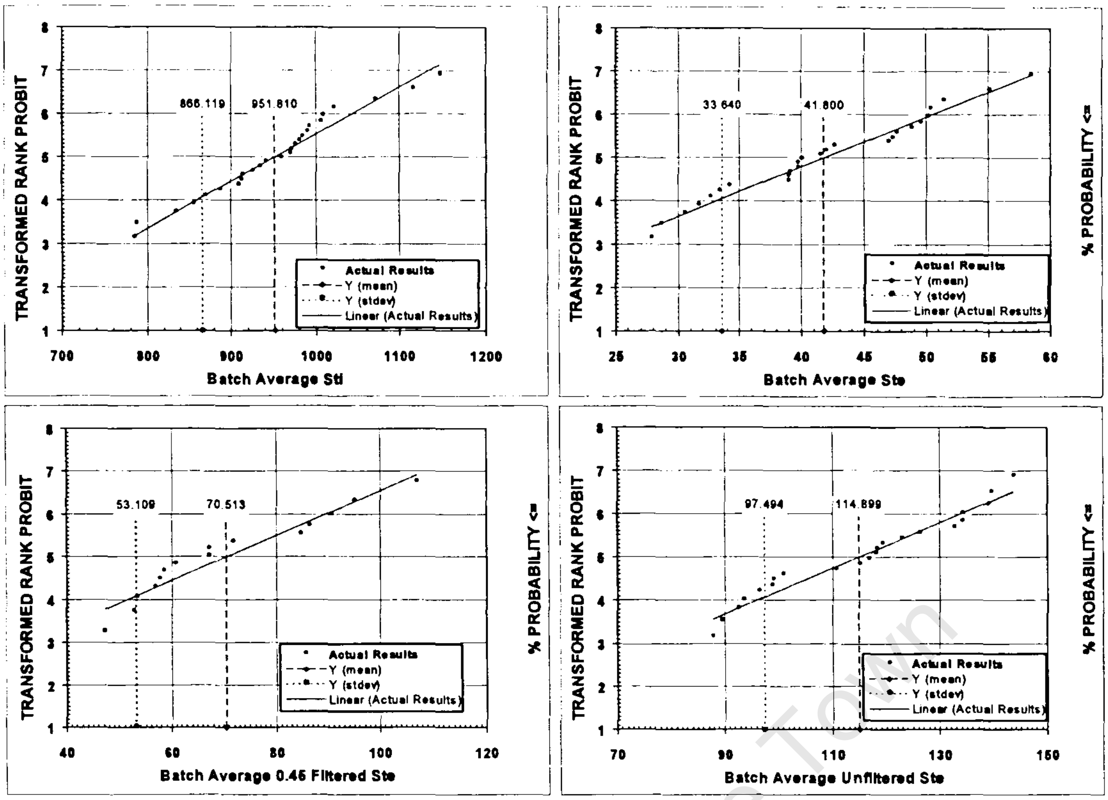


Figure 4.24: Influent and effluent COD variations for sewage batch averages.



Figures 4.25a, b, c and d: *Statistical distribution of the influent feed (Sti); membrane filtered effluent (Ste); Aerobic supernatant filtered through a 0.45µm filter; and "unfiltered" samples taken from the DSVI supernatant.*

Fig. 4.25 shows statistical analyses of the influent and the three effluent COD concentrations, namely membrane effluent, 0.45µm filtered effluent and unfiltered effluent, illustrating that in all cases the data are normally distributed. The mean influent is 951.8 mgCOD/ℓ and the mean effluent 41.8 mgCOD/ℓ giving an effective COD removal of 95.7%. Statistical analyses of the daily values recorded were not advisable due to one dominant factor that affected each batch, namely dilution of the batch with tap water (Chapter 3, Section 3.4.2). The investigation means for the 0.45 µm filtered and unfiltered effluent COD, presented in Table 4.8. clearly illustrate the efficient COD removal and solids/liquid separation by the system membranes, and that the membrane pore size is significantly less than 0.45µm.

Table 4.8: *Percent removals of the various effluent samples from the MBR system.*

	Influent COD	Effluent		
		MBR	0.45	unfiltered
mgCOD/l	951.8	41.8	70.5	114.9
% removal	N/A	95.7%	92.7%	88.1%

4.9.2 Nitrogen Removal

Nitrogen is removed from the waste water through nitrogen accumulation in the mixed liquor, removal with the waste flow and through sequential nitrification/ denitrification. Since the operational parameters sludge age and influent organic load were kept constant, the sludge production and wasting, and its associated N content, were relatively constant. Hence variations in the nitrogen removal were due to either variations in the TKN/COD load to the system, or to fluctuations in the nitrification/ denitrification performance.

Of the influent TKN the biodegradable organic nitrogen gets converted to ammonia through heterotrophic activity and adds to the influent ammonia. In nitrification this ammonia is converted sequentially to NO_2 and then NO_3 in the aerobic zone. The aerobic mass fraction achieved during the investigation was approximately 59.5%, and the system was run at a long sludge age (~20 days) which ensured complete nitrification. pH measured at regular intervals throughout the testing period indicated that the pH remained within the required range of 7 – 8.5 so as not to inhibit autotrophic activity. Results of the effluent TKN and ammonia concentrations indicated that throughout the investigation complete nitrification was achieved.

In the UCT configuration, although much of the NO_3 is recycled to the anoxic zone where denitrification occurs (the NO_3 is consumed as electron acceptor in metabolism and nitrogen gas is released), a portion of the NO_3 will always escape in the effluent from the aerobic reactor. Thus, the nitrogen removal must take into account the NO_3 concentration in the effluent.

Nitrification

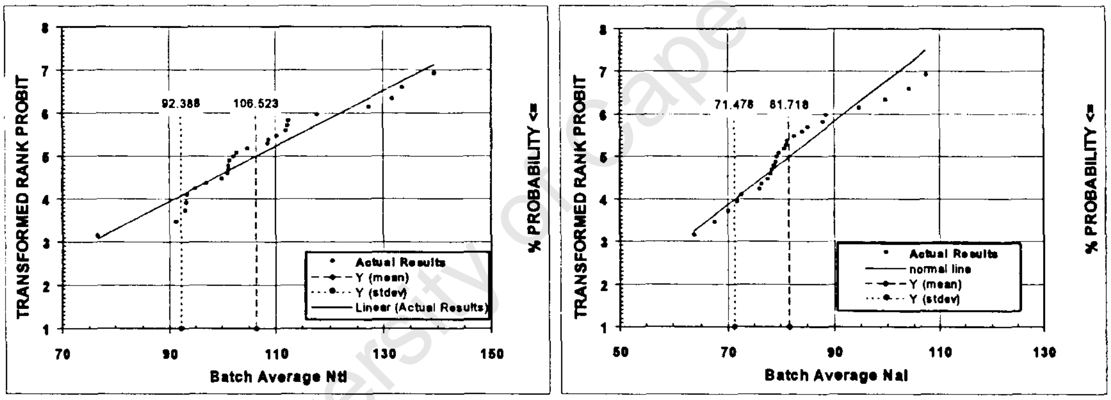
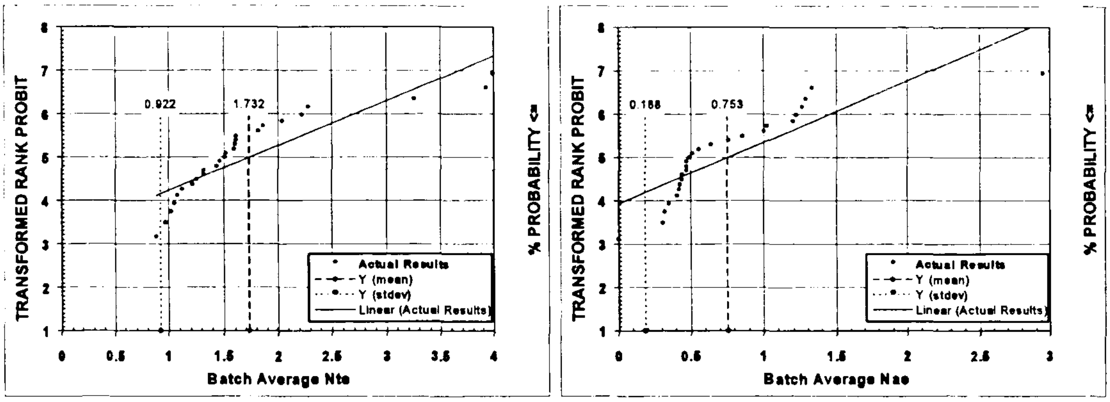


Figure 4.26 a and b: Statistical plots of the influent TKN (N_{ti}) and FSA (N_{ai}) concentrations

The sewage batch average influent TKN and FSA concentrations are plotted in Figs. 4.26a and 4.26b respectively giving means for the investigation of 106.5 (±14.1) and 81.7 (±10.2) mgN/ℓ respectively. The data are not particularly well normally distributed, but this is to be expected as the concentration for each batch should vary since the COD was diluted to constant concentration and the TKN/COD ratios for each wastewater batch differed, see below. The effluent concentrations similarly are not normally distributed (Fig. 4.27a and 4.27b) due to the insensitivity of the TKN and FSA analytical tests at such low concentrations. Means for the batch average effluent TKN and FSA concentrations of 1.7 (±0.8) and 0.8 (±0.5) mgN/ℓ were obtained.



Figures 4.27 a and b: *Effluent TKN (N_{te}) and FSA (N_{ae}) concentrations from the MBR system.*

At the start of the investigation the influent TKN was dependant on the batch sewage TKN/COD ratio which varied considerably. This influent TKN was augmented with the addition of ~20mgN/ℓ ammonia (200mgCOD/ℓ sodium acetate was added to the feed in order to augment BEPR; however this caused a decrease in the TKN/COD ratio which thus needed to be corrected). Variations in the influent and effluent TKN and FSA concentrations are illustrated in Figs. 4.28 and 4.29. From sewage batch 13 it was decided to try maintain a constant influent TKN/COD ratio, of approximately 0.1 mgN/mgCOD through addition of variable concentrations of ammonia. This strategy significantly reduced the variation in influent TKN/COD ratio, Fig.4.28.

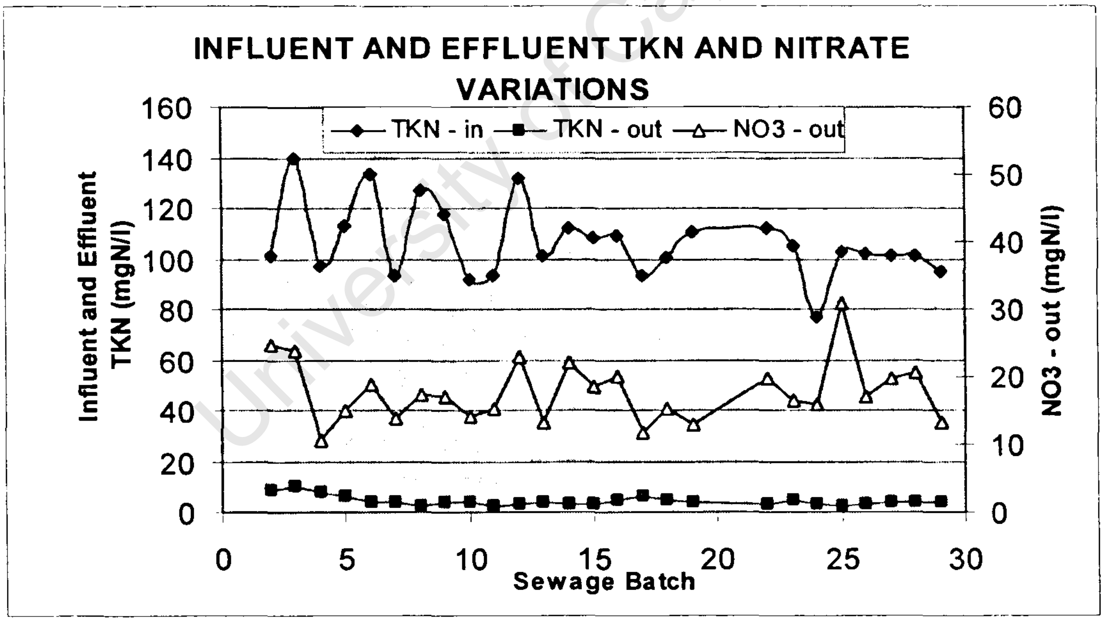


Figure 4.28: *TKN influent and effluent variations with effluent NO_3.*

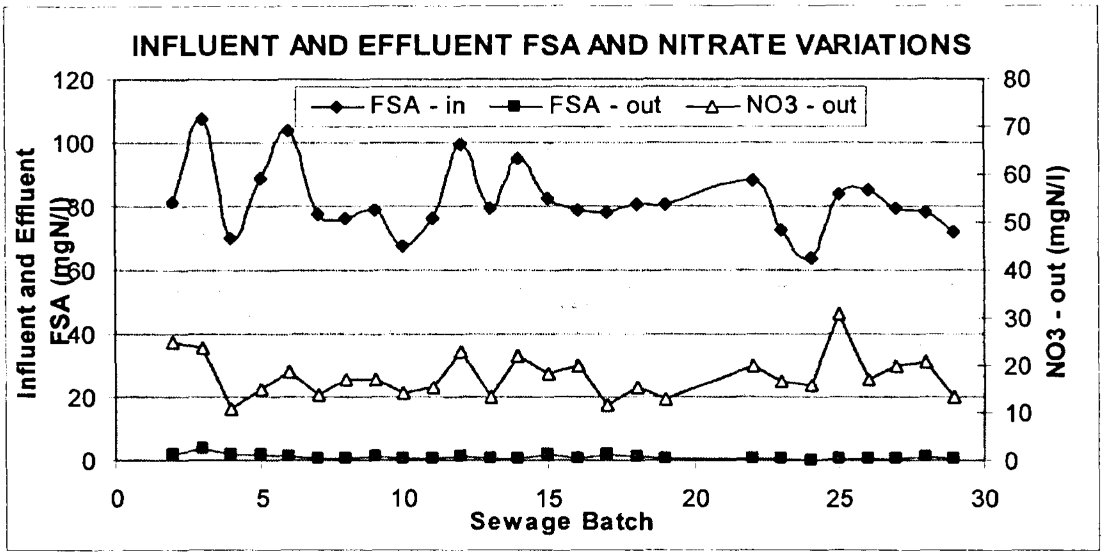


Figure 4.29: The FSA influent and effluent concentrations with the effluent NO_3.

From the investigation means, the TKN and FSA removals were calculated. See Table 4.9. The TKN and FSA removals were high (98 and 99% respectively), confirming complete nitrification throughout the test period with the removals listed in the table below:

Table 4.9: TKN and FSA removals

	Influent	Effluent	% Removal
	mgN/l	mgN/l	-
TKN	106.7	1.74	98.4%
FSA	82	0.75	99.1%

The difference between the effluent TKN (N_{te}) and FSA (N_{ae})is assumed to be equal to the unbiodegradable soluble organic N concentration of the influent TKN (N_{ousi} = 1.74 – 0.75 mgN/ℓ = 0.99mgN/ℓ). This gave 0.9% as a percent of the average influent TKN, which is close to the 1% value determined in Phase 1 (Ramphao *et al.*, 2004). However, the influent feed was augmented with ammonia by 20% on average, which would increase the actual percent N_{ousi} of the raw sewage to 1.2%. This is substantially lower than conventionally accepted values of 2.5 to 3.0% for typical South African waste waters (WRC, 1984). This may be attributed to the membranes retaining unbiodegradable soluble organics (with associated organic N) that would otherwise escape with the effluent in a conventional system and be included in N_{ouse}.

Denitrification

NO_3 concentrations in the MBR system effluent (N_{ne}) are shown in Figs.4.28 and 4.29. Variations in reactor NO_3 concentrations are plotted with reactor phosphate concentrations in Figs. 4.27-4.30. For all reactors and the effluent, NO_2 concentrations were less than 1mgN-NO_2/ℓ and could be considered negligible.

Denitrification occurs in the anoxic reactor. NO_3 is returned with the "combined" as-recycle and is used by heterotrophic organisms as electron acceptor. The denitrification potential (D_{pp}) is the maximum amount of NO_3 that could be removed in the anoxic reactor, if sufficient NO_3 was available. It is dependant on the anoxic mass fraction, the biodegradable COD that enters the anoxic reactor and the kinetics of denitrification. In NDBEPR systems the role of the influent RBCOD for denitrification is small due to it being taken up by the PAOs in the anaerobic reactor and their small contribution to denitrification (Hu *et al.*, 2002). The NO_3 load (N_{nL}) is the mass of NO_3 brought to the anoxic reactor via the recycles. It is dependant on the nitrification capacity, N_C, (mgN-NO_3/ℓ influent flow) which is the concentration of NO_3 generated in the aerobic reactor via nitrification (hence the prerequisite of complete nitrification for designing and modelling denitrification), and the as-recycle ratio.

The actual mass of NO_3 that is denitrified is dependant on the amount of NO_3 loaded on the reactor, N_{nL}, relative to the D_{PP}. If $N_{nL} \geq D_{PP}$ then all the denitrification potential is used and denitrification is close to the maximum achievable. Denitrification is thus dependant on D_{PP} and the residual nitrate that remains in the anoxic reactor is recycled to the anaerobic reactor and returned to the aerobic reactor. If $N_{nL} < D_{PP}$ then the anoxic reactor is underloaded and all NO_3 to the anoxic reactor is denitrified giving an anoxic NO_3 concentration of 0mgN/ℓ. In this case denitrification is effectively governed by N_{nL}. Hence, the anoxic reactor NO_3 concentration is a good indicator of the state of denitrification (Fig. 4.32). The effluent with concentration N_{ne} is given by Equation (4.10):

$$N_{ne} = \frac{N_C}{(as+1)} \text{ mgN}/\ell \qquad (4.10)$$

and N_{nL} and the nitrate concentration denitrified (N_{nd}) are given by Equation (4.11):

$$N_{nd} \;\&\; N_{nL} = N_C - N_{ne} = N_C - \frac{N_C}{as+1} = \frac{as.N_C}{as+1} \qquad (4.11)$$

As N_{nL} is dependant on the influent TKN concentration and D_{PP} is dependant on the influent COD concentration, the TKN/COD ratio of the influent should have a direct affect on the N_{ne} concentration. As the TKN/COD ratio increases, N_{ne} will increase, and *visa versa*, and this behaviour pattern is largely reflected in the experimental results, see Fig. 4.30.

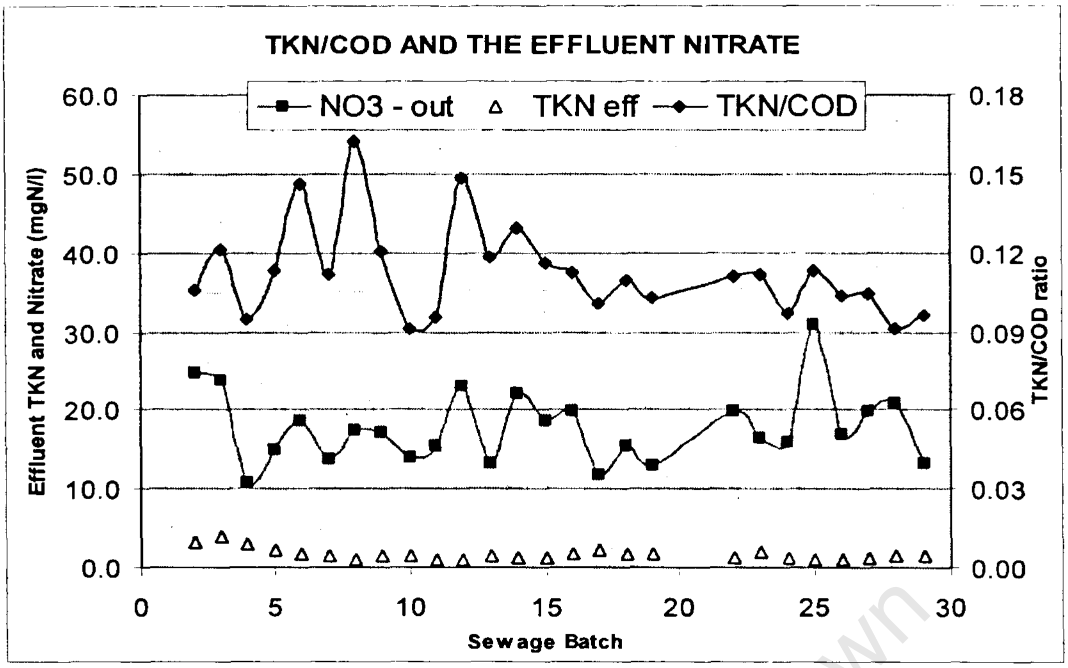


Figure 4.30: *TKN/COD ratios of the influent feed and the effluent TKN and NO3 concentrations.*

Anoxic NO_3 concentrations were generally very low throughout the investigation: Apart from sewage batches 12 and 14 which had anoxic NO_3 concentrations of 2.5 and 2.4mgN/ℓ respectively, all other batches had values less than 1.3mgN/ℓ. The mean of the sewage batch averages over the investigation was 0.5mgN/ℓ indicating that for the most part the N_{nL} to the anoxic reactor equalled or slightly exceeded the D_{PP}. These observations indicated negligible NO_3 recycled to the anaerobic reactor, and hence BEPR was operated independently of nitrate. Consistently overloaded anoxic reactors stimulate the growth of denitrifying PAOs and anoxic P uptake BEPR. This is observed from time to time in BEPR systems and causes a reduction in P removal because the denitrifying PAOs use the influent RBCOD less efficiently than the aerobic PAOs. In the MBR system, P uptake took place mostly in the aerobic reactor indicating negligible denitrification contribution by PAOs.

System Nitrogen Removal

The total system N removal is the difference between the influent TKN (N_{ti}) and the sum of effluent TKN and NO_3 (the NO_2 is negligible). This value varied greatly from 13.7 – 32.0 mgTN/ℓ. The batch average total nitrogen removals ranged from 68.9% to 86.1 % with an average of 81.7%. This is substantially higher than the 67 and 76% nitrogen removals observed in Phase 1, with a-recycle ratios <2:1 and 3:1 respectively, and can be attributed in part to the higher a-recycle ratio in this Phase 2 investigation of >3:1, which loaded the anoxic reactor with nitrate close to its denitrification potential.

4.9.3 BEPR

Biological Excess Phosphorus Removal (BEPR) is achieved in BNR systems by promoting the growth of phosphorus accumulating organisms (PAOs) which store a high concentration of intracellular polyphosphate (polyP), 0.38mgP/mgVSS in comparison to 0.02mgP/mgVSS in conventional heterotrophic organisms (Wentzel *et al.*, 1990). This is achieved through incorporating an anaerobic/aerobic sequence with sewage fed to the anaerobic zone. In the anaerobic reactor PAOs store short chain fatty acids (SCFA) internally as polyhydroxyalkanoates (PHA). In order to convert the SCFAs to PHA, energy is required. This energy is sourced from complex polyP stored in the PAOs. In utilizing polyP, orthophosphate is released into the bulk liquid around the organism. Thus, in the anaerobic reactor SCFAs, which are generated from the influent RBCOD through acid fermentation by ordinary heterotrophic organisms (OHOs) in the mixed liquor, are sequestered and stored by the PAOs and as a result orthophosphates are released into solution. In the aerobic reactor the internally stored PHA is utilized as a carbon and energy source with oxygen as electron acceptor for growth and maintenance, and as an energy source for taking up orthophosphate from solution and forming polyP to replenish the polyP pool. The new PAO biomass that is generated in the growth process also takes up polyP, with the result that the P uptake is greater than the P release. The difference between the P uptake and P release is the P removal.

Hence, under aerobic conditions there is a net increase in polyP bound up in PAO sludge mass and a net decrease of orthophosphates in solution. At steady state the production of new polyP and the reduction of orthophosphates in solution per day is equal to the polyP in the sludge wasted per day. In order to augment and hence accentuate the BEPR performance in the system the RBCOD in the influent was increased by dosing 200mgCOD/ℓ influent sodium acetate. Additionally, to ensure that the system was not P limited, 20mgP/ℓ influent orthophosphate was dosed in the daily feed.

To evaluate and observe the BEPR performance in the system, total P concentrations were measured on the influent, filtrate (0.45μm) of each reactor, and the effluent, and are illustrated in Figs. 4.31-4.34. However, as the P content of the mixed liquor was not measured a complete system P mass balance could not be carried out on the system, as was the case with nitrogen and COD.

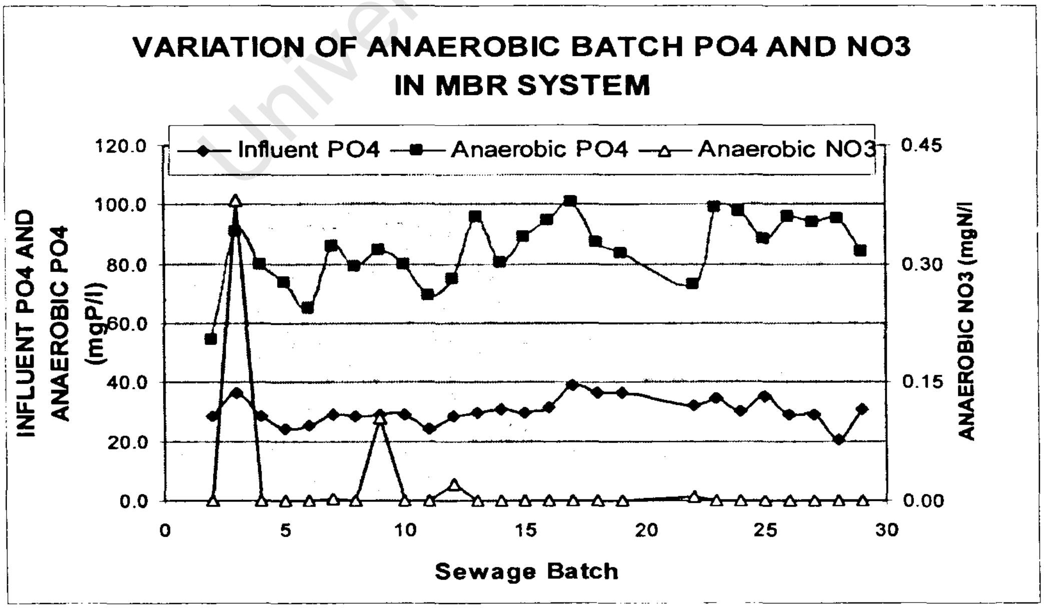


Figure 4.31: *Time dependant variation in anoxic reactor total soluble phosphorus and anoxic nitrate concentrations.*

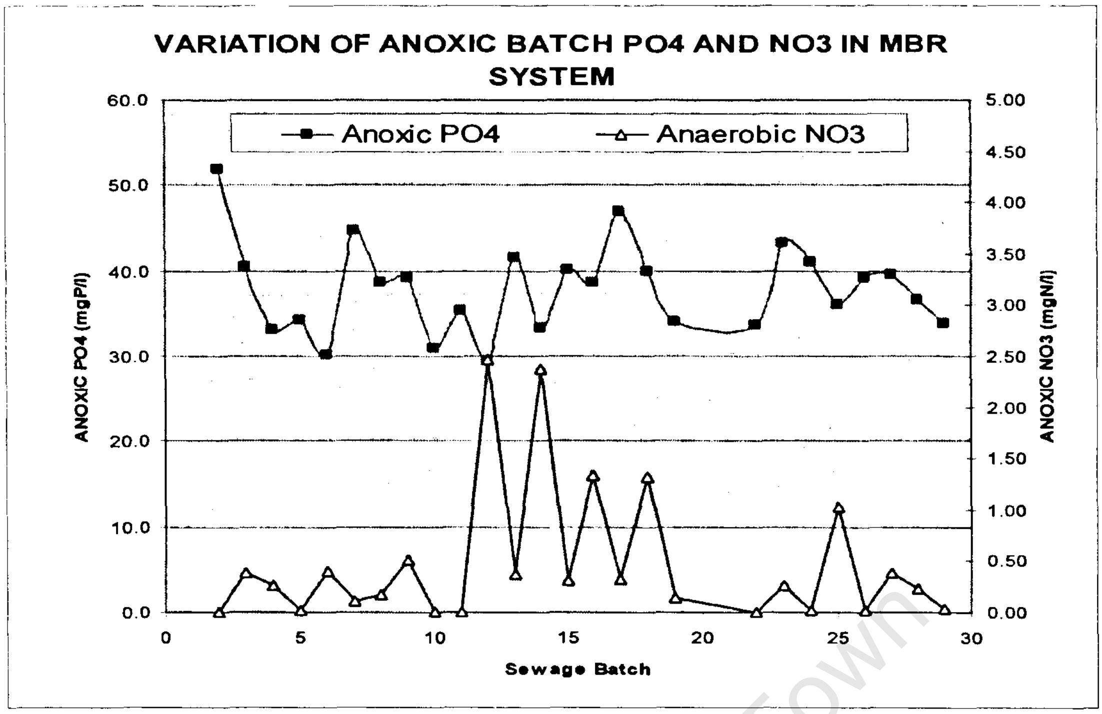


Figure 4.32: *Time dependant variation in anoxic reactor total soluble phosphorus and anoxic nitrate concentrations*

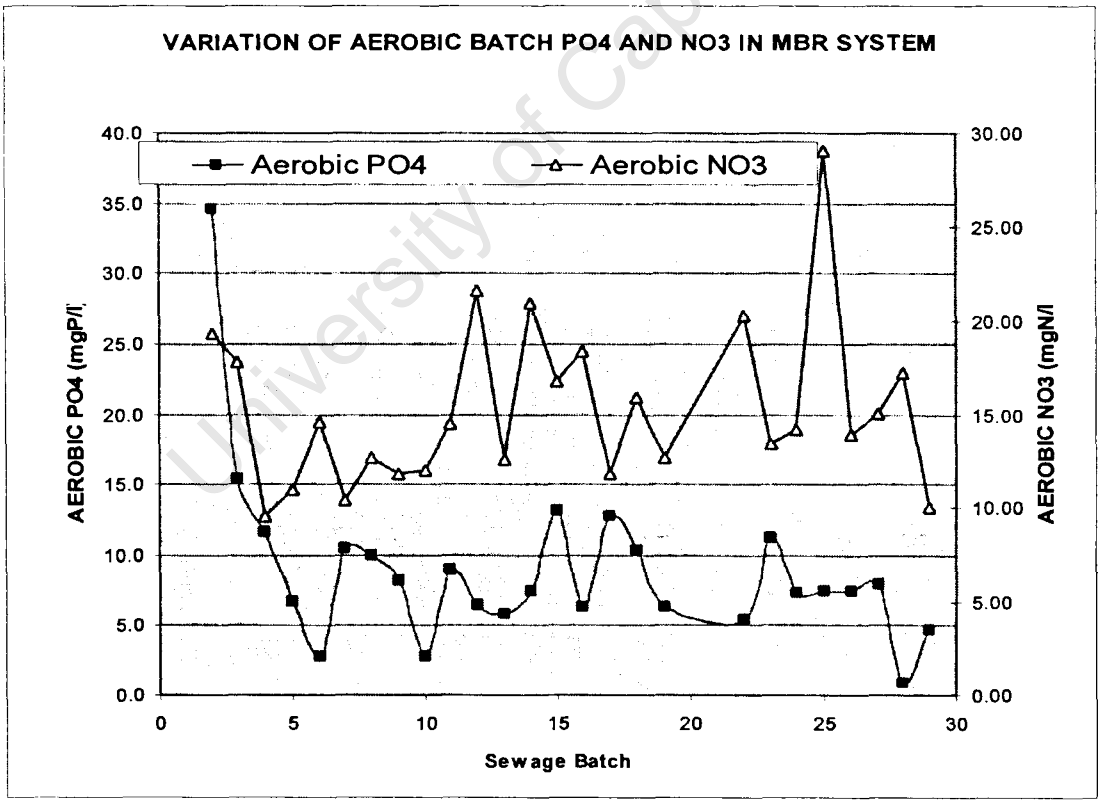


Figure 4.33: *Time dependant variation in anoxic reactor total soluble phosphorus and anoxic nitrate concentrations*

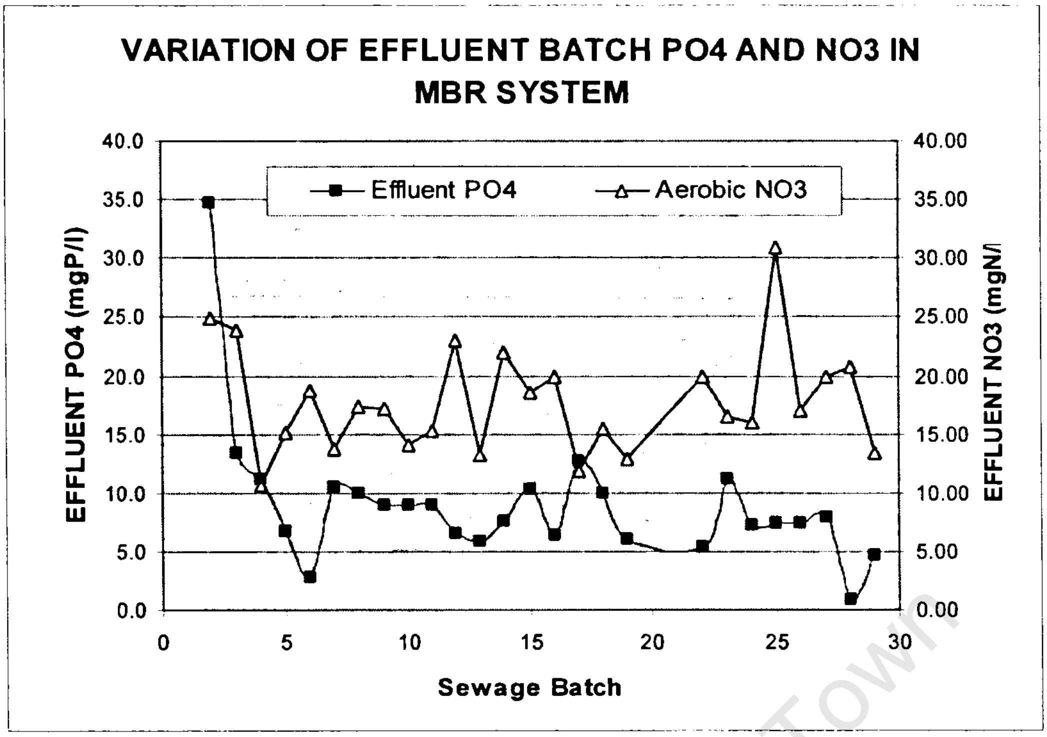


Figure 4.33: Time dependant variation in anoxic reactor total soluble phosphorus and anoxic nitrate concentrations

To evaluate the P removal performance across the reactors a P balance (Table 4.10) was set up, whereby the change in P mass across each reactor was calculated via a reactor P mass balance, i.e. the difference between P mass entering the reactor and P mass leaving the reactor. This difference, indicating P uptake if positive and P release if negative, divided by the influent flow gave the P uptake/release per litre influent flow, see Table 4.10.

Table 4.10: *Sewage batch average P release (-ve) and P uptake (+ve) in the reactors and across the membranes of the MBR system, and the total P removal.*

Batch Number	Influent	Anaerobic	Anoxic	Aerobic	Membrane	M (P-PO4) removal
	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf
2	28.6	-29.2	-109.7	133.1	-10.1	-5.8
3	36.2	-109.1	-50.8	182.6	0.6	22.8
4	28.4	-110.5	33.7	94.0	0.3	17.3
5	24.0	-93.2	5.6	104.8	1.7	17.2
6	25.1	-84.4	-5.3	112.1	-0.7	22.3
7	29.1	-101.6	-33.0	153.3	0.3	18.7
8	28.5	-103.1	-20.1	141.7	0.1	18.5
9	29.3	-108.9	8.4	120.8	0.5	20.3
10	29.3	-99.0	-14.5	134.0	-0.9	20.5
11	24.0	-87.5	-25.3	127.9	-0.3	15.0
12	28.3	-107.8	14.4	115.2	0.0	21.9
13	29.6	-132.8	-10.8	167.3	0.1	23.8
14	31.2	-114.3	25.5	112.5	0.3	23.7
15	29.8	-124.0	22.0	121.4	1.4	19.4
16	31.4	-128.4	28.7	124.7	1.3	25.0
17	39.1	-121.4	8.8	139.0	-0.5	26.4
18	36.6	-114.3	14.4	126.7	-0.1	26.8
19	36.5	-100.1	16.8	113.8	1.0	30.4
22	32.0	-88.9	-15.1	130.7	1.0	26.6
23	34.7	-127.0	9.2	141.3	-0.3	23.5
24	30.2	-135.5	13.7	144.6	0.8	22.9
25	35.2	-117.2	17.3	127.7	0.5	27.8
26	28.9	-136.5	19.9	138.1	0.7	21.5
27	29.2	-128.7	31.2	118.6	5.5	21.2
28	20.7	-144.2	24.1	139.8	3.5	19.7
29	31.0	-112.8	21.3	117.9	-0.6	26.3
Average	30.3	-113.3	5.6	130.0	0.7	22.4
Ramphao *et al.*, (2004)	40.8	-136.1	14.67	147.8	0.5	26.9

The results for sewage batch 2 have been excluded from the investigation average as these were identified as being outliers and inconsistent with the rest of the data at the commencement of the investigation. The results of Ramphao *et al.* (2004) from Phase 1 are included in Table 4.10. The overall higher average results achieved in Phase 1 are attributed to a larger PAO population at steady state, and this is discussed later. Small differences in measured P concentrations in the aerobic and effluent samples prompted the inclusion of a mass balance around the membranes in the aerobic reactor. However, apart from sewage batches 27 and 28 which followed on from the intermittent power failures, the changes in P across the membranes were very small. The anaerobic, anoxic and aerobic P release/uptake for the different sewage batches are shown in Fig. 4.34.

Both P uptake and release occurred in the anoxic reactor. P release occurred less often and typically early on in the investigation (sewage batches (2), 6-8, 10, 11, 13 and

22), whereas P uptake occurred more regularly and predominately in the latter half of the investigation. However, as a fraction of the total P uptake, anoxic P uptake was small (8.5%).

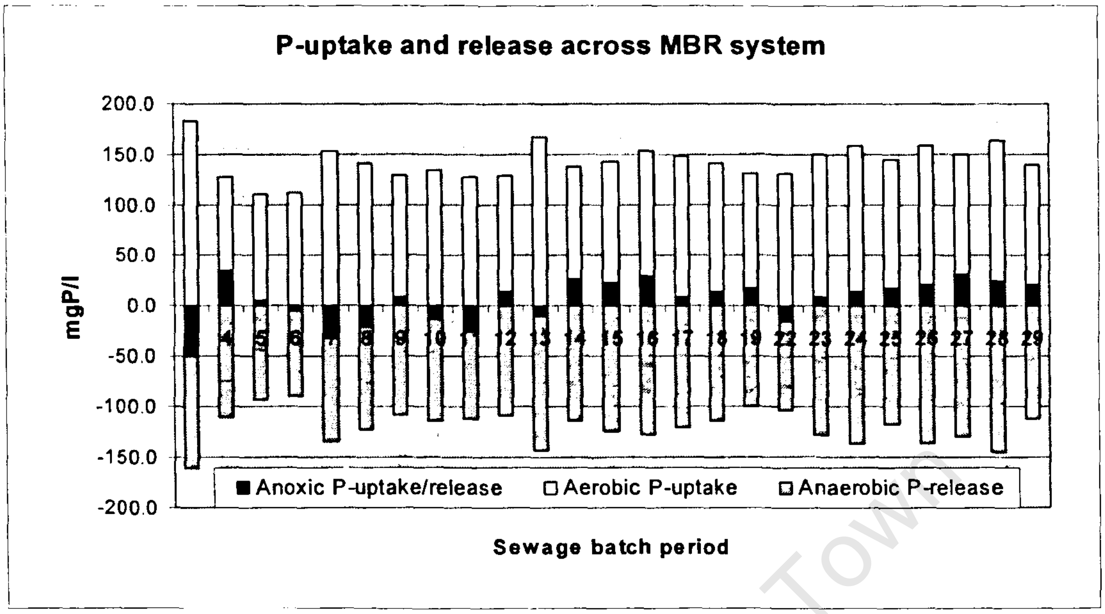


Figure 4.34: *A stacked bar breakdown of Anaerobic P release (-ve), anoxic P release/uptake (-ve/+ve) and aerobic P uptake (+ve).*

The magnitude of anoxic P release corresponded quite closely with lower P release in the anaerobic reactor (see Fig 4.35). If the anaerobic P release was low, significant anoxic P release tended to occur. This is probably due to leakage of RBCOD through the anaerobic reactor to the anoxic reactor, possibly due to an initially low PAO population which increased with time in the investigation as reflected in the improved P removal. However, factors such as anoxic reactor NO_3 concentration influence the anoxic P release/uptake (Hu *et al.*, 2002) and hence no definitive conclusion can be drawn.

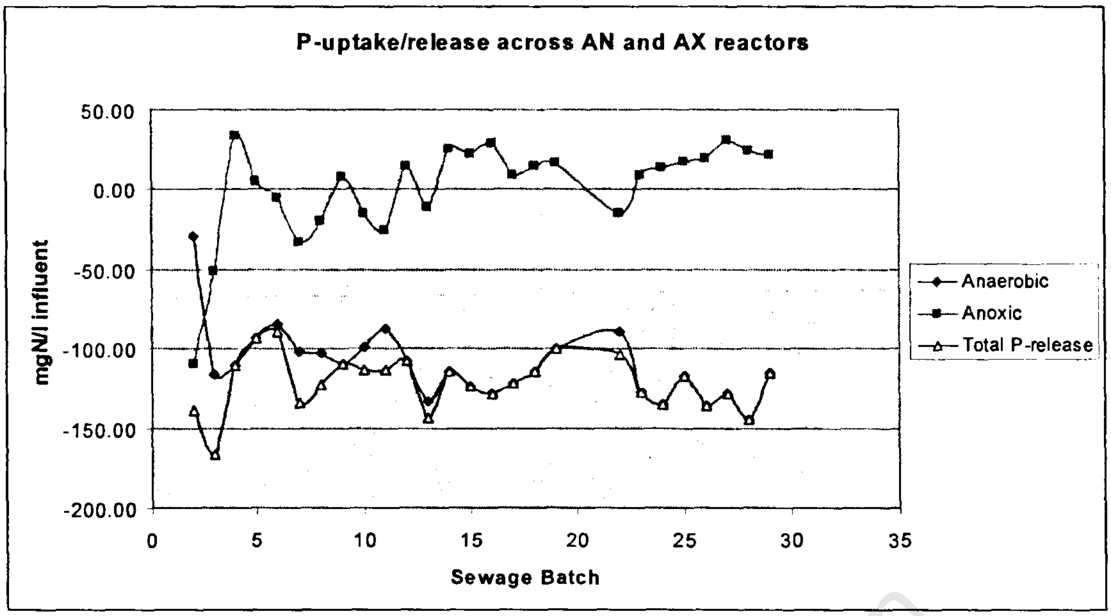


Figure 4.35: *The average P release and P uptake across the AN and AX reactors appeared consistent.*

System P removal (Fig. 4.36) showed a steady increase through the investigation, up until sewage batch 18, after which it stabilized, suggesting that the slow growing PAO population only reached steady state around that time in the study. Sewage batch average P removals are statistically plotted in Fig 4.37, giving a mean P removal for the investigation of 22.4mgP/ℓ, which is substantially lower than that observed in Phase 1 of 27.0mgP/ℓ (Ramphao *et al.*, 2004). However, if only the P removals from sewage batch 18 onwards are considered, a mean removal of 24.7mgP/ℓ is obtained which is substantially closer to the P removal observed in Phase 1 above.

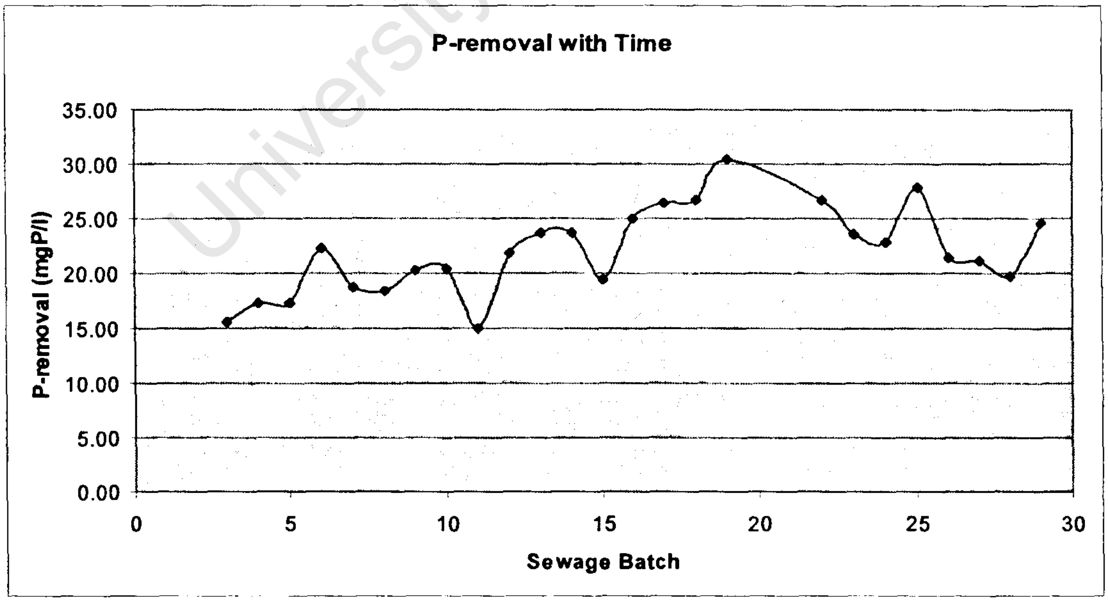


Figure 4.36: *P-removal over time for the sewage batch periods.*

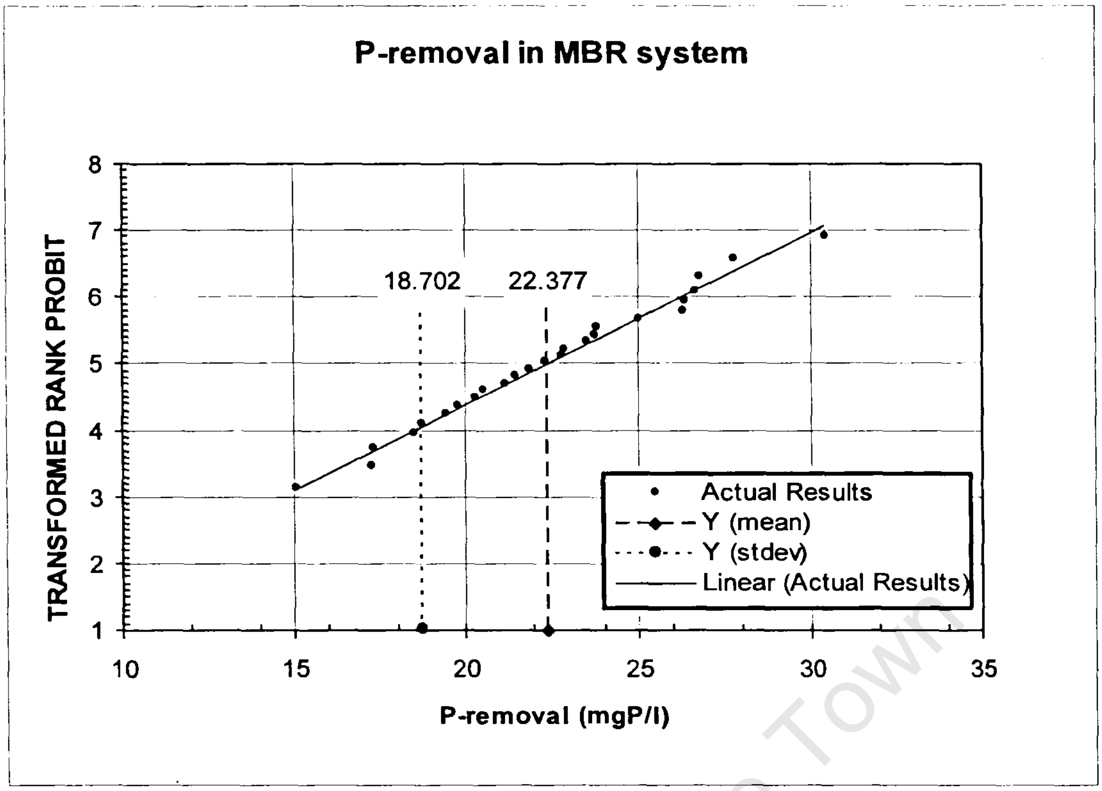


Figure 4.37: Statistical plot of the system P removal for sewage batch periods.

The UCT configuration is designed to protect the anaerobic reactor from recycled NO_3, whereby all NO_3 entering the anoxic reactor is utilized for denitrification. If NO_3 does enter the anaerobic reactor, it can be utilised with the available COD for denitrification by OHOs and thus less COD is available to the PAOs, which in turn reduces the P release and subsequent P uptake and hence P removal. For every 1 mgN-NO_3/ℓ recycled to the anaerobic reactor 8.6mgCOD/ℓ is no longer available to the PAOs, and the P removal reduces by approximately 0.85mgP/ℓ (Wentzel *et al.*, 1990).

Anoxic reactor NO_3 concentrations for the different sewage batches are shown in Fig. 4.38, together with the anaerobic P release. On five occasions (sewage batches 12, 14, 16, 18 and 25) the anoxic NO_3 concentration exceeded 1mgN-NO_3/ℓ which would have been recycled to the anaerobic reactor.

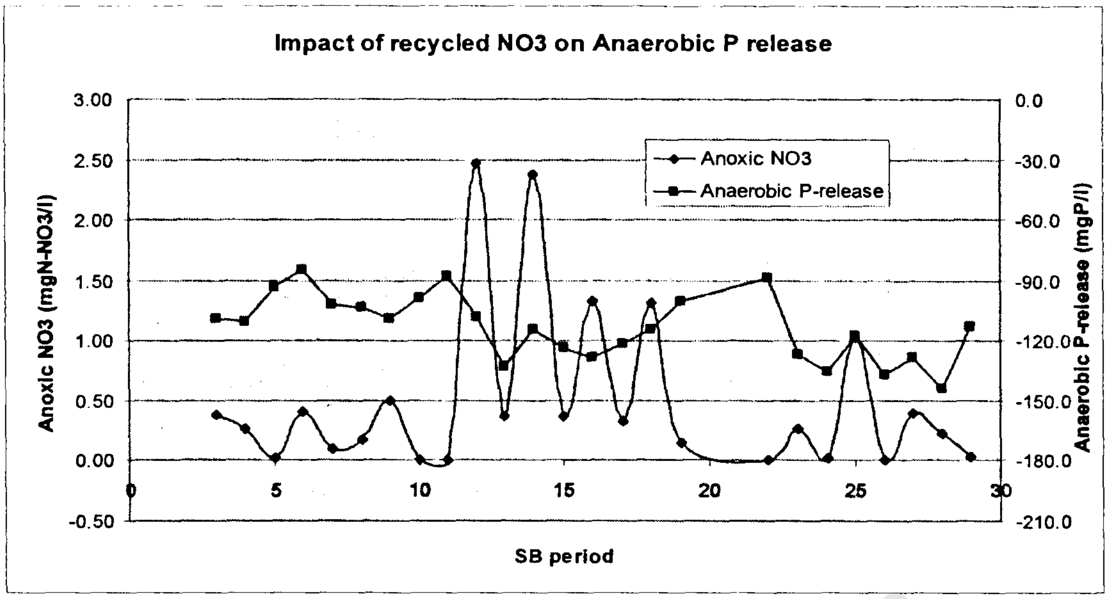


Figure 4.38: Anoxic NO₃ concentration and its impact on anaerobic P release.

The anaerobic P release is dependant *inter alia* on the influent RBCOD concentration. The more RBCOD available, the more PHA can be stored by the PAOs and hence the more P release will occur in the anaerobic reactor. In the calculations for characterizing the mixed liquor (Section 4.4.4) it was assumed that 90% of the influent RBCOD would be anaerobically converted through fermentation by OHOs to SCFAs and would thus be available to be utilized by PAOs. Additionally it was assumed that for every 1mg RBCOD used 0.5mgP would be released in the anaerobic reactor (Wentzel *et al.*, 1990). Thus plots of 90%RBCOD concentration for the sewage batches and the observed P release/0.5 should show close correlation, see Fig. 4.39. The correlation is reasonably close, except for the first four sewage batches.

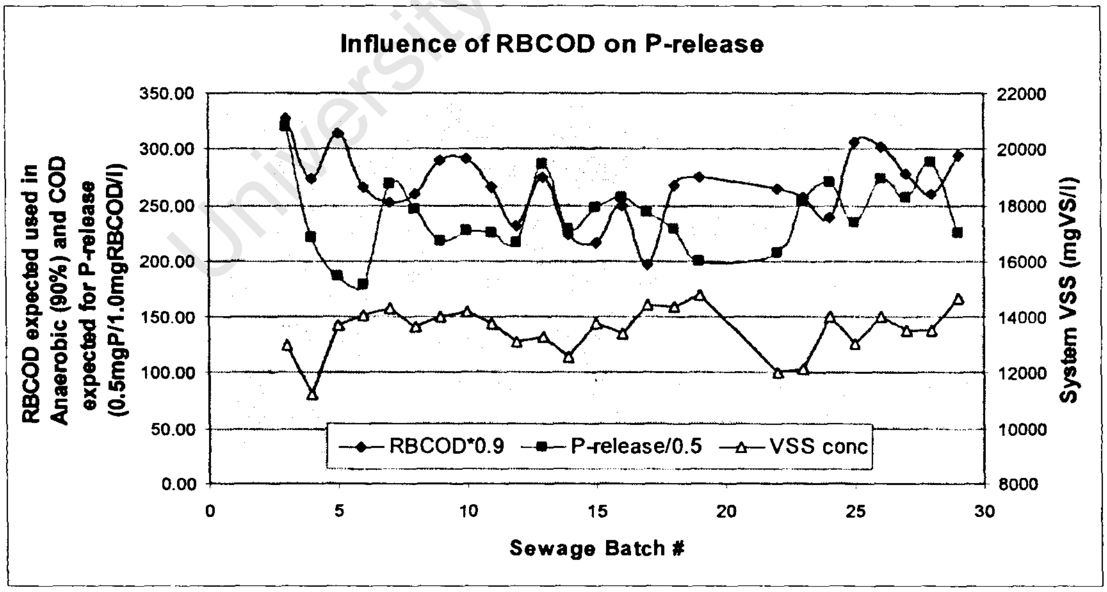


Figure 4.39: The relationship between RBCOD P removal and VSS concentration. Apart from batches 2-4, 7-8, 19, 22 and 29 the values are very close supporting the assumptions made on the relationship between RBCOD and P release in the anaerobic reactor. It was assumed that the spills in batches 4 and 22 would have had an impact on the P release as sludge loss would have meant a loss of PAO's which take time to develop. However the data does not seem to support this hypothesis.

Additionally, from the understanding of BEPR, the P release and P removal, should track each other closely. This arises because the magnitude of P removal is relative to the new PAO cell mass, which is dependant on the amount of RBCOD stored in the anaerobic reactor with its consequent P release. Sewage batch average anaerobic P release and system P removal are shown plotted in Fig 4.40. Up to sewage batch 16, both P release and P removal increase conforming to expectations. However, from sewage batch 19 the P removal decreased, whereas the P release increased contrary to expectation. No explanation for this latter behaviour is evident.

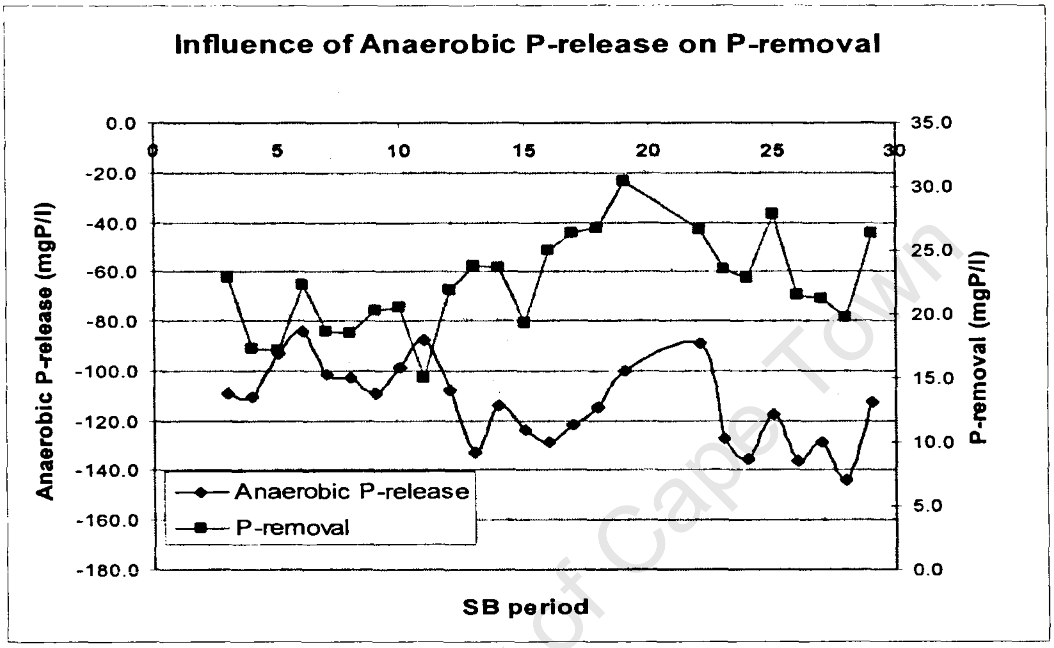


Figure 4.40: *The relationship between anaerobic P release and system P removal is not clear.*

Anoxic P Uptake

Early observations on BEPR systems indicated that P uptake took place only in the aerobic reactor, i.e. PAOs did not denitrify (Wentzel *et al.*, 1990; Clayton *et al.*, 1991). However more recent investigations indicate that some strains of PAOs can denitrify, termed denitrifying (D)PAOs (Kerry-Jasperson and Henze *et al* 1993; Baker and Dold, 1996; Kuba *et al.*, 1993, 1997; Ekama and Wentzel, 1999; Hu *et al.*, 2002) with associated anoxic P uptake. With anoxic P uptake by DPAOs, significantly reduced BEPR has been reported (Ekama and Wentzel, 1999; Hu *et al.*, 2002), presumably due to less efficient utilization of the influent RBCOD (Hu *et al.*, 2002). Conditions identified as contributing to anoxic BEPR include i) NO_3 load to anoxic reactor exceeding the denitrification potential of the reactor, ii) low aerobic mass fractions, iii) anoxic-aerobic sequence of reactors, and iv) frequency of sludge alternation between anoxic and aerobic states (Hu *et al.*, 2002).

The frequency of anoxic P uptake was evaluated in this investigation and in Figure 4.41. the occurrence of anoxic P uptake is presented together with the concentration of NO_3 in the anoxic reactor for the different sewage batches:

- P release occurs in 8 sewage batches (3, 6-8, 10-11, 13, 22), which apart from sewage batch 22 all occur in the first half of the study.
- Anoxic P uptake as a percentage of the total P uptake is very variable and ranged from 0 – 26.4% (sewage batch 4), with an average of 8.5%.
- A correlation between anoxic P uptake and anoxic NO_3 concentration was observed: Where anoxic P uptake was observed there was, in most cases, anoxic NO_3 present (except sewage batches 5, 24, 26 and 29). The converse was less often true, that is where anoxic NO_3 was present anoxic P uptake did not necessarily occur. This indicates that observable anoxic NO_3 is a necessary, but not the only, requirement for anoxic P uptake.

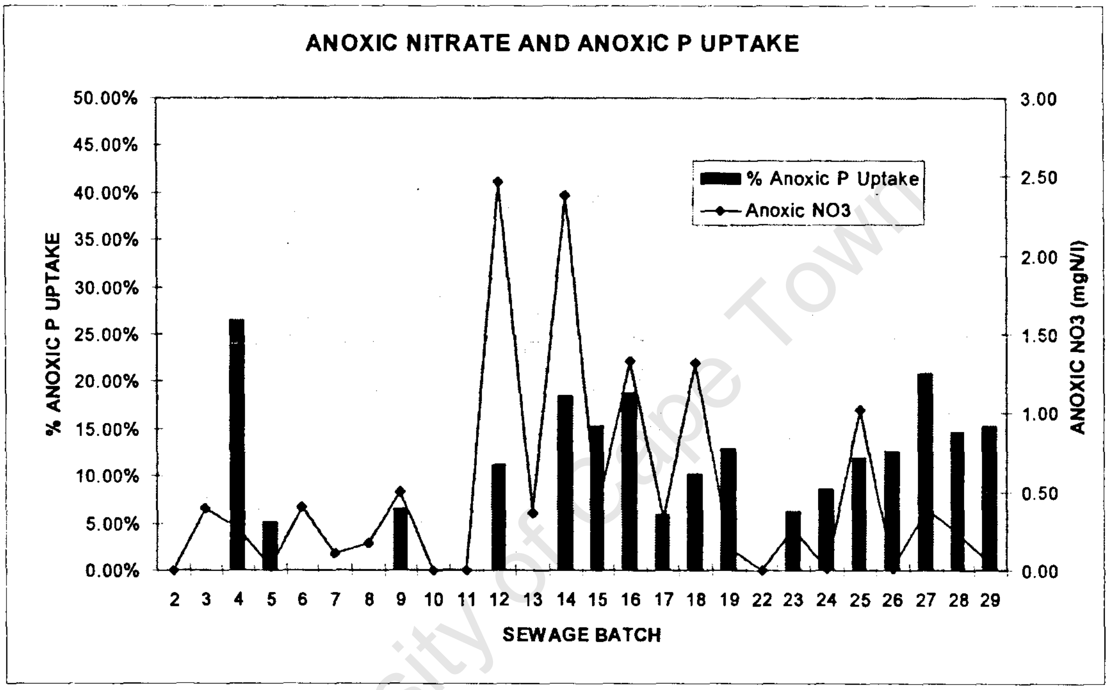


Figure 4.41: *The frequency of anoxic P-uptake may be linked to the concentration of anoxic* NO_3.

4.10 THEORETICAL EVALUATION OF ND AND BEPR PERFORMANCE IN THE MBR SYSTEM

Theoretical evaluations of nitrification/denitrification (ND) and biological excess phosphorus removal (BEPR) were undertaken to assess the MBR UCT system performance.

4.10.1 Nitrification

In order to predict the nitrification and denitrification performance of the MBR UCT system, and hence the effluent NO_3 concentrations, the steady state design model for BNR systems (WRC, 1984; WRC, *in prep.)* was used and predictions compared with measurements.

For each steady state period the nitrification capacity of the system was predicted from (WRC, 1984):

$$N_C = N_{ti} - N_S - N_{te} \tag{4.12}$$

Where: N_{ti} = sewage batch average TKN in influent (mgN/ℓ)

N_S = nitrogen bound up in sludge production and wasted from the system (mgN/ℓ influent)

$= \frac{f_N M X_V}{R_S Q_i}$

f_N = fractional content of nitrogen in volatile suspended solids (VSS), (mgN/mgVSS)

M_{Xv} = total mass of solids (VSS) in the system (mgVSS)

R_S = sludge age, taken as 20 (d)

Q_i = batch average influent flow, taken as 140 (ℓ)

N_{te} = the effluent TKN concentration, calculated below (mgN/ℓ):

From nitrification theory (WRC, 1984) with a maximum specific growth rate of nitrifiers (μ_{nm}) = 0.45/d and half saturation constant K_N = 1.0mgN/ℓ, the effluent ammonia concentration (N_{ae}) could be calculated. Thereafter, the effluent TKN concentration (N_{te}):

$$N_{te} = N_{ae} + N_{ouse} \tag{4.13}$$

Where: N_{ouse} = effluent organic unbiodegradable soluble nitrogen, taken as the batch average difference between effluent TKN and FSA, see Section 4.4.7.2.

For comparison, the measured N_{te} and N_{ae} values were used. N_C was measured as:

$$N_C = N_{ne} + N_{nd} \tag{4.14}$$

Where: N_{ne} = Effluent nitrate concentration

N_{nd} = Nitrate denitrified in the anoxic (and anaerobic reactors), calculated from a nitrate mass balance around the anoxic and aerobic reactors.

From comparison of the predicted and measured values, Table 4.11:

- The measured N_{ae} values were typically higher than those predicted, 0.63 mgN/ℓ vs 0.24 mgN/ℓ respectively. This could be influenced by the sensitivity of the FSA test which, as discussed earlier, is not very sensitive at low concentrations. However, in the Phase 1 investigation Ramphao *et al.* (2004) found a substantial difference between the N_{ae} measured and that predicted, 0.51 mgN/ℓ vs 2.16 mgN/ℓ. This suggests that for modelling purposes a higher nitrifier half saturation constant (K_N) value should be used. In this investigation using K_N = 2.9 mgN/ℓ as opposed to 1.0 mgN/ℓ gave similar measured and predicted N_{ae} values (0.70 mg N/ℓ for both).

Table 4.11: *Theoretical evaluation of NDBEPR in the MBR system compared to measured values in Phase 2 and evaluation results from Phase 1 (Ramphao,* et al., *2004)*

	Batch #		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	[redacted]	23	24	25	26	27	28	29	Average	Ramphao
Influent	Sti	(mgCOD/l)	958	1148	1022	992	912	835	785	980	1006	976	888	856	870	934	971	926	914	1071			1009	941	787	909	989	969	1116	983	951.5	
	Nti	(mgN/l)	101	139	97	113	134	93	127	118	91	93	132	101	112	109	109	93	100	110			112	105	77	103	102	101	101	95	106.7	103.6
	Influent TKN/CO	mgN/mgCO	0.11	0.12	0.09	0.11	0.15	0.11	0.16	0.12	0.09	0.10	0.15	0.12	0.13	0.12	0.11	0.10	0.11	0.10			0.11	0.11	0.10	0.11	0.10	0.10	0.09	0.10	0.11	
Nitrification	Nc - predicted	mgN/l	76.7	113.0	72.2	85.6	105.5	67.6	101.4	93.2	65.3	68.5	108.5	78.2	89.7	83.2	82.8	66.1	71.1	82.7			91.7	83.2	54.1	81.2	78.4	74.8	73.5	68.2	77.85	75.0
	Nc - measured	mgN/l	128.9	128.0	45.2	60.1	73.5	61.5	84.8	65.8	66.9	73.6	103.3	60.0	85.9	76.9	73.9	46.2	59.5	54.7			94.3	70.8	69.9	135.3	75.3	84.7	87.0	52.6	76.16	75.0
	Ns	mgN/l	22.4	24.6	23.0	25.7	27.2	24.2	25.2	23.6	24.8	24.0	22.6	21.9	21.6	25.1	24.5	26.1	27.9	26.1			19.3	19.9	21.1	20.6	22.9	25.1	26.9	25.6	23.98	
	Nte-predicted	mgN/l	2.3	1.8	1.9	1.3	0.9	1.3	0.7	1.0	1.4	0.8	0.7	1.3	1.1	0.3	1.6	1.2	1.1	1.4			1.0	1.8	1.3	0.9	0.8	1.3	0.9	1.2	1.16	3.85
	Nte- measured		3.3	3.9	3.0	2.2	1.6	1.5	1.0	1.4	1.5	0.9	1.1	1.4	1.3	1.3	1.8	2.3	1.8	1.6			1.2	1.9	1.1	1.0	1.1	1.3	1.5	1.5	1.61	3.36
	Nae-predicted	mgN/l	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2			0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.24	0.51
	Nae-measured		1.2	2.4	1.3	1.2	1.0	0.4	0.5	0.7	0.4	0.3	0.6	0.4	0.4	1.3	0.4	1.3	1.0	0.5			0.5	0.3	0.0	0.4	0.5	0.3	0.8	0.6	0.70	2.16
Denitrification	Dpp - predicted	mgN/mgCO	49.0	55.1	46.6	45.3	37.5	35.8	32.3	43.3	46.0	43.4	39.4	40.0	38.9	39.5	42.1	40.1	35.2	44.2			46.1	43.5	31.8	40.1	43.7	43.2	40.6	42.3	41.43	40.10
	Dpp - measured	mgN/mgCO	104.0	104.2	34.5	45.0	54.7	47.7	67.5	48.7	52.8	58.3	80.3	46.8	64.0	58.4	54.0	34.4	44.1	41.7			74.5	54.3	53.9	104.4	58.3	64.9	66.3	39.3	58.12	54.05
	a-opt - predicted		1.8	1.0	1.8	1.1	0.6	1.1	0.5	0.9	2.4	1.7	0.6	1.0	0.8	0.9	1.0	1.6	1.0	1.2			1.0	1.1	1.4	1.0	1.3	1.4	1.2	1.6	1.16	1.51
	a-sel		4.2	4.5	3.3	3.0	3.0	3.5	4.0	3.0	3.8	3.8	4.0	3.7	3.4	3.2	3.0	3.0	3.2	3.3			3.8	3.4	3.4	3.5	3.4	3.4	3.3	3.0	3.43	
	Nl at a-opt	mgN/l	48.8	55.0	46.6	45.2	37.4	35.9	32.4	43.3	45.9	43.4	39.4	39.8	38.7	39.6	42.2	40.2	35.2	44.3			46.1	43.6	31.8	40.0	43.7	43.2	40.7	42.4	41.12	
	Nl at a-sel	mgN/l	61.2	90.6	54.7	63.5	78.7	52.4	80.8	69.4	51.4	54.2	86.6	61.3	69.2	62.8	61.8	48.8	53.7	63.2			72.2	64.1	41.9	63.2	60.6	57.6	55.8	50.8	59.95	
NO_3	Nne at a-opt	mgN/l	27.9	57.9	25.6	40.4	68.1	31.7	69.0	49.8	19.4	25.1	69.1	38.3	51.0	43.6	40.6	25.9	35.9	38.5			45.6	39.6	22.4	41.2	34.7	31.6	32.8	25.8	40.14	34.60
	Nne - msrd	mgN/l	24.9	23.8	10.7	15.1	18.7	13.7	17.3	17.1	14.1	15.3	23.0	13.2	21.9	18.5	19.9	11.9	15.4	12.9			19.8	16.5	16.0	31.0	17.0	19.8	20.7	13.3	17.47	23.10
	Nne-a sel	mgN/l	14.6	20.3	16.4	21.2	26.1	15.0	20.4	23.4	13.7	14.3	21.5	16.6	20.4	19.4	20.8	16.2	16.6	19.3			19.2	19.0	12.4	17.9	17.7	17.2	17.2	17.1	18.37	23.45

- The differences in N_{ae} are reflected in the N_{te} values, and the correction to K_N above brings the predicted and measured N_{te} values very close (1.62 and 1.61 mgN/ℓ respectively).
- Due to doubts about the reliability of the NO_3 data up until sewage batch 9 only the sewage batch average values from sewage batch 9 onwards were taken into consideration in calculating the measured and predicted N_C values. Their respective averages were very close, 76.16 mgN/ℓ versus 77.85 mgN/ℓ, which correspond to the values reported in Ramphao *et al.* (2004), of 75 mgN/ℓ for both measured and predicted values.

From the above observations, nitrification in the system can be closely predicted by the existing nitrification theory, and hence this theory can be applied directly to the design of MBR BNR systems. The unbiodegradable soluble organic nitrogen fraction determined in this investigation, taking into account the dosing of FSA into the influent, was 0.009 and should be used in design. Additionally, in this investigation the half saturation constant for the nitrifiers, K_N, was increased to 2.6 mgN/ℓ to match measured and calculated N_{ae} (and N_{te}) values. This adjustment in K_N is however largely attributed to the insensitivity of TKN and FSA testing at very low concentration such as were measured in the MBR effluent. Thus a revision of K_N is not recommended.

4.10.2 Denitrification

The theoretical denitrification potential of the primary anoxic rector (D_{pp}) in the MBR UCT system was calculated according to the procedure set out in the new steady state design denitrification theory for NDBEPR systems, Equation (4.15) (WRC, in prep):

$$D_{PP} = \frac{S_{bsN}(1+r)(1-f_{CV}Y_H)}{2.86} + \frac{f_{X1}K'_{2T}(S_{bi}-S_{seq})Y_H R_S}{(1+b_{HT}R_S)} \qquad (4.15)$$

Where:

S_{bsN} = concentration of fermentable RBCOD leaving the anaerobic reactor, calculated according to Wentzel *et al.* (1990) (mgCOD/ℓ)
Y_H = the OHO and PAO biomass yield = 0.45 mgCOD/mgCOD
r = recycle ratio, anoxic to anaerobic reactors
2.86 = the oxygen equivalence of nitrate (measured as 1mgN-NO_3)
f_{X1} = primary anoxic mass fraction (from Table 4.3)
K'_{2T} = OHO specific denitrification rate in NDBEPR systems = 0.145 mgN/mgVSS/d at 20°C
S_{bi} = influent biodegradable COD concentration (mgCOD/ℓ) = S_{ti} (1- $f_{S,us}$- $f_{S,up}$) with $f_{S,us}$ and $f_{S,up}$ available from Table 4.7, Section 4.8.
S_{seq} = substrate sequestered by PAO's in the anaerobic reactor, calculated according to Wentzel *et al.* (1990) (mgCOD/ℓ influent)
b_{HT} = the rate of endogenous respiration for OHO's (0.24mgVSS/ℓ at 20°C)

Actual denitrification achieved was calculated from a mass balance around the anoxic and anaerobic reactors (as some, though very little, denitrification did occur in the anaerobic reactor as the r-recycle contained small amounts of measurable NO_3). Comparing the predicted D_{PP} with the actual denitrification (Table 4.11):

- Generally in all but three cases the D_{PP} predicted was substantially less than that measured, 41.4 mgN/mgCOD versus 58.1 mgN/mgCOD despite the fact that virtually all nitrate entering the anoxic reactor was used (~0.5mgN/ℓ anoxic nitrate) indicating that denitrification was limited by the nitrate load not the denitrification kinetics. Ramphao *et al.* (2004) observed similar deviations between measured and predicted values, 40.1 mgN/mgCOD and 54.1mgN/mgCOD respectively.
- Reasons cited by Ramphao *et al.* (2004) for the difference were either i) incorrect K'_{2T} values for the OHOs in the Equation 4.15, or ii) anoxic P uptake that was observed in the system which implies denitrification by the PAOs, which is not included in the theoretical D_{PP} equation, or both. The extent of denitrification with associated P uptake by the PAOs appears to be very variable (Ekama and Wentzel, 1999), from near zero anoxic P uptake (Clayton *et al.*, 1989; 1991) to anoxic P uptake dominant over aerobic P uptake (Sorm *et al.*, 1996). Experimental evidence tends to suggest that the magnitude of P uptake is influenced by the anoxic mass fraction and the mass of NO_3 loaded on the anoxic reactor relative to its denitrification potential (Hu *et al.*, 2002) and this was supported by the observations here. However, as yet, it does not seem possible to make a definite statement as to exactly which conditions will induce the presence of denitrifying PAOs and associated anoxic P uptake in NDBEPR systems, or what the relative magnitude of these will be. Accordingly, it is difficult to incorporate such a process into predictive models. Clearly, further investigation is required in this area. In the meantime, denitrification design with existing theory will tend to be conservative, and performances exceeding predictions can be expected.
- Hence, in order to improve the denitrification predictions for this investigation the $K'_{2(20)}$ value was increased from 0.145mgN/mgCOD/d to 0.216mgN/mgCOD/d at 20°C to match the average D_{PP} predicted with that measured. This value falls within the range of values reported for K'_{2T} by Hu *et al.*, (2002) for NDBEPR systems, 0.05 – 0.32mgN/mgVSS/d.

4.10.3 a-Recycle Ratio

In evaluating the MBR system theory, the a-recycle noted below is the as-recycle, as described in Chapter 3. The optimum a-recycle ratio (a_{opt}), is the a-recycle that matches the nitrate load (N_{nL}) to the primary anoxic reactor with its denitrification potential (D_{PP}), i.e. at a_{opt} $D_{PP} = N_{nL}$. The N_{nL} is calculated as follows:

$$N_{nL} = \frac{as.Nc}{(1+as)} \qquad (4.16)$$

Where:

as = the as-recycle
N_C = the nitrification capacity, as calculated earlier in this chapter

a_{opt} values were determined for both the standard ($K'_{2(20)}$ = 0.145mgN/ℓ) and adjusted ($K'_{2(20)}$ = 0.216mgN/mgCOD/d) theoretical D_{PP} values and are presented in Table 4.11:

- a-opt values for D_{PP} predicted (pred.) = $N_{nL\ pred.}$ were very low, 1.2, in comparison to the measured a-recycle values in the system of 3.45:1. However this is clearly influenced by the $D_{PP\ pred.}$ values which were substantially lower than the D_{PP} values measured.
- Calculating a_{opt} with $D_{PP\ pred.}$ adjusted by increasing $K'_{2(20)}$ to 0.216mgN/mgCOD/d gives a higher a_{opt}, 2.5:1, which is much closer to the measured a-recycle (a_{msrd}).
- The average measured D_{PP} and N_{nL} in the anoxic reactor were very close, 58.1mgN/ℓ and 58.6mgN/ℓ respectively which corresponds closely with the measured anoxic NO_3 concentration of 0.5mgN/ℓ which would be the difference between the two. This indicates that on average the a-recycle was operating very close to, or just above the theoretical a-opt recycle.

4.10.4 Effluent Nitrate Concentration

At $N_{nL} \leq D_{PP}$ in the MBR UCT configuration the effluent NO_3 concentration (N_{ne}) is given by Equation 4.10. With Equation 4.10 N_{ne} is calculated for each sewage batch with the theoretical a_{opt} and a_{msrd}. As noted above, measured anoxic reactor NO_3 concentrations were negligible indicating that on average $N_{nL} \geq D_{PP}$, but only marginally so (anoxic NO_3 = 0.5mgN/ℓ). Measured and predicted N_{ne} values are listed in Table 4.11.

- At a_{opt} = 1.2 a very high N_{ne} is calculated of 40.0 mgN/ℓ, which is reasonable since at this a-recycle far less NO_3 is recycled to the anoxic reactor for denitrification. However, using the higher a_{opt} = 2.5 calculated with the increased K'_{2T} gives a lower N_{ne} = 23.1mgN/ℓ, which is far closer to the N_{ne} observed below.
- At the measured a-recycle ratio, the measured and predicted N_{ne} values are very close, 17.5 mgN/ℓ and 17.0 mgN/ℓ respectively. This is expected since the measured and predicted N_C values are close and effectively the same a-recycle value applies to both. This does however provide indirect confirmation of the value accepted for the a-recycle ratio.

4.10.5 Theoretical BEPR Performance

In order to simulate the theoretical BEPR performance of the MBR system, the steady state design model of Wentzel *et al.* (1990) was used. The model required the readily biodegradable COD (RBCOD) concentration of the influent sewage to be known. This was measured in a separate system set up specifically for this purpose (Ekama *et al.*, 1986) described in Section 4.3. Other waste water characteristics required as input to the model were obtained from the averages of the measured values for each sewage batch period (S_{ti}) as well as from the estimated $f_{S,us}$ and $f_{S,up}$ values for these periods (Section 4.4.5). Operational parameters (Q_i, R_S, anaerobic mass fraction, r-recycle ratios) required in the model were also taken from batch average values, and the default kinetic and stoichiometric constants of Wentzel *et al.* (1990) were accepted. The design model equations have not been included in the text but are as in Wentzel *et al.* (1990).

In the steady state design model of Wentzel *et al.* (1990), PAO active mass has a higher P content to account for the polyphosphate stored by these organisms, expressed as a fractional P content, f_{XGBP}, in mgP/mgVSS. Wentzel *et al.* (1990) assigned a value of f_{XGBP} = 0.38 mgP/mgVSS to this constant. This was based on the P removal response observed in BEPR systems with predominately aerobic P uptake, and has been confirmed in subsequent model applications to investigations with similarly dominant aerobic P uptake (Hu *et al.*, 2002). However, in applications of the model to systems with anoxic P uptake, to account for the lower P removal observed in these systems, Ekama and Wentzel (1999) found that the value for f_{XGBP} had to be reduced significantly, into the range of 0.1 to 0.26 mgP/mgVSS (Hu *et al.*, 2002). Since anoxic P uptake was observed in the MBR UCT system here, a similar reduction in f_{XGBP} was expected. Accordingly, for each sewage batch the value for f_{XGBP} was varied to match the model predicted P removal to that measured, see Fig. 4.37.

- The results varied considerably from sewage batch to sewage batch with a range of 0.153 – 0.425 mgP/mgVSS and an average of 0.303 mgP/mgVSS for the different sewage batches. Up to sewage batch 22 no explicit relationship between anoxic P uptake and the f_{XBGP} value could be discovered, probably due to the sewage batch periods being shorter than the sludge ages, and the increase in P removal towards steady state noted above. From sewage batch 22, as the anoxic uptake increased, the f_{XBGP} value decreased, and *visa versa*, in conformity with the observations of Ekama and Wentzel (1999).
- Using the average f_{XBGP} = 0.303 mgP/mgVSS, the model was used to predict P removal, Table 4.11 and Figs. 4.38 and 4.39. Overall the predictions are reasonably close to the measured values.

Table 4.11: Comparison of measured and predicted P release, P uptake and P removal, and the fraction P content of PAOs (f_{XBGP}) for the MBR system, and the % differences

Sewage	P-release			P-uptake			P-removal			fxgbp
Batch #	meas	pred	%dif	meas	pred	%dif	meas	pred	%dif	
	(mgP/l)	(mgP/l)		(mgP/l)	(mgP/l)		(mgP/l)	(mgP/l)		
2	-138.9			133.1			-5.8	6.9		
3	-159.8	-164.7	3%	182.6	197.4	7%	22.8	32.7	30%	0.24
4	-110.5	-136.5	19%	127.8	164.1	22%	17.3	27.6	38%	0.205
5	-93.2	-154.4	40%	110.4	185.4	40%	17.2	31.6	45%	0.165
6	-89.7	-126.6	29%	112.1	153.8	27%	22.3	27.2	18%	0.287
7	-134.6	-119.4	-13%	153.3	144.2	-6%	18.7	24.8	25%	0.25
8	-123.2	-121.6	-1%	141.7	125.6	-13%	18.5	22.1	16%	0.29
9	-108.9	-140.2	22%	129.2	169.7	24%	20.3	29.5	31%	0.225
10	-113.5	-144.3	21%	134.0	175.2	23%	20.5	30.2	32%	0.223
11	-112.8	-131.6	14%	127.9	159.2	20%	15.0	27.6	45%	0.153
12	-107.8	-101.5	-6%	129.7	123.8	-5%	21.9	22.3	2%	0.37
13	-143.6	-131.3	-9%	167.3	157.7	-6%	23.8	26.3	10%	0.33
14	-114.3	-97.8	-17%	138.0	126.3	-9%	23.7	22.1	-7%	0.42
15	-124.0	-105.3	-18%	143.4	136.1	-5%	19.4	24.3	20%	0.275
16	-128.4	-116.8	-10%	153.4	143.1	-7%	25.0	25.5	2%	0.37
17	-121.4	-95.4	-27%	147.7	135.6	-9%	26.4	24.6	-7%	0.42
18	-114.3	-123.1	7%	141.1	147.5	4%	26.8	25.6	-5%	0.405
19	-100.1	-135.2	26%	130.6	161.3	19%	30.4	28.9	-5%	0.405
20										
21										
[redacted]	-104.0	-132.4	21%	130.7	152.9	15%	26.6	26.0	-2%	0.39
23	-127.0	-125.9	-1%	150.5	151.9	1%	23.5	26.0	10%	0.335
24	-135.5	-110.7	-22%	158.3	128.3	-23%	22.9	21.2	-8%	0.425
25	-117.2	-145.0	19%	145.0	173.1	16%	27.8	28.0	1%	0.375
26	-136.5	-149.1	8%	158.0	184.9	15%	21.5	30.3	29%	0.24
27	-128.7	-135.8	5%	149.9	163.7	8%	21.2	27.9	24%	0.26
28	-144.2	-127.4	-13%	163.9	182.2	10%	19.7	31.5	37%	0.193
29	-112.8	-143.4	21%	139.2	179.2	22%	26.3	30.2	13%	0.315
Average	-120.2	-128.6	5%	142.6	156.9	8%	22.4	27.0	16%	0.303

- There was a steady increase in P removal from the beginning of the investigation to sewage batch 18 (Fig. 4.40). As noted in Section 4.9.3 this possibly indicates the development of the slow growing PAO population in the system, which would suggest that the system PAO population had not reached steady state until around sewage batch 18. Thus, for this period the model overpredicted the measured values.
- From Fig. 4.40 it is evident that there is a period in the middle of the investigation, from sewage batches 12 – 25, where the predictions and the measured values correspond very closely. The calculated f_{XBGP} for this period alone is 0.376 mgP/mgVSS, which is very close to the value used in the predictions of 0.38 mgP/mgVSS.
- From sewage batch 25 to the end of the investigation predicted and measured P releases correspond closely (Fig. 4.38), but predicted P removals are

significantly higher than those observed (Fig. 4.40). During this period, observed anoxic P-uptake increased (Fig 4.37) which would cause the reduction in P-removal.

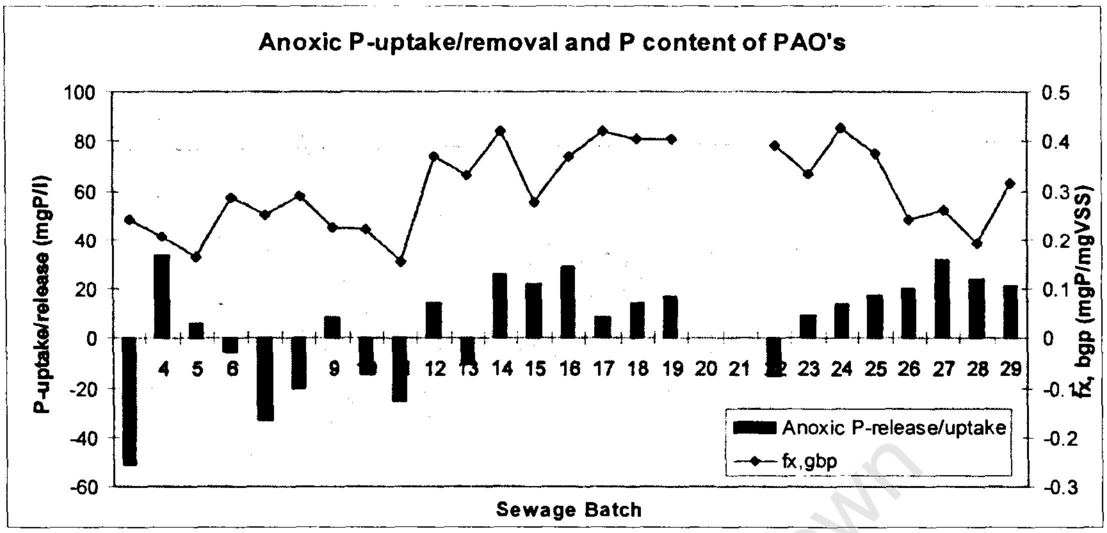


Figure 4.37: *The P content of PAO's (f_{XBGP}) and the P-update/release from the anoxic reactor.*

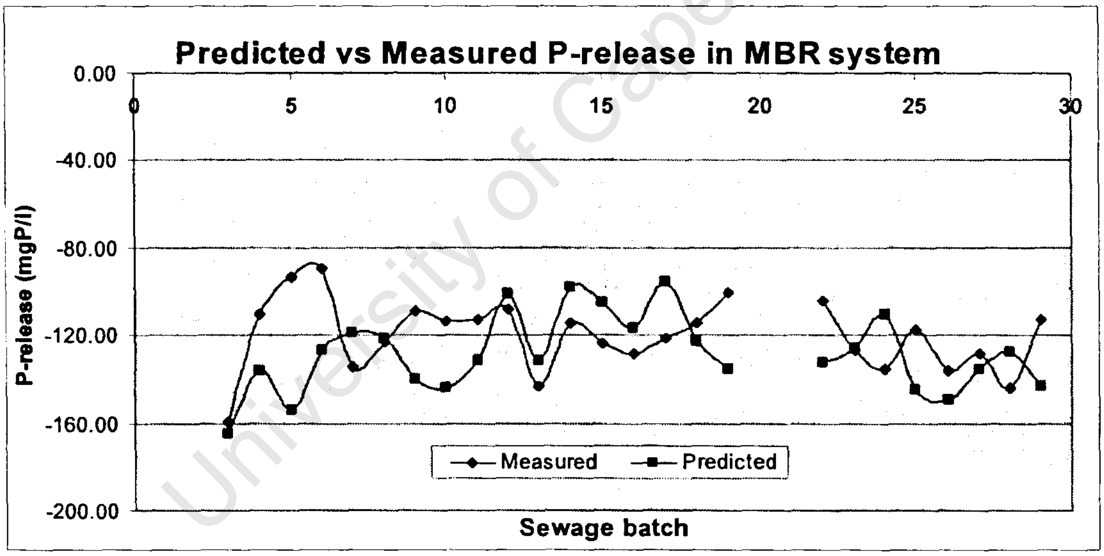


Figure 4.38: *Comparison of predicted and measured P release in the MBR system using f_{XGBP} = 0.38.*

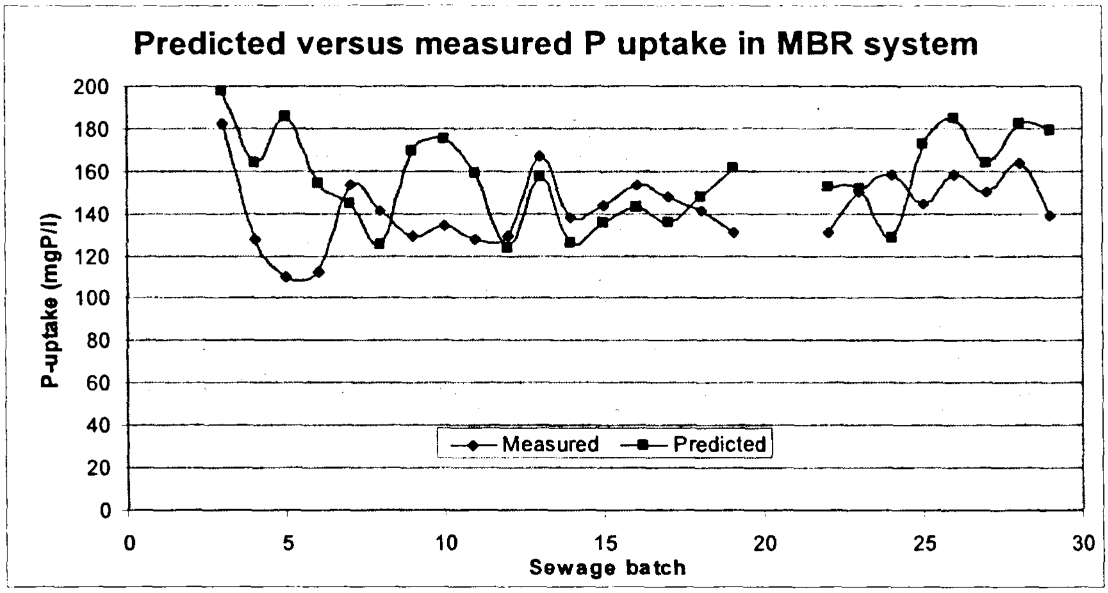


Figure 4.39: *Comparison of predicted and measured P uptake in the MBR system using f_{XGBP} = 0.38*

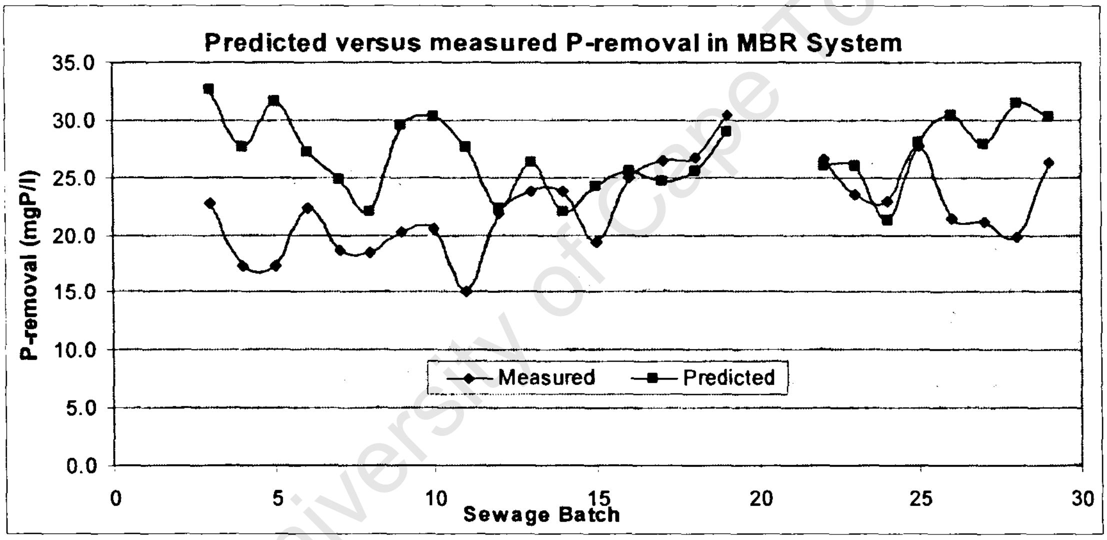


Figure 4.40: *Comparison of predicted and measured P removal in the MBR system keeping f_{XBGP} = 0.38*

4.11 LONG SLUDGE AGE (40 DAY) INVESTIGATION

4.11.1 Introduction

Following on from the Phase 2 investigation the sludge age of the MBR UCT system was increased to 40 days by adjusting the influent flow and sludge waste flows in order to maintain an MLSS concentration of approximately 18000mgTSS/ℓ. The system was operated and run by a BSc student, Muhimba *et al.* (2006) as partial fulfilment of his BSc (Eng) degree and results observed are reported here.

The observations of high sludge production and high calculated $f_{S,up}$ values in Phase 2 of the investigation were of concern to the writer, hence it was proposed to run the system at a high sludge age in order to accent the sludge production in order that comparative observations could be made. In order to allow such a comparison all operational and design parameters were kept the same apart from the influent feed and sludge waste flows. Once steady state had been reached (after two sludge ages) the system was monitored for four sewage batch periods. The system data is presented in Appendix G.

4.11.2 MLSS

All sampling and testing was conducted as in Phase 2, (Chapter3, Section 3.5). On average a system sludge age of 39.5 days was achieved through controlled wasting from the aerobic reactor. Unexpected sludge loss did occur, however volumes lost were calculated and incorporated into the sludge wasting.

System MLSS concentrations varied considerably with ranges of 5000-7000mgTSS/ℓ, 12000-17000mgTSS/ℓ and 15000-20000mgTSS/ℓ reported for the anaerobic, anoxic and aerobic reactors respectively. System VSS/TSS ratios were consistent within each reactor with 0.85mgVSS/mgTSS, 0.82mgVSS/mgTSS and 0.80 mgVSS/mgTSS reported for the anaerobic, anoxic and aerobic reactors respectively. These values are close to those reported in Phase 1 (Ramphao *et al.* 2004) and Phase 2. Initial f_{CV} values were low (1.18 and 1.22 for sewage batches 1-2) however in sewage batches 3-4 f_{CV} values of 1.46 and 1.42 were obtained which are far closer to the expected f_{CV} values. Similarly TKN/VSS values were particularly low for the first two sewage batches (0.077 and 0.072), but increased to values comparable to those in Phase 2 in the second two batch periods (0.095 and 0.090). These values indicated that MLSS concentrations were inconsistent in the first two sewage batches and only sewage batches 3-4 should be used for further analysis

A sludge production for the system was determined as (18.8mgVSS/d) /(mgCOD/d). This value is substantially lower than sludge productions reported in Phase 1 and 2 of the project of 0.32 and 0.31 respectively. However a lower sludge production is expected for a longer sludge age as more sludge is degraded and COD is converted to CO_2 through longer aeration.

4.11.3 Mass Balances

As a check for the accuracy of analytical measurements mass balances were performed as set out in Appendix C. Table 4.12. presents a summary of the system N and COD mass balances. Mass balances from sewage batches 1-2 were poor indicating that these sewage batches should be interpreted with caution. However sewage batches 3-4 fell within the range of acceptable confidence interval for mass balances of 90-110% and can be used for further analysis with confidence. Thus the previous observations of poor analytical results from sewage batches 1-2 are cofirmed.

Table 4.12: *System N and COD mass balances for the MBR (Rs=40d) system.*

Sewage Batch #	% Nitrogen Balance	%COD Balance
1	**61%**	**88%**
2	**89%**	**92%**
3	**100%**	**106%**
4	**99%**	**99.23%**

4.11.4 System Removals

System removals were typically consistent with the removals reported in Phases 1 and 2 of the investigation.

COD removal

Consistently low effluent COD concentrations were observed with an average COD concentration of 31.1mgCOD/ℓ in the effluent. This value is lower than was observed in Phase 1 (35.5mgCOD/ℓ) and Phase 2 (41.2mgCOD/ℓ) and is attributed to the longer sludge age which may allow sufficient time to degrade COD otherwise considered unbiodegradable soluble.

N removal

High N removal was observed with investigation average effluent TKN and FSA concentrations of 1.9mgN/ℓ and 1.0mgN-NH_4/ℓ respectively. Effluent nitrate concentrations of 20.7mgN-NO_3/ℓ and 0.9 mgN-NO_2/ℓ were reported. All reported values were close to those observed in Phases 1 and 2.

P removal

In order to assess P removal performance a P balance was set up across the system and is presented in Table 4.13. Only three sewage batch periods were evaluated due to difficulties with the spectrometer which measured P concentration. Clearly in this study anoxic P release was dominant over anaerobic P release which is unusual as both reactors were of similar size, RBCOD was present in the anaerobic reactor and NO_3 was present in the anoxic reactor. However similar P removals to those achieved in Phase 1 and 2 were reported indicating that good P removal is possible even at very long sludge ages in an MBR system. As was done in Phase 1 and 2 the f_{XBGP} required to match measured and predicted P removals was calculated and are also reported in Table 4.13. These values varied considerably. No reasons are proposed for the unusual P removal performance of the system in this period of the study.

Table 4.13: *Summary of P release (-ve) and P uptake (+ve) across the 40 day sludge age MBR system.*

Sewage Batch #	Influent	Anaerobic	Anoxic	Aerobic	Membrane	M (P-PO4) removal	fxbgp
	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf	-
2	45.0	-58.8	-81.3	167.5	4.0	31.4	0.53
3	37.2	-41.6	-81.7	130.3	11.9	18.8	0.22
4	44.5	-58.8	-60.0	141.3	2.9	25.4	0.44

4.11.5 Influent unbiodegradable COD fractions and sludge production

The primary reason for conducting this study at a longer sludge age was to further investigate the high sludge production and $f_{S,up}$ values observed in Phase 1 and 2. Due to the lower effluent COD concentrations the $f_{S,us}$ value calculated for the 40 day sludge age investigation, of 0.029, was lower than that calculated for Phase 1 and 2 of the investigation. Additionally the $f_{S,up}$ determined of 0.113 was consistently lower than that observed in Phase 1 and 2 of 0.224 and 0.200 respectively.

A number of reasons are proposed for these differences. Firstly this investigation was performed over a short period of time (6 weeks), the equivalent of one sludge age, which is not enough time to draw conclusions on the system performance. Additionally, though the consistent $f_{S,up}$ values calculated indicate that the system was at steady state, the system did experience frequent sludge losses due to spills and may have not actually achieved steady state resulting in low $f_{S,up}$ values.

4.12 CLOSURE

In this section the MBR UCT system performance has been evaluated through detailed analysis of the data obtained from measurements on the system, and through application of steady state design theory to the system. It has been shown that the current steady state design models are indeed adequate for design of MBR BNR systems.

The results of the conventional system, which was used as a control against which to compare the impact of the membranes on the BNR performance of the MBR system are analysed in Chapter 5. Chapter 6 compares the performances of the two systems in order to elucidate the relative performance of the MBR BNR system.

CHAPTER 5

CONVENTIONAL UCT SYSTEM EXPERIMENTAL RESULTS AND ANALYSIS

5.1. INTRODUCTION

The conventional UCT system was operated as a control against which the BNR performance of the MBR UCT system could be evaluated. Both systems were run, as close as possible, to the same design and operating parameters, see Section 3.3.2, Chapter 3. The major differences between the two systems primarily comprised the increased organic loading on the MBR system (3.1 times) in order to achieve higher mixed liquor solids concentrations necessary for operation; and the reconfiguration of the *a*- and *s*-recycles into the *as*-recycle as the SST had been replaced by membranes in the MBR system.

The same parameters as in the MBR system were measured to assess the performance of the conventional UCT system (see Section 3.5, Chapter 3). All experimental data for the conventional system collected in the Phase 2 investigation is presented in Appendix B. In this chapter the performance of the conventional UCT system is evaluated.

Overall the conventional system data failed to show sufficient stability and mass balances consistently failed to close. Hence, some parameters could not be used to calibrate the results observed in the MBR system. Thus, in order to meet the project objective of calibrating the MBR performance, results from previous studies are used instead. However the performance of the system is discussed and where possible the data is compared.

5.2. SYSTEM CONDITIONS AND STEADY STATE PERIODS

Sewage batches and days of operation were as for the MBR UCT system, Table 4.1, Chapter 4. The same approach followed for the MBR UCT system: to identify sewage batches as steady state periods, identify outliers, average sewage batches behaviour and evaluate the system from sewage batch averages, was followed for the conventional UCT system. Detailed daily results are listed in Appendix B.

As was noted in Phase 1, the measured system recycles corresponded closely with the design recycle values and did not vary during the investigation (Ramphao *et al.*, 2004). Accordingly, the expected recycle flow rates can be accepted for analysis. The RBCOD values calculated from the square wave (SQW) system described in Section 4.3, Chapter 4, are applied to this analysis also.

From the beginning of the investigation until sewage batch 15 the conventional system was operated by laboratory assistants while the writer focused his attention on the MBR system, and from day 236, sewage batch 15, the writer ran both systems entirely. Unfortunately a thorough record and understanding of system operation was not available prior to sewage batch 15.

5.3 MIXED LIQUOR SOLIDS

5.3.1 MLSS and MLVSS Concentrations

The Phase 2 investigation continued on from Phase 1 (Ramphao *et al.*, 2004). In the interim period between Phase 1 and Phase 2 the conventional UCT system had continued being operated and monitored by lab assistants, with the same design operation conditions, but no testing and analysis. Thus at the beginning of the investigation the system was assumed to be at steady state and testing could commence with immediate effect.

Variations of solids concentrations with time are reported in Figs. 5.1 to 5.3. In sewage batches 4 – 11 the solids concentrations varied sporadically, ranging from 3200 – 6700 mgTSS/ℓ before returning to a consistent range of 2500-3500 mgTSS/ℓ in the aerobic reactor. This variability was consistent in all three reactors suggesting that it is attributed to a systematic error in measurement over that period, which unfortunately was not noticed until sewage batch 11. Doubts over the validity of measurements in the initial period resulted in them being excluded from further analysis of mixed liquor characteristics.

In sewage batches 2, 3, 12 - 29 the mixed liquor solids concentrations remained consistently within the range 2500 – 3500 mgTSS/ℓ which is substantially lower than the expected range 4500 – 5500 mgTSS/ℓ (see Table 3.1, Chapter 3). Ramphao *et al.*, (2004) also reported lower solids concentrations in the system, 3500 – 5000 mgTSS/ℓ.

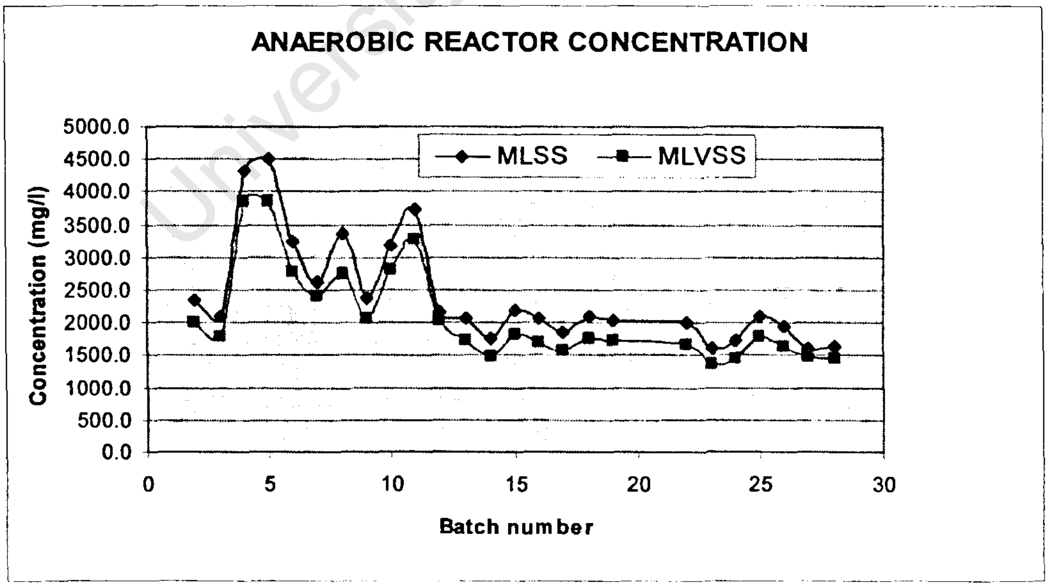


Figure 5.1: *Anaerobic MLSS/MLVSS concentrations with time*

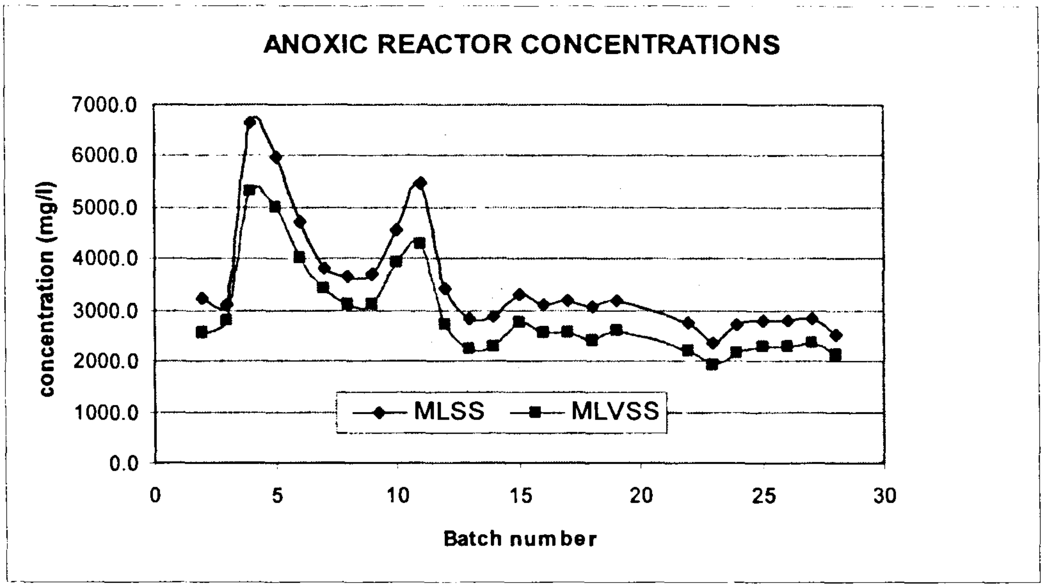


Figure 5.2: *Anoxic MLSS/MLVSS concentrations with time*

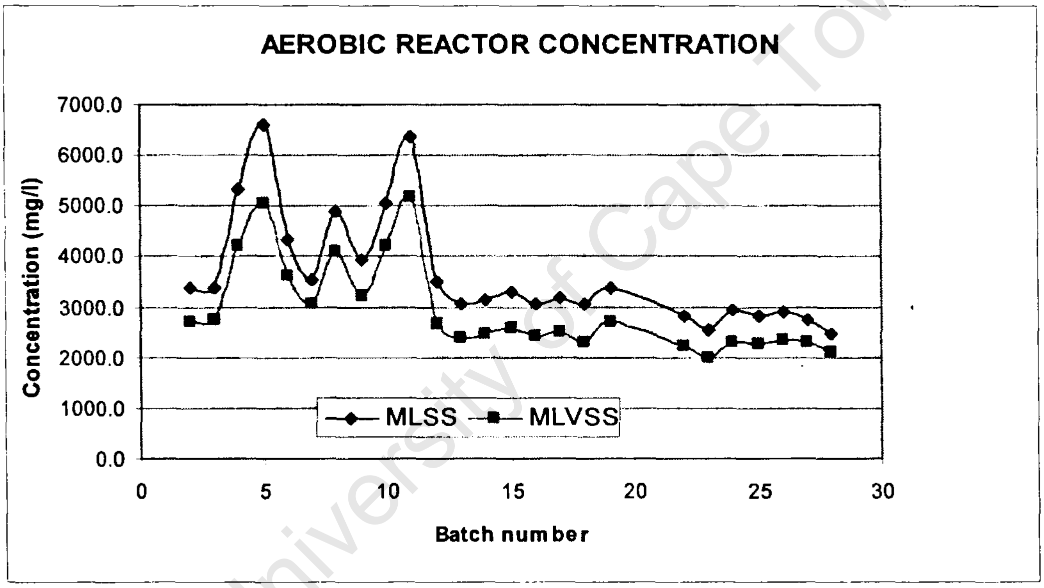


Figure 5.3: *Aerobic MLSS/MLVSS concentrations with time*

In an effort to improve solids concentrations in the conventional system 1.0 ℓ sludge from the membrane system waste stream was added to the conventional system to boost the solids content of the sludge at the end of sewage batch 18 (day 291). A minor increase was noticed in the following sewage batch, however on returning from a period of leave, the writer observed that the system mixed liquor solids concentration had decreased to even lower concentrations.

5.3.2 System VSS/TSS Ratios

As can be seen from Figs 5.1 to 5.3, the MLVSS tracked the MLSS values very closely. The VSS/TSS ratio of the sludge for each reactor is illustrated in Fig. 5.4. There was some variation in the VSS/TSS ratio for the first 11 sewage batches, however values generally remained consistent. VSS/TSS ratios of 0.85 mgVSS/mgTSS (anaerobic), 0.82 mgVSS/mgTSS (anoxic) and 0.81 mgVSS/mgTSS (aerobic) were measured across the system with a mean weighted average of 0.814 (SSD=0.027) mgVSS/mgTSS, Fig. 5.5, which is very close to that measured in Phase 1 with a mean = 0.817mgVSS/mgTSS (Ramphao *et al.*, 2004). Differences in VSS/TSS ratios between anaerobic, anoxic and aerobic solids are expected due to the PAO release and uptake behaviour.

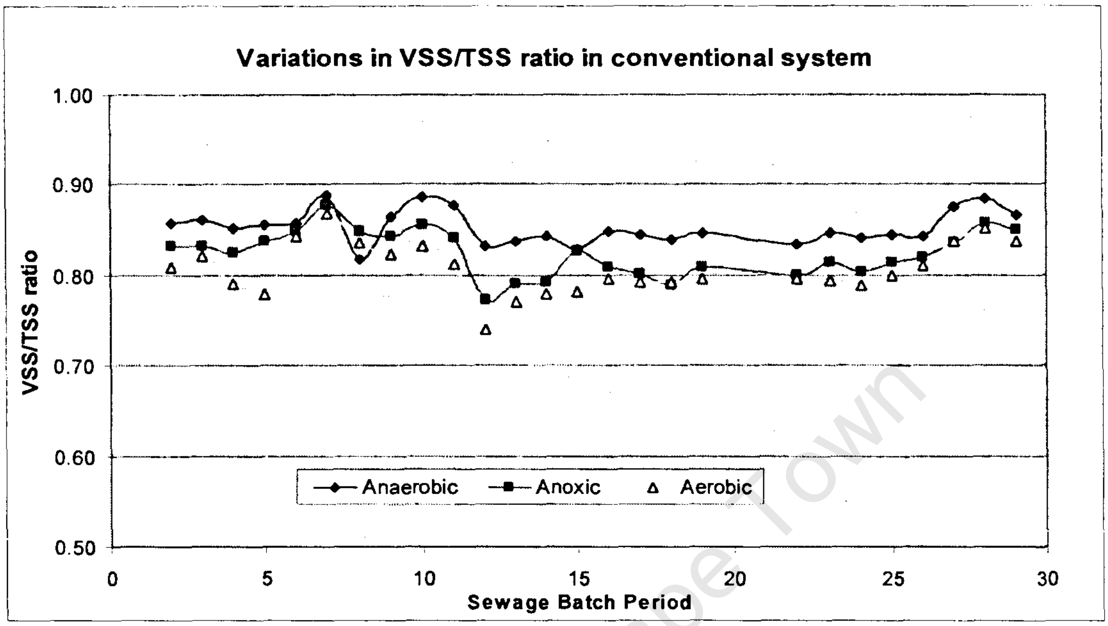


Figure 5.4: *Variations of VSS/TSS ratios in the conventional UCT system over time.*

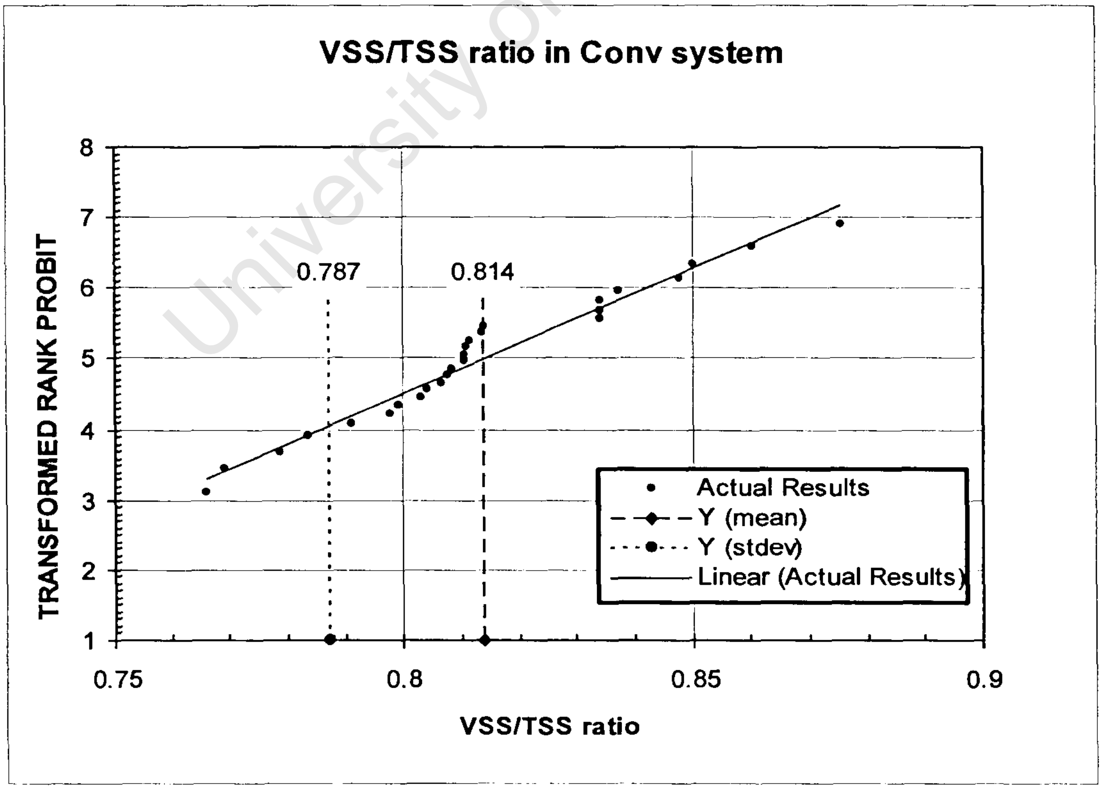


Figure 5.5: *Statistical plot of the sewage batch average VSS/TSS ratios in the system.*

5.3.3 COD to VSS Ratio (f_{CV})

The variations in VSS concentration in sewage batches 4 - 11 adversely affected the COD/VSS (f_{cv}) ratio providing evidence that the measured VSS values for this period were incorrect. Thus, to calculate the average f_{cv} only the sewage batch averages from sewage batches 2, 3, and 12 to 29 were taken into account.

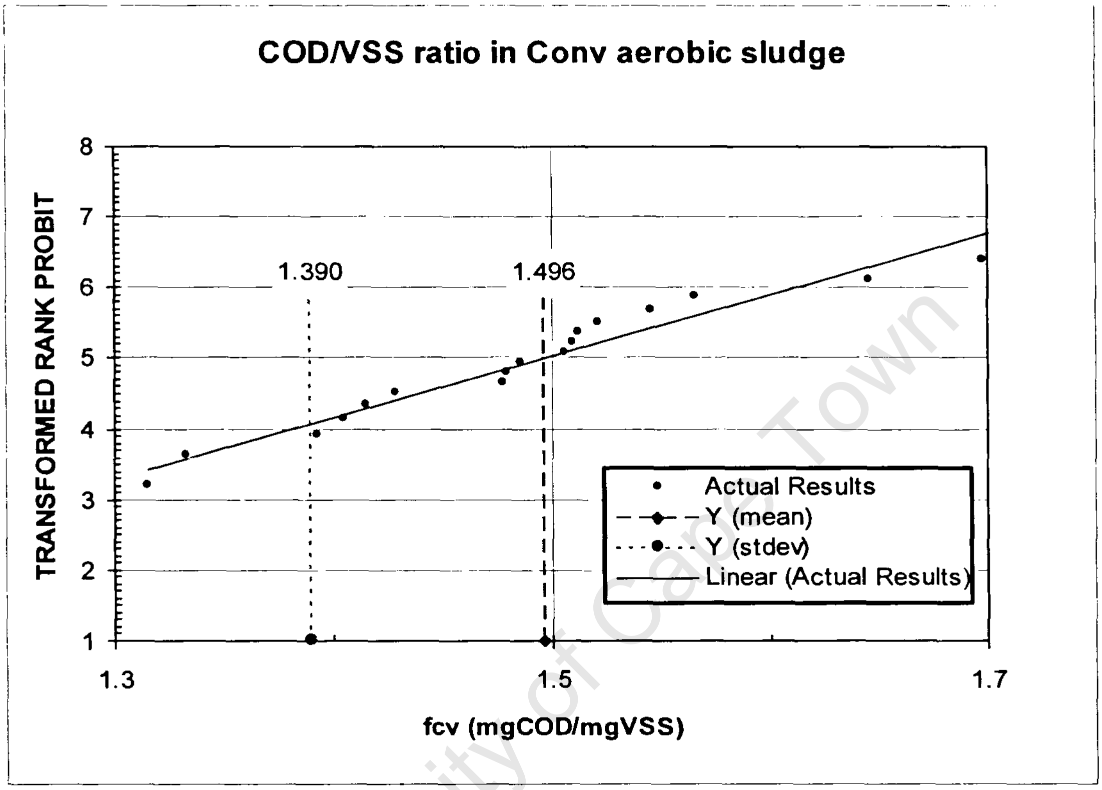


Figure 5.6: *Statistical plot of the sewage batch average COD to VSS ratios (f_{cv}) in the conventional UCT system.*

The mean average f_{cv} observed was 1.496 (SSD = 0.106) mgCOD/mgVSS, Fig. 5.6. This f_{cv} value is close to the commonly accepted value of f_{cv} of 1.48 (WRC, 1984) and is within the range of values (1.3 – 1.5) previously found in laboratory experiments in the Water Research Laboratory (WRL), (see Chapter 4, Section 4.6.3 for comparisons with other values). Ramphao *et al.* (2004) reported an f_{cv} of 1.36 in the conventional UCT system run in Phase 1 of the project.

5.3.4 TKN/VSS Ratio

The TKN/VSS ratios, like with the f_{cv} values, showed substantial deviations over sewage batches 4 to 11, again providing confirmation that errors lay with the VSS measurement in sewage batches 4 to 11. Taking the remaining data from batches 2,3,12 - 29 a normal distribution was observed with a mean of 0.094 (SSD = 0.009) mgN/mgVSS. This value is lower than that reported by Ramphao *et al.* (2004) of 0.113 mgN/mgVSS for the same system, but falls within the range of values noted in Chapter 4, Section 4.6.4, and is close to the value of 0.10 mgN/mgVSS commonly accepted for municipal waste-waters.

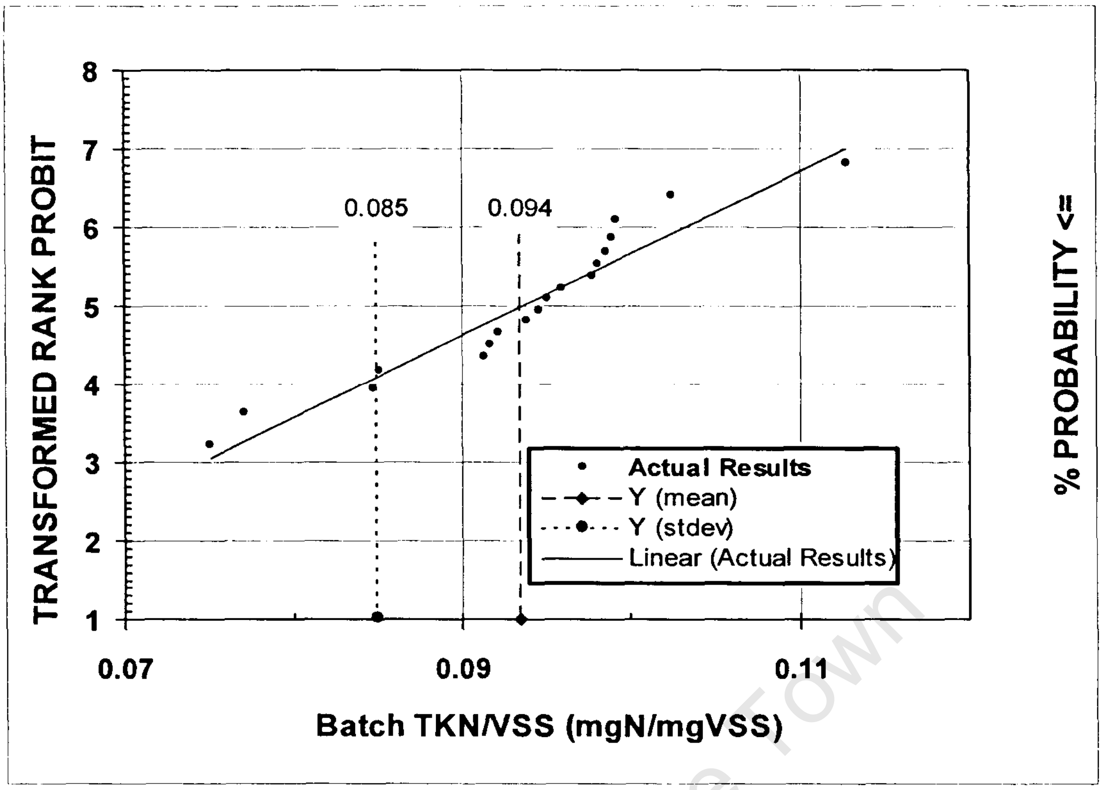


Figure 5.7: *Statistical plot of the sewage batch average mixed liquor TKN/VSS ratios in the conventional UCT system.*

5.3.5 Re-evaluation of VSS Values

As was noted earlier in this section there was substantial variation in the measured VSS results for sewage batches 4 to 11. This resulted in the measured VSS values from sewage batches 4 to 11 being discarded for analysis. However aerobic sludge COD and TKN values, also taken during this period remained consistent. Thus, theoretically the suspect VSS concentrations could be recalculated using either the COD or TKN values and their respective measured fraction f_{cv} or TKN/VSS, determined in Sections 5.3.3 and 5.3.4 above.

The VSS calculated from the sewage batch average aerobic COD concentrations and the calculated system average f_{cv} are presented in Fig. 5.8. Similarly VSS calculated from the sewage batch average aerobic sludge TKN concentration and system average TKN/VSS results are presented in Fig 5.9.

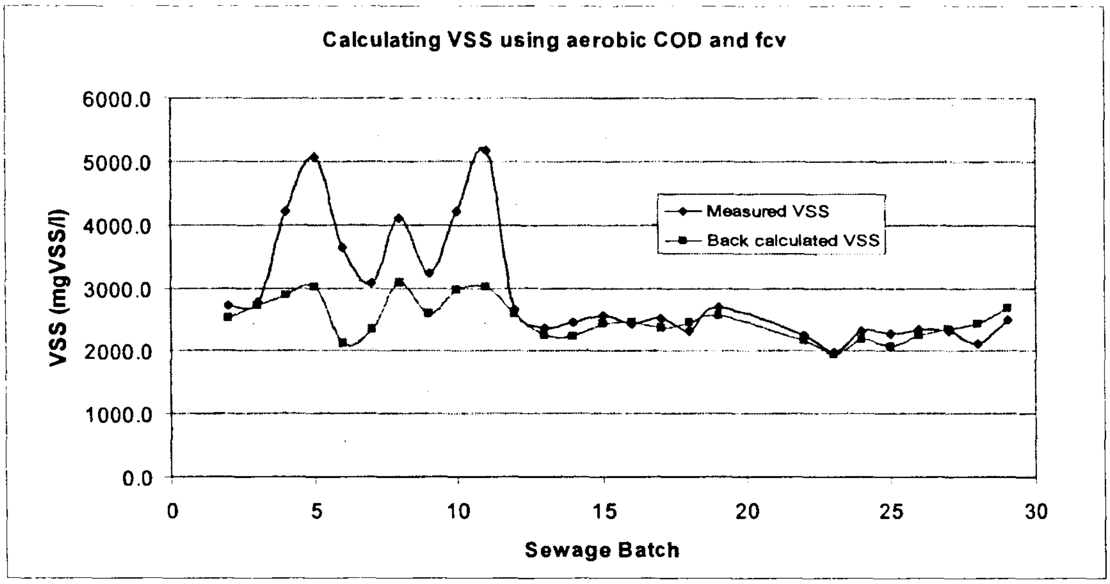


Figure 5.8: *The measured and predicted VSS concentrations in the aerobic reactor using the aerobic COD concentration and average fcv*

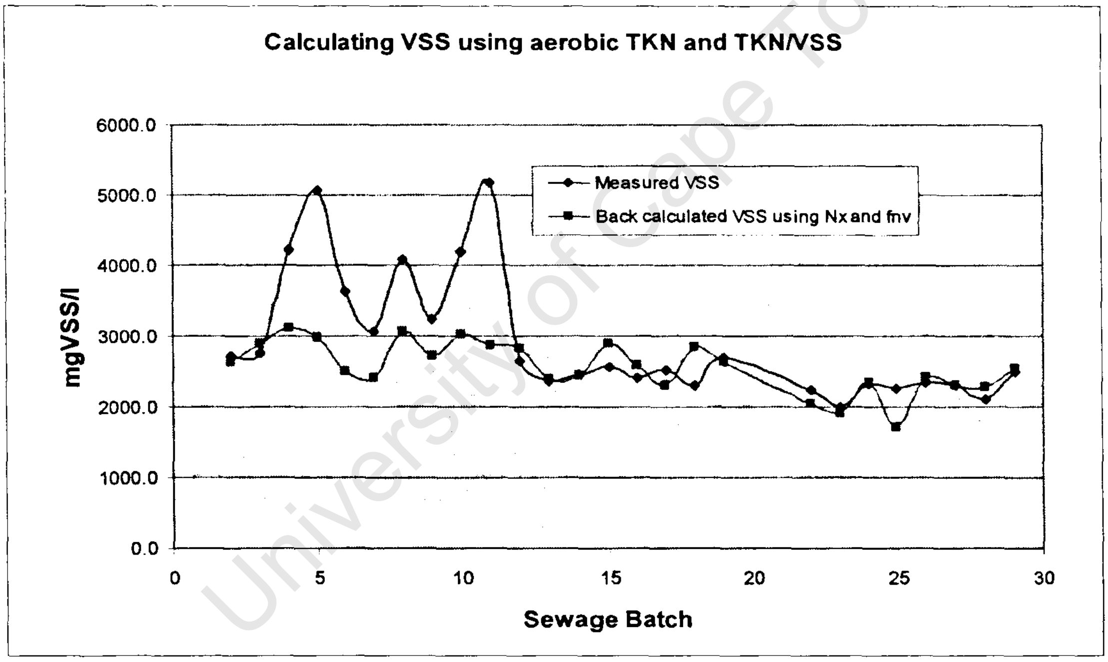


Figure 5.9: *The measured and predicted VSS concentrations in the aerobic reactor using the aerobic TKN concentrations and average TKN/VSS.*

- Both sets of results presented in Figs. 5.8 and 5.9 indicated that the solids concentrations should have remained consistently in the range of 2000 – 3000 mgVSS/ℓ. The COD predictions seemed to track the measured values closer than the TKN predictions, thus demonstrating its applicability in predicting solids concentrations.
- Hence, for all further analysis MLVSS values are used calculated using mixed liquor COD concentrations instead of the direct MLVSS measurements.

5.3.6 Sludge Production

In order to quantify the sludge production in the conventional UCT system Equations (4.8) and (4.9) (Chapter 4) were used. As discussed in Section 5.3.5 above, the measured VSS values were re-evaluated and all further analysis would use the MLVSS values calculated from the mixed liquor COD measurements as these predicted measured VSS in sewage batches 13 – 29 more closely. Using the COD calculated MLVSS values the sludge production in the conventional UCT system ranged from 0.145 – 0.311mgVSS/mgCOD with a mean sludge production of 0.205mgVSS/mgCOD (SSD = 0.036). This result differs significantly from that reported for the MBR system in Chapter 4 Section 4.3.6 of 0.311mgVSS/mgCOD, but is close to the results reported for the conventional UCT system in Phase 1 (Ramphao *et al.*, 2004) of 0.22mgVSS/mgCOD, and results of ND systems run at 20 day sludge ages using the same wastewater source: 0.20 (Ubisi *et al.*, 1997) and 0.18 (Lee *et al.*, 2002a). Note that these sludge ages are only valid for the 20 day sludge age of the MBR and conventional systems – difference sludge ages yield different sludge production rates.

5.3.7 Diluted Sludge Volume Index

The sludge settleability of the conventional system was monitored by means of the diluted sludge volume index (DSVI). Detailed results are presented in Appendix B, with the settleability trend during the investigation shown in Fig. 5.10. As was noted in Section 5.3.5 the VSS values used for the calculation of DSVI were calculated from the aerobic COD measurements.

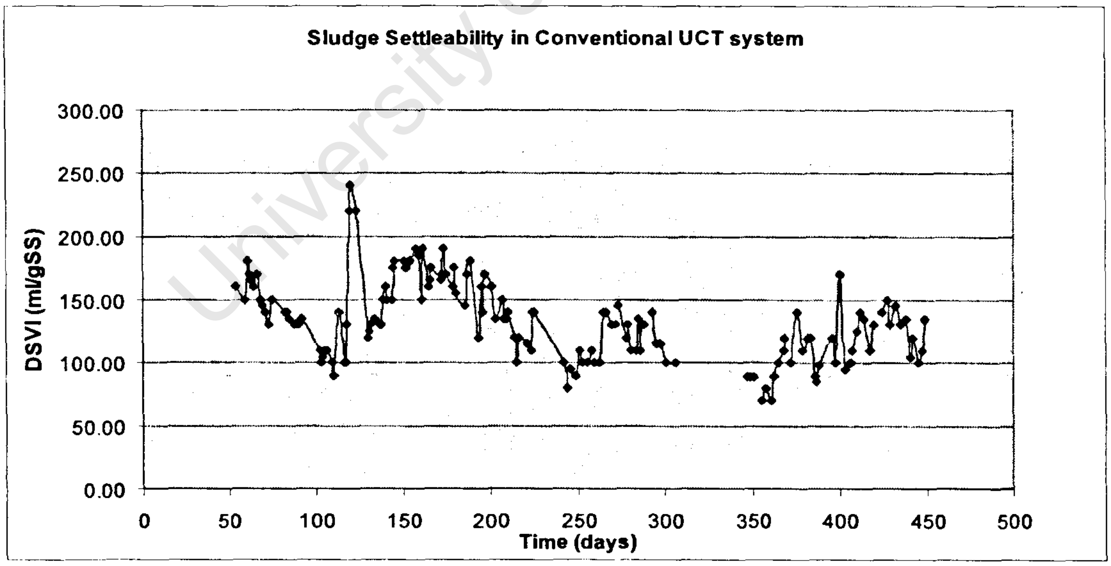


Figure 5.10.: *General trend of diluted sludge volume index (DSVI).*

Although DSVI records were kept from the beginning of the Phase 2 investigation, observations on the system performance were only recorded by the writer when he took over operation of the system on day 236, sewage batch 15.

From the start of the investigation the DSVI ranged between 100 and 180. On day 119 aeration in the conventional system was blocked which may have resulted in a poor settling sludge developing over that period. From day 236 the DSVI increased from 100 to 150 ml/gTSS. Mixed liquor spills were recorded on days 280 and 281 and on day 286 high ammonia concentrations were noted in the effluent indicating poor aeration which may have caused the increase in DSVI over this period. On day 291 1.0 ℓ sludge from the MBR waste stream was added to the conventional system to boost the solids concentration. The MBR sludge showed improved settleability (see Section 4.6.6) which may have influenced the conventional sludge as evidenced by a drop in DSVI from 150ml/gTSS on day 291 to below 100ml/gTSS on day 309. Between days 374 and 383 the laboratory experienced regular power outages which affected system aeration and a similar increase in DSVI was noticed. On day 424 and the days immediately following the DSVI rose sharply to 220 ml/gSS due to no aeration in the sludge on that day, the level however returned to normal shortly thereafter.

In Phase 1 of the project a high DSVI (>>150 ml/mgSS) was noticed throughout the first 260 days, thereafter dropping to the range observed in this study.

Throughout the investigation filamentous organisms were present in the conventional sewage sludge, with a predominance of *Microthrix Parvicella* and *Type 0092* organisms. A summary of the microbiological analyses performed on the conventional system is presented in Table 5.1.

Table 5.1: *Microbiological analyses for the conventional system.*

CONVENTIONAL SYSTEM									
Date	Day #	Sewage Batch	Morfology floc	Floc diameter (µm)	Filamentous microorganisms			DSVI	observations
						Rank	Abundance		
2005-03-24	42	3	weak, irregular, diffuse	150-500	M.Parvicella Type 0092	2 1	2 4	n	n
2005-04-21	70	4	firm	150-500	M.Parvicella	1	5	167	n
2005-05-23	102	6	firm, irregular, diffuse	150-500	M.Parvicella Type 0092	2 1	2 3	172	n
2005-06-22	132	8	firm, irregular, diffuse	150-500	M.Parvicella Type 0092	2 1	2 3	128	n
2005-07-22	162	10	firm, round, compact	150-500	M.Parvicella Type 0092 Type 1701	2 1 3	3 4 2	198	n
2005-08-15	186	11	weak, irregular, diffuse	150-500	M.Parvicella Type 0092	1 2	2 2	191	n
2005-09-19	221	14	weak, irregular, diffuse	150-500	M.Parvicella Type 0092	1 2	3 1	115	n
2005-10-17	249	16	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	1 3	102	irregular feeding
2005-11-29	292	18	weak, round, compact	150-500	M.Parvicella Type 0092	2 1	2 4	131	high NH4 in effluent
2006-01-24	348	22	weak, irregular, diffuse	150-500	M.Parvicella Type 0092	2 1	2 3	101	n
2006-02-07	362	23	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	2 3	111	n
2006-02-28	383	24	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	3 3	133	Sludge loss through spills; power failures
2006-03-15	398	26	firm, round, compact	150-500	M.Parvicella Type 0092	2 1	3 4	122	n
2006-03-28	411	27	firm, round, compact	<150	M.Parvicella Type 0092	2 2	2 2	162	minor spill
2006-04-11	425	28	weak, irregular, diffuse	<150	M.Parvicella Type 0092	1 2	4 3	220	low solids, poor aeration
2006-04-25	439	29	weak, irregular, diffuse	<150	M.Parvicella Type 0092	1 2	2 2	134	n

5.4 MASS BALANCES

Mass balances were performed on the conventional UCT system data, as was done for the MBR system, in order to evaluate the accuracy and reliability of the data. The range of 90 – 110 % was considered to be acceptable for N and COD mass balances. The N and COD mass balances for the conventional system are shown in Table 5.2 and Figs. 5.11 and 5.12 respectively.

Table 5.2: *Nitrogen and COD mass balances for the conventional UCT system.*

Sewage Batch number	Percent N Mass Balance	Percent COD Mass Balance
	%	%
2	162.04%	60.86%
3	87.59%	87.48%
4	71.54%	122.00%
5	105.68%	82.38%
6	80.41%	62.95%
7	108.87%	123.92%
8	78.90%	118.37%
9	77.75%	97.92%
10	66.97%	92.31%
11	76.68%	99.71%
12	102.79%	70.01%
13	62.90%	85.67%
14	82.93%	72.12%
15	71.47%	75.09%
16	74.69%	73.85%
17	57.34%	87.05%
18	69.16%	73.78%
19	55.93%	75.16%
20	*no measurement*	*no measurement*
21	*no measurement*	*no measurement*
22	84.34%	70.56%
23	76.14%	77.89%
24	104.04%	101.26%
25	88.26%	84.47%
26	79.10%	67.13%
27	78.25%	78.87%
28	87.06%	50.97%
29	61.66%	68.52%
Average	**79.61%**	**78.20%**

5.4.1 Nitrogen Mass Balance

As can be seen in Table 5.1 and Fig. 5.11, nitrogen mass balances ranging from 55.9% to 108.9% were obtained giving an average N mass balance of 79.6% (excluding sewage batch 2) for the entire investigation. Sewage batch 2 is an outlier and was not taken into account in assessing the N mass balances. This average is substantially lower than the averages obtained in Phase 1 of the investigation and provides substantial uncertainty on the data. Most values fell below 100% indicating that there was a systematic error in one or more of the measurements which accounted for the low mass balances.

The mass balance measurement is independent of the direct VSS measurement as aerobic N and COD results are used directly to calculate N and COD removal through sludge wasting. Thus the error lay in TKN and nitrite/nitrate measurements, or operational parameters: influent flow (Qi), waste flow (Qw), or the a- and s-recycles.

Ramphao *et al.* (2004) reported a low, but adequate mass balance of 96% for Phase 1 noting that less nitrogen was accounted for as leaving than entering the system.

Of the nitrogen entering the system (comparisons with Ramphao *et al.*, 2004 are in brackets):

- 39.3 % left through the denitrification of nitrate/nitrite (37.9)
- 16.8 % left as nitrogen in the waste sludge (37%)
- 15.9 % left as effluent nitrite/nitrate (17.7%)
- 7.5% left as effluent TKN (2.8%)
- 20.4% is unaccounted for (4.6%)

From the above comparison the denitrification and effluent N values are comparable, however the N in the sludge wasted is substantially less. This could indicate that an error in the amount of sludge wasted daily is responsible for the poor N mass balances, or sludge losses regularly occurred that the writer was not aware of. It is important to notice however that the TKN/VSS value for Phase 1 (0.113, Ramphao *et al.*, 2004) was significantly higher than in Phase 2 (0.094) which would have greatly influenced the mass of N in the wasted sludge.

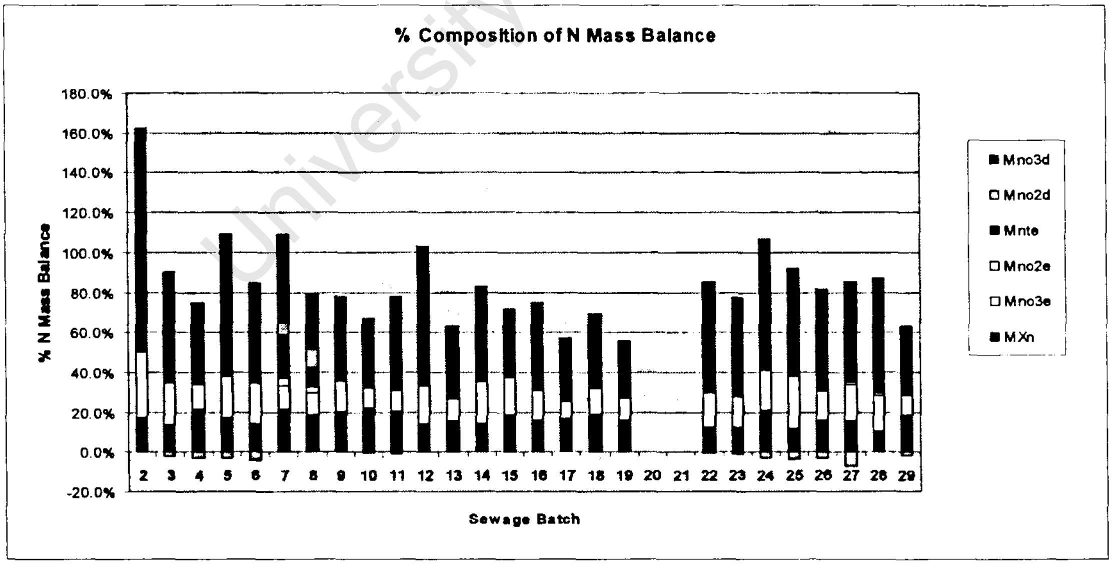


Figure 5.11: *Graphical representation of the percentage nitrogen (N) mass balance for the sewage wastewater batches for the conventional UCT system. Percentages shown are for nitrate for denitrification (MNO3d), nitrite for denitrification (MNO2d), TKN nitrogen in the effluent stream (Nte), effluent nitrite and nitrate (MNO2e) and (MNO3e) respectively and nitrogen in the waste stream (MXn).*

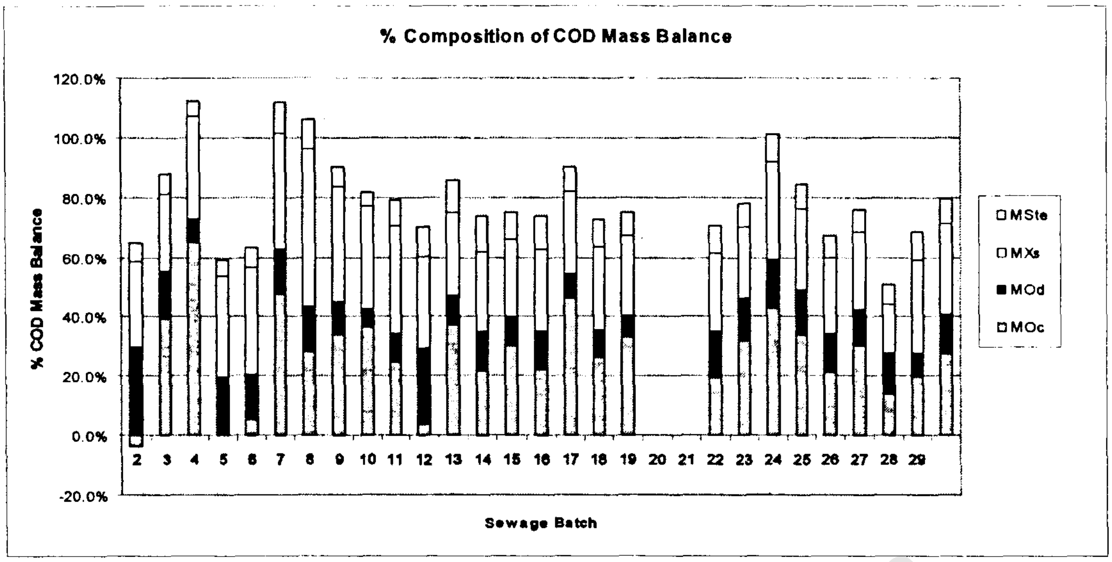


Figure 5.12: *Graphical representation for the percentage COD mass balance for the sewage wastewater batches for the conventional UCT system. Percentages are also shown for the COD in the effluent stream (MSte), COD in the waste sludge (MXs), equivalent oxygen demand for denitrification (Mod) and the carbonaceous oxygen demand (MOc).*

5.4.2 COD Mass Balance

As can be seen in Table 5.1 and Fig. 5.12, COD mass balances ranging from 51.0% to 123.9% were obtained, giving an average mass balance of 78.2% for the entire investigation. Again this result is substantially lower than that obtained in Phase 1, 87.1% (Ramphao *et al.*, 2004).

As with the nitrogen mass balances only a few sewage batch results fell above 100%, with the majority of values falling consistently lower indicating a systematic error in the measurements. This too was noted in Phase 1 where COD leaving the system could not be accounted for.

A comparison of the COD leaving the system relative to the COD entering follows with the values of Ramphao *et al.* (2004) in brackets:

- 28.7% is removed as oxygen consumed (45.2%)
- 12.9% is removed through denitrification (10.8%)
- 30.3% is removed through sludge wasting (26.4%)
- 8.2% is removed in the effluent flow as COD (4.7%)
- 20.6% is unaccounted for (12.9%)

From the above comparison the denitrification, sludge wasting and effluent COD give comparative removals, however OUR readings were substantially lower than those observed in Phase 1 (Ramphao *et al.*, 2004). Thus it is suspected that the measured OUR readings were regularly less than they should have been. This is explained by the lower sludge mass in the conventional system reported earlier. Additionally as noted above for the N-mass balance the unintentional loss of solids through spillages or inconsistent wasting may have resulted in the poor mass balances in the conventional system, as unaccounted for sludge loss would impact directly on mass balances.

5.5 INFLUENT UNBIODEGRADABLE COD FRACTIONS

The MLVSS concentrations observed in the system were substantially lower than those generated in the UCTPHO simulation (Dold *et al.*, 1991) using unbiodegradable soluble and particulate COD fractions of $f_{S,us} = 0.05$ and $f_{S,up} = 0.13$. This had been observed in the conventional UCT system in Phase 1 and prompted an investigation into the influent unbiodegradable fractions. Similarly an attempt to understand the low MLVSS concentrations of the conventional UCT system is presented here.

5.5.1 Unbiodegradable Soluble COD Fraction ($f_{S,us}$)

The unbiodegradable soluble COD fraction ($f_{S,us}$) is calculated on the assumption that all biodegradable COD in the system is utilized, thus only the unbiodegradable soluble COD remains in the effluent. $f_{S,us}$ with regard to the influent COD (sewage + acetate) was determined as in Chapter 4, Section 4.8.

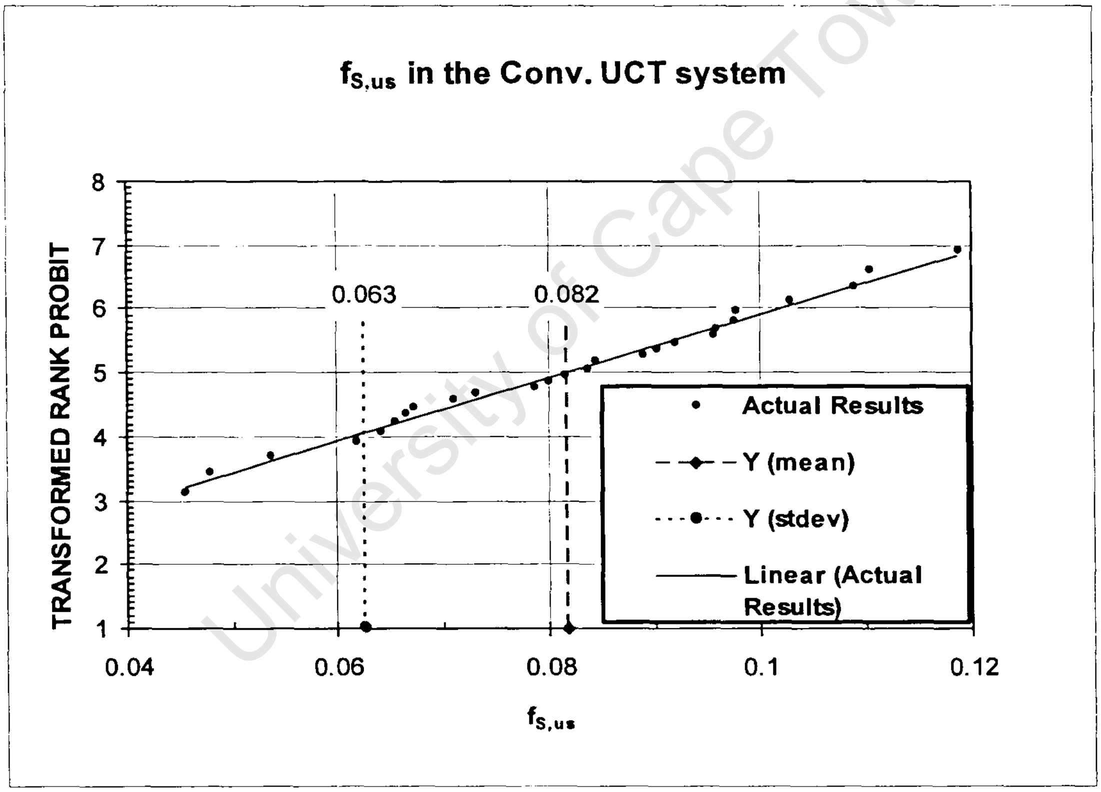


Figure 5.13: *Statistical analysis of the unbiodegradable soluble component of the raw wastewater.*

The average $f_{S,us}$ for each batch period was calculated from the corresponding batch influent and 0.45μm filtered effluent averages. The sewage batch average $f_{S,us}$ values are plotted on a linearized probability graph (Fig. 5.13) to check for normality. The data lie close to the true normal line indicating a normal distribution. The mean sewage batch average is 0.054 (SSD = 0.012), very close to $f_{S,us} = 0.058$ measured in Phase 1 (Ramphao *et al.*, 2004). Noting that 200mgCOD/ℓ in the influent was sodium acetate and hence completely biodegradable, and that the overall average total

COD is 951.2 mgCOD/ℓ, the raw wastewater $f_{S,us}$ = 0.068 before the addition of sodium acetate. This average falls within the range of typical values expected for raw domestic wastewaters in South Africa (0.04 to 0.10, WRC 1984) and compares favourably with values found by other researchers who used waste water from the same source: 0.085, Cronje *et al.* (2000); 0.09, Ubisi *et al.* (1997a,b); 0.075 Musvoto *et al.* (1992); 0.09, Mbewe *et al.* (1995) and 0.096, Muller *et al.* (2003).

5.5.2 Unbiodegradable Particulate COD Fraction ($f_{S,up}$)

The unbiodegradable particulate COD fraction ($f_{S,up}$) was calculated using the same method outlined for the MBR UCT system (Chapter 4, Section 4.8.2). The calculation is dependant on the system VSS mass (M_{Xv}) in the system, which as noted in Section 5.3 was calculated using the mixed liquor COD measurements. With the sewage batch average values for the conventional system applied directly into Equation (4.9) the $f_{S,up}$ results plotted in Fig. 5.14 were obtained.

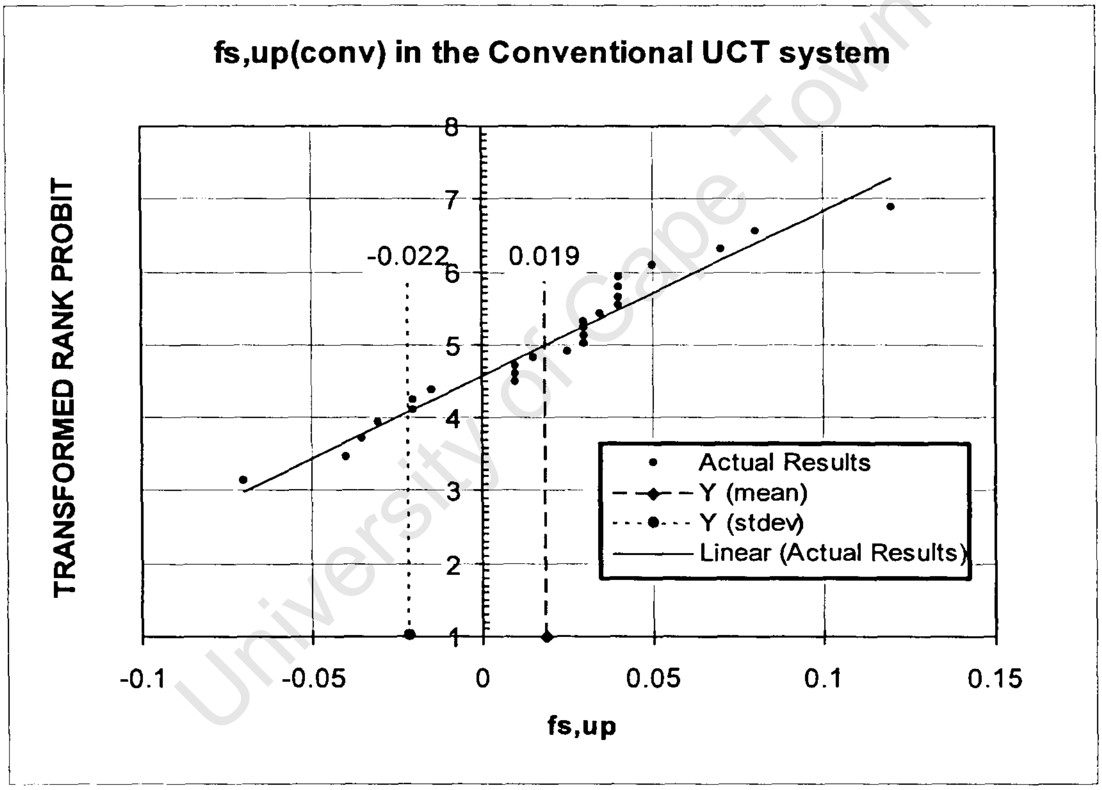


Figure 5.14: *Statistical plot of the $f_{S,up}$ values determined in the conventional UCT system.*

A mean value of $f_{S,up}$ = 0.019 (SSD = 0.041) was observed. This result is significantly lower than that expected from raw domestic wastewaters in South Africa, 0.07 – 0.20 (WRC, 1984) and corresponding values reported by other researchers using the same wastewater source: for aerobic (0.108, Mbewe *et al.*, 1995), MLE (0.135, Warburton *et al.*, 1991; 0.120, Ubisi *et al.*, 1997; 0.155, Mellin *et* al., 1998; 0.160, Beeharry *et al.*, 2001; 0.150, Lee et al 2002a), MUCT (0.15 Clayton *et al.*, 1991; 0.29 & 0.32 Musvoto *et al.*, 1992) and UCT (0.045 & 0.062 Sneyders *et al.*, 1998; *0*.067 Ramphao *et al.*, 2004) configurations. Such a low average $f_{S,up}$ value (and in some sewage batches negative values) indicates that the mass of VSS in the system (as measured via the COD) was comparatively much lower than for systems in which higher $f_{S,up}$ values were obtained.

An effort was made to try understand why the $f_{S,up}$ in the conventional system was so low, particularly in comparison to the MBR system which had a relatively high $f_{S,up}$ (0.20). Equation (4.9) is based on the assumption of a 100% COD mass balance, which as reported in Section 5.4.2 was not achieved in almost every sewage batch fed to the conventional system. The low COD mass balance could be taken into consideration in one of two ways:

- either it could be assumed that COD was lost from the system via the influent feed, in which case the reported influent COD was higher than the actual influent COD,
- or unaccounted for COD was lost from the system through increased uncontrolled sludge losses resulting in a shorter sludge age,

In the first instance, a reduced influent COD mass is assumed. Only the COD accounted for should be used as influent. This reduces the influent COD mass by 20% of the measured influent COD feed. This amounts to 3 ℓ of the 15 ℓ fed daily, which is a significant volume to lose without being able to account for it. Calculating the $f_{S,up}$ from influent COD mass gives an average $f_{S,up}$ of 0.125 (SSD = 0.074). A statistical plot of the results (Fig. 5.15) shows a relatively normal distribution.

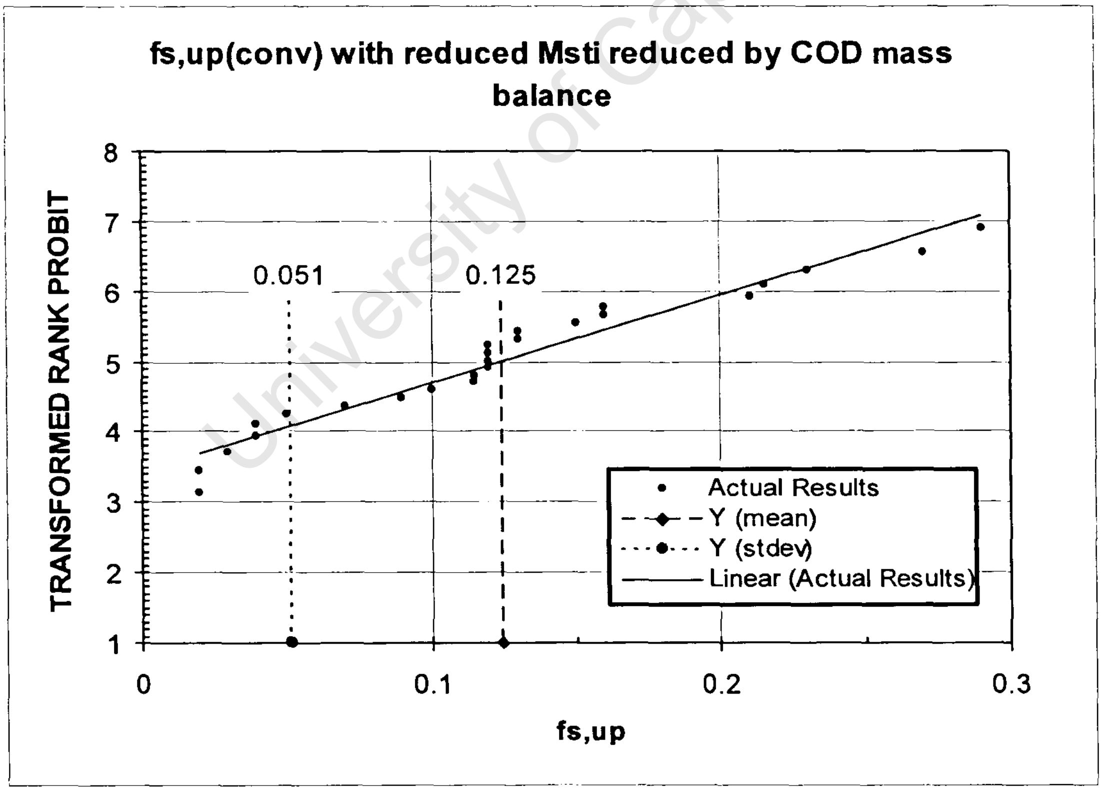


Figure 5.15: *$f_{S,up}$ calculated taking the COD-mass balance into consideration*

If it is accepted that the MS_{ti} measurements were correct then the remaining variable in Equation 4.9 is the sludge age. In order to achieve an overall COD mass balance of 100% a sludge age of 12.2d, or an additional 0.9 ℓ mixed liquor would need to have been wasted daily over and above the 1.1 ℓ already wasted. This too seems unlikely, though frequent sludge spills may have occured without the knowledge of the writer. These were dealt with by the laboratory assistant.

Alternative method of calculating $f_{S,up}$ for the conventional UCT system.

An additional investigation into alternative methods of calculating $f_{S,up}$ was conducted using the method described below:

The unbiodegradable fraction of influent COD ($f_{S,u}$) can be calculated as in Equation (5.1):

$$f_{S,u} = f_{S,us} + f_{S,up} \tag{5.1}$$

If $f_{S,u}$ is accepted to be an influent wastewater characteristic and is constant for both the MBR system and the conventional UCT system, then $f_{S,up}$ for the conventional system could be calculated as the difference between $f_{S,u}$ measured in the MBR system and $f_{S,us\ (0.45)}$ measured in the conventional system, (Equation 5.2). (It is assumed that the difference between $f_{S,us\ (0.45\ conv\ eff)}$ and $f_{S,us\ (membrane\ effluent)}$ is incorporated in the MBR $f_{S,up}$ fraction).

$$f_{S,up(\text{conv})} = \left(f_{S,up(\text{MBR})} + f_{S,us(\text{MBR eff})}\right) - f_{S,us(\text{conv})} \tag{5.2}$$

Using sewage batch averages for $f_{S,u}$ (MBR) and $f_{S,us}$ (conv) a new set of $f_{S,up}$ (conv) values were calculated, these are presented in a statistical plot, Fig. 5.16.

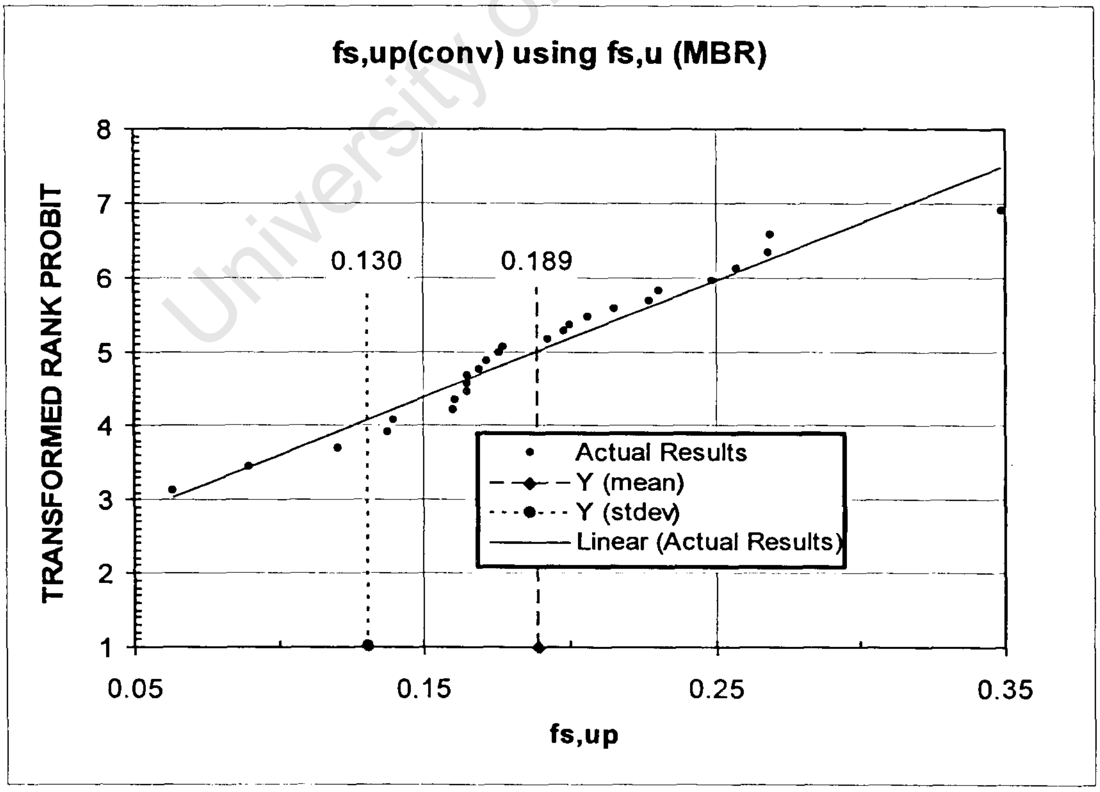


Figure 5.16: Statistical plot of recalculated $f_{S,up}$ values using the $f_{S,u}$(MBR) values.

If these values are applied back into the M_{Xv}/M_{Sti} equation (Chapter 4, Equation 4.9) and instead the sludge age (R_s, and consequently the waste flow, Q_w) or influent flow (Q_i) are used as variables then the equivalent variations in these parameters can be determined to suggest reasons for the poor COD balance in the conventional UCT system.

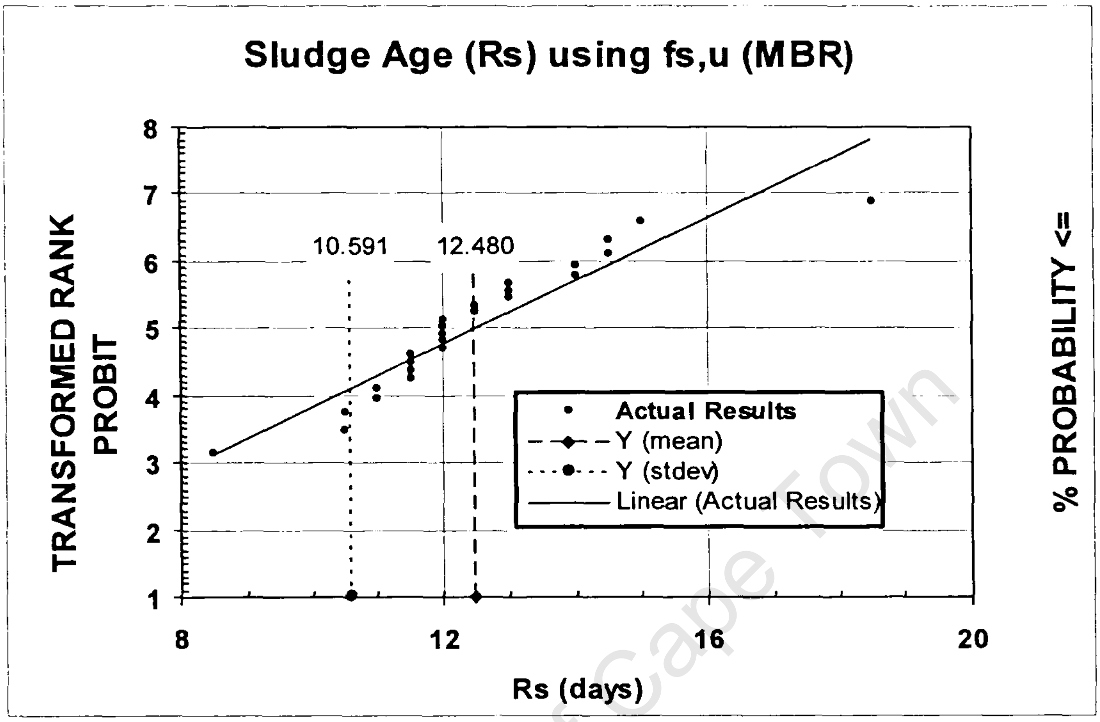


Figure 5.17: *Variations in sludge age as determined using $fs_{,up}$ calculated using MBR $fs_{,u}$*

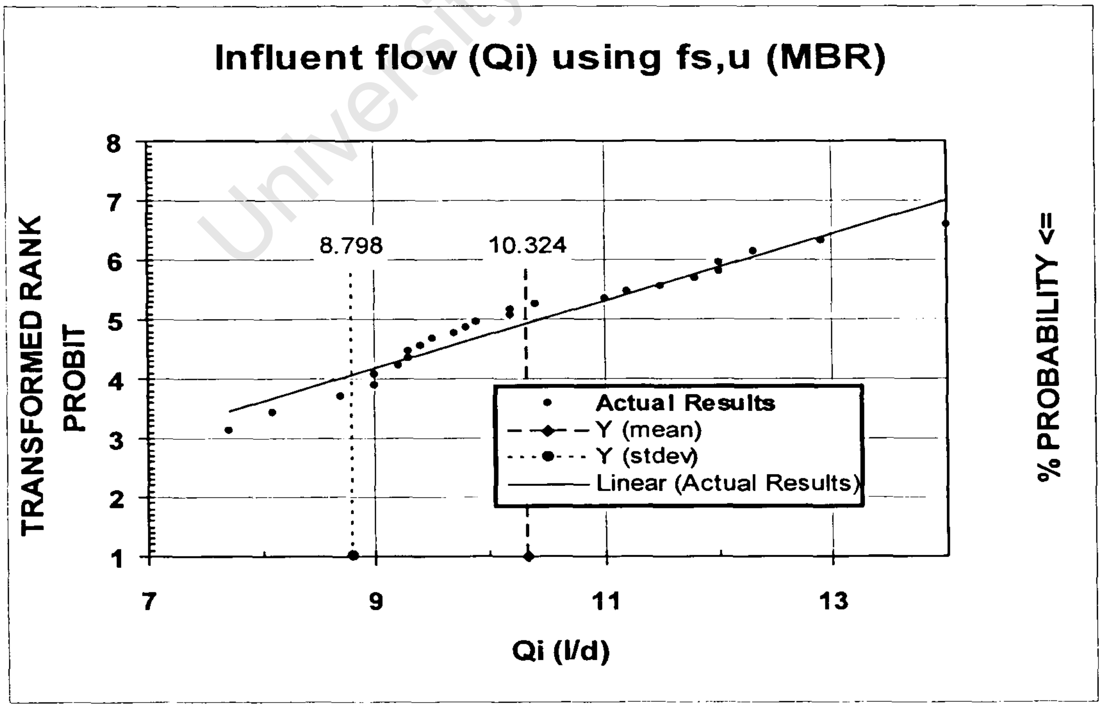


Figure 5.18: *Variations in influent flow as determined using $fs_{,up}$ calculated using MBR $fs_{,u}$.*

From the above investigation, in order for the $f_{S,up}$ in the conventional system to compare with the $f_{S,u}$ in the MBR investigation, the sludge age (R_s) of the conventional system would have to decrease substantially from 20 days on average to 12.5 days, or similarly the influent flow rate (Q_i) would have to decrease substantially from 15 ℓ/d to 10.3 ℓ/d.

The results from Phase 1 (Ramphao *et al.*, 2004) also indicated a significantly reduced $f_{S,up} = 0.067$ in the conventional UCT system, thus suggesting that the $f_{S,u}$ value is not the same for the MBR and conventional UCT systems as is assumed above. In Phase 1, the $f_{S,u}$ for the MBR system was 0.252 but for the conventional UCT system 0.125. Regardless it is concluded that unaccounted for sludge losses from the conventional UCT system resulted in poor mass balances and low $f_{S,up}$ values.

5.5.3 Revision of Sludge Production

The system sludge production is dependant on sludge age (R_s), COD (MS_{ti}) load on the system and influent COD characteristics. In Section 5.5.2 above, Rs and Qi values were proposed for the conventional system in accordance with revised COD mass balances. In order to determine the impact of these revisions on the system sludge production, the calculations of Section 4.6.6 are repeated below:

- With the revised sewage batch average R_s values above, the system sludge production ranged from 0.251 – 0.451 mgVSS/mgCOD, with a mean of 0.351 (SSD = 0.048). This value is higher than that observed in Phase 1, but is in the range of sludge production values expected for a sludge age of 12.5 days.

- Retaining the original system sludge age of 20 days and instead using the revised influent flow rate Q_i as determined above the system sludge production ranged from 0.239 – 0.429mgVSS/mgCOD, with a mean of 0.317 mgVSS/mgCOD (SSD = 0.049). This result is very close to that observed in the MBR UCT system of 0.311mgVSS/mgCOD.

5.5.4 Discussion

In this section difficulties with the calculation of the $f_{S,up}$ values for the conventional system have been presented. Reasons proposed for the unusually low $f_{S,up}$ values were a loss of COD from the influent, or an additional loss of sludge from the system. The writer was however unaware of either occurring. Due to the volumes lost in order to account for the decreased COD or sludge age it would appear that the loss of sludge was more likely, or a combination of the two occurred.

5.6 SYSTEM PERFORMANCE

5.6.1 COD Removal

Daily influent (S_{ti}) and effluent (S_{te}) COD concentrations are shown in Fig. 5.19. Both unfiltered and 0.45 µm filtered S_{te} values are presented.

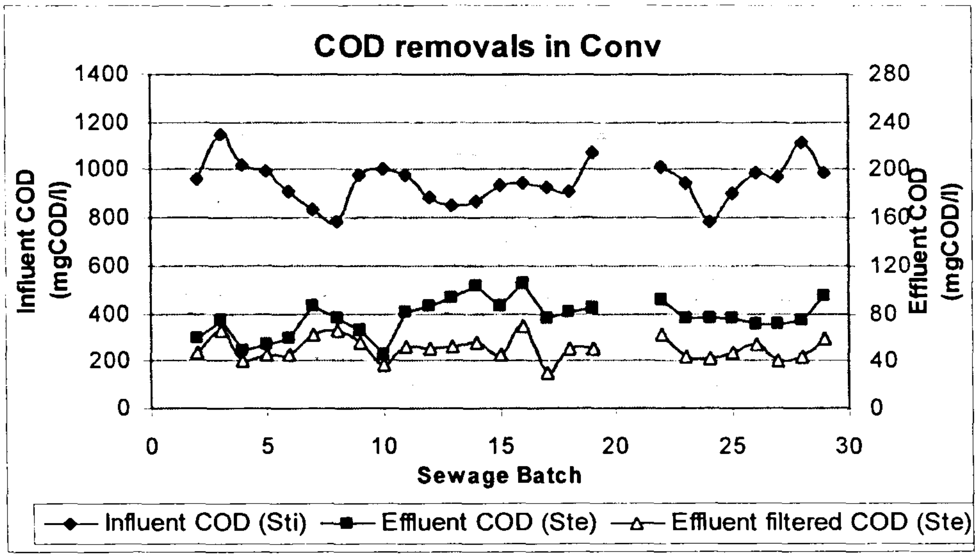


Figure 5.19: *Comparison of influent (S_{ti}), effluent unfiltered and effluent unfiltered (S_{te}) for each batch period.*

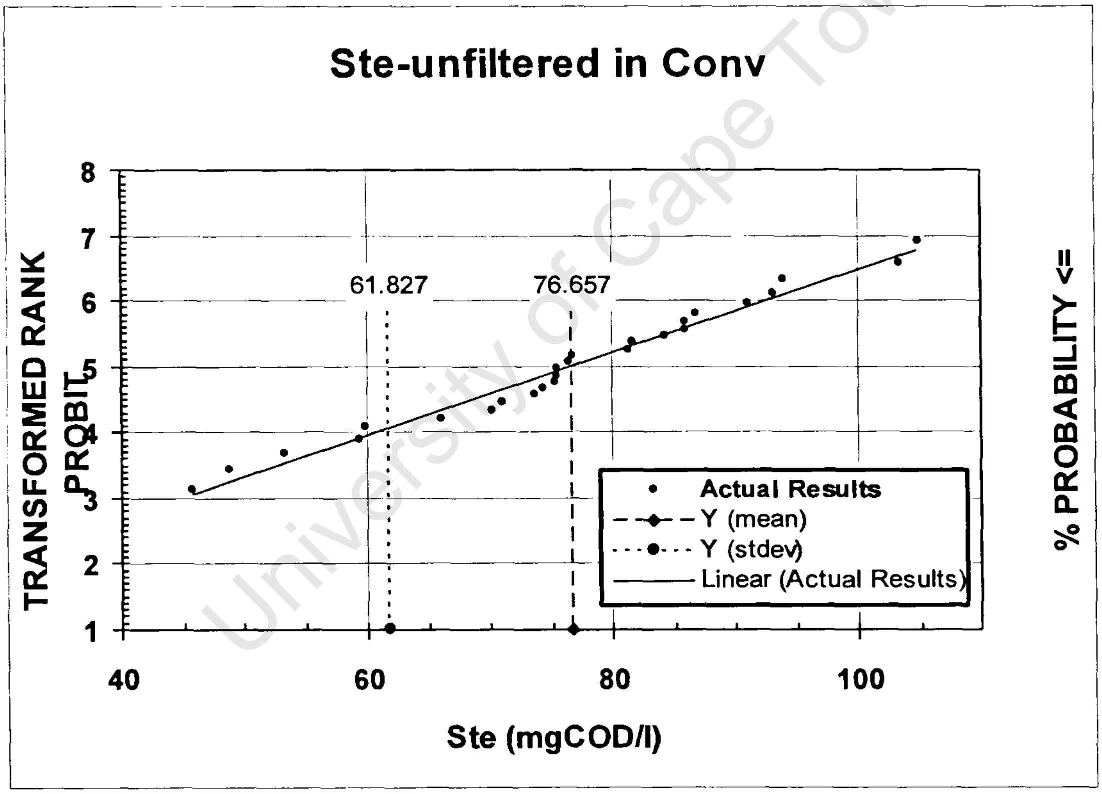


Figure 5.20: *Statistical plot of the effluent unfiltered COD (Ste) in the conventional UCT system.*

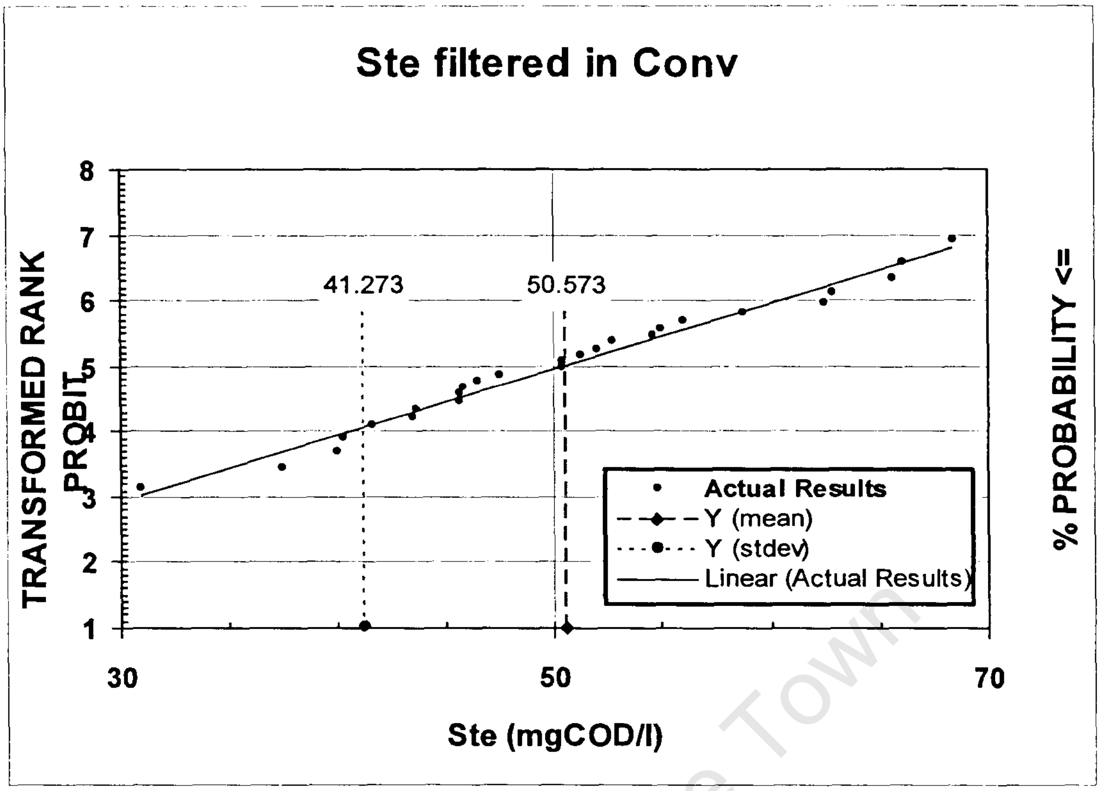


Figure 5.21: Statistical plot of the effluent filtered COD in the conventional UCT system.

- The conventional UCT system provided reasonably high COD removal efficiency. Despite fluctuations in the influent feed, from 785 mgCOD/ℓ (sewage batch 8) to 1147 mgCOD/ℓ (sewage batch 24), effluent COD removals remained within the range of 46 – 105 mgCOD/ℓ for the unfiltered effluent COD and 31 – 66 mgCOD/ℓ in the effluent filtered COD.
- Statistical plots of the effluent COD filtered and unfiltered concentrations are presented in Figs. 5.20 and 5.21. The mean average effluent COD concentrations are 76.7 mgCOD/ℓ (SSD = 14.8 mgCOD/ℓ) for the unfiltered effluent COD and 50.6 mgCOD/ℓ (SSD = 9.3) for the filtered effluent COD. Thus, throughout the investigation an average of 26.1 mgCOD/ℓ was lost through the effluent as non-settleable solids. Using the f_{CV} and VSS/TSS ratios calculated in Section 5.3 this amounts to approximately 21.5 mgTSS/ℓ lost in the effluent.
- The COD removal efficiencies of 0.45 μm filtered and unfiltered samples in the system were 95.7% and 92.7% respectively.
- The difference between 0.45 μm filtered and unfiltered effluent COD demonstrates the loss of solids with the effluent in conventional systems with SSTs. This solids loss, as noted by Ramphao *et al.* (2004) impacts directly on the quality of the effluent.

5.6.2 Nitrogen Removal

System nitrogen removal through the nitrification and denitrification mechanisms is examined in Fig. 5.22.

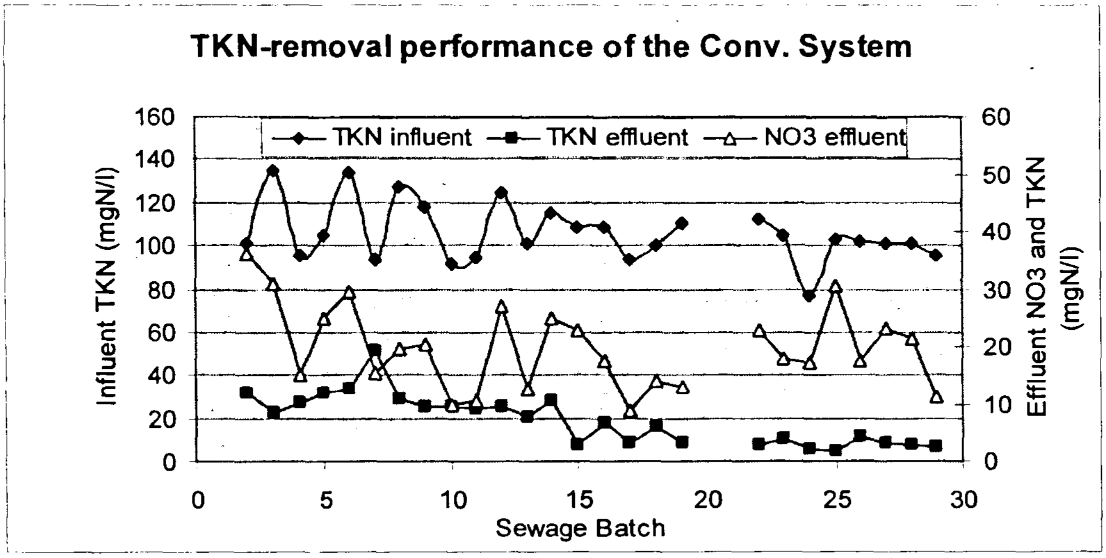


Figure 5.22: *System influent (N_{ti}) and effluent (N_{te}) TKN concentrations plotted against the effluent nitrate (N_{ne}).*

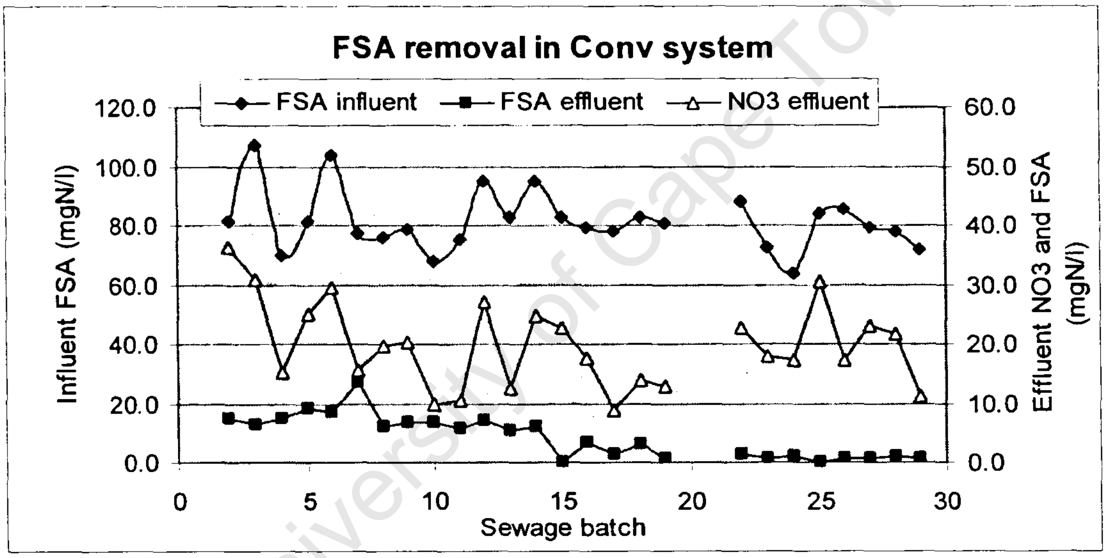


Figure 5.23: *System influent (N_{ai}) and effluent (N_{ae}) TKN concentrations plotted against the effluent nitrate (N_{ne}).*

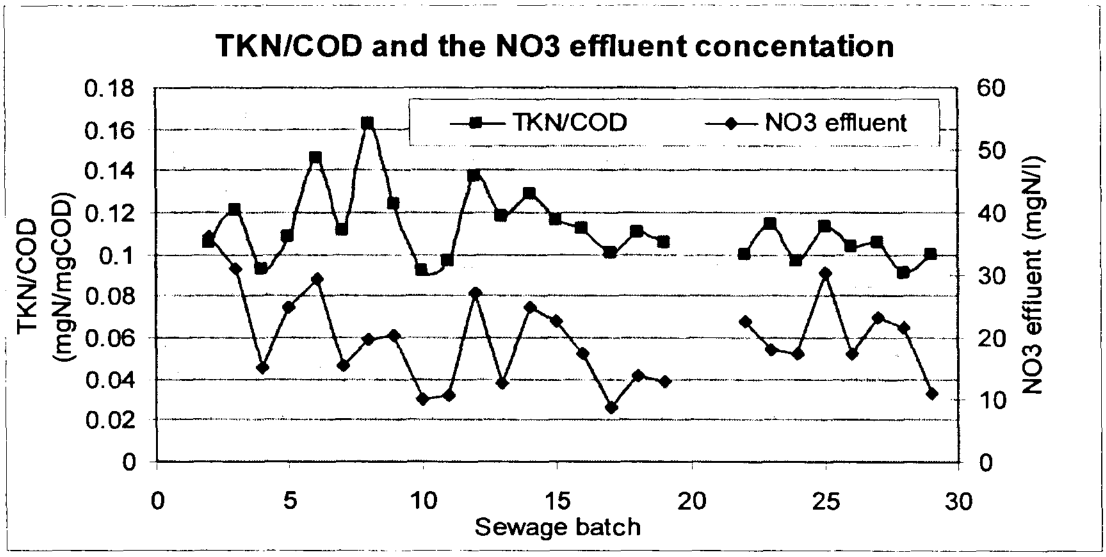


Figure 5.24: *TKN/COD ratio on the influent feed and its influence on the effluent nitrate.*

Nitrification

Variations in influent and effluent TKN and FSA concentrations (as well as effluent nitrate) are presented in Figs. 5.23 and 5.24.

- Approximately 80% of the influent TKN is FSA with the balance being organic nitrogen. Early tests on the influent confirmed that nitrate and nitrite concentrations in the influent were negligible. The high FSA fraction of the TKN is due to the dosing of ammonia to the feed in order to maintain a TKN/COD ratio of 0.1mgN/mgCOD.
- For the first 12 sewage batches 20mgN/ℓ ammonium chloride was added to the feed daily. However it was noticed that the TKN/COD ratio fluctuated dramatically ranging from 0.09 to 0.16 mgN/mgCOD. The TKN/COD ratio was dependant on the collected wastewater characteristics and the dilution necessary to obtain an influent feed of 800mCOD/ℓ to be augmented with RBCOD. Thereafter, from day 204 (sewage batch 13), an attempt was made to maintain the TKN/COD ratio at 0.1 mgN/mgCOD by controlled dosing of ammonium. This strategy significantly reduced the variation in influent TKN/COD ratio, Fig.5.24.
- Two distinct periods of testing are observed. From sewage batch 2-15 high effluent ammonia (N_{ae}) was measured ranging from 2.4 (day 134) to 20.7 (day 117) with an average of 7.4 mgN/ℓ. This could be attributed to poor testing for that period, or poor nitrification. Poor nitrification would be due to poor aeration which would effectively reduce the aerated sludge mass fraction; or to a reduced sludge age, close to the minimum sludge age for nitrification which would result in incomplete nitrification.
- From sewage batch 15 onwards there was a dramatic decrease in the measured FSA ranging from 0 to 3.9mgN/l with a mean average of 1.3mgN/ℓ.
- This variation in FSA impacted directly onto the TKN measured. Hence for the purposes of evaluating conventional N removal performance only sewage batches 15-29 are used.

- The filtered effluent TKN and FSA, and the unfiltered effluent TKN values were averaged for sewage batches 15 - 29. Statistical plots of these results are shown in Figs. 5.25-5.27. The mean average values for the unfiltered N_{te}, filtered N_{te} and filtered N_{ae} were 3.45 mgN/ℓ (SSD = 1.39), 1.97 mgN/ℓ (SDD = 1.07) and 1.15 mgN/ℓ (SDD = 1.01) respectively.
- Accepting that the difference between the filtered effluent TKN and FSA is the organic unbiodegradable soluble nitrogen (N_{ouse}), the average N_{ouse} over the investigation is calculated as 1.97 – 1.15 = 0.82 mgN/ℓ. Expressed as a fraction of the influent N_{ti} = 100.9 (for the period: batches 15 – 29), f_{Nouse} = 0.009. If it is accepted that on average 20mgN/ℓ ammonia was dosed to the influent the resulting f_{Nouse} is 0.011. As was noted in Chapter 4, Section 4.9.2.1, this is substantially lower than the value of 0.025 – 0.030 conventionally accepted for typical South African waste waters.
- The difference between the filtered and unfiltered TKN is the unsettleable solids that are lost from the SST. In the conventional system this difference was on average 1.48mgN/ℓ. Adopting the measured TKN/VSS = 0.094 for this system (Section 5.3) the sludge loss using TKN measurements was on average 15.7mgVSS/ℓ. This is reasonably close to that estimated from COD removal (Section 5.6.1).

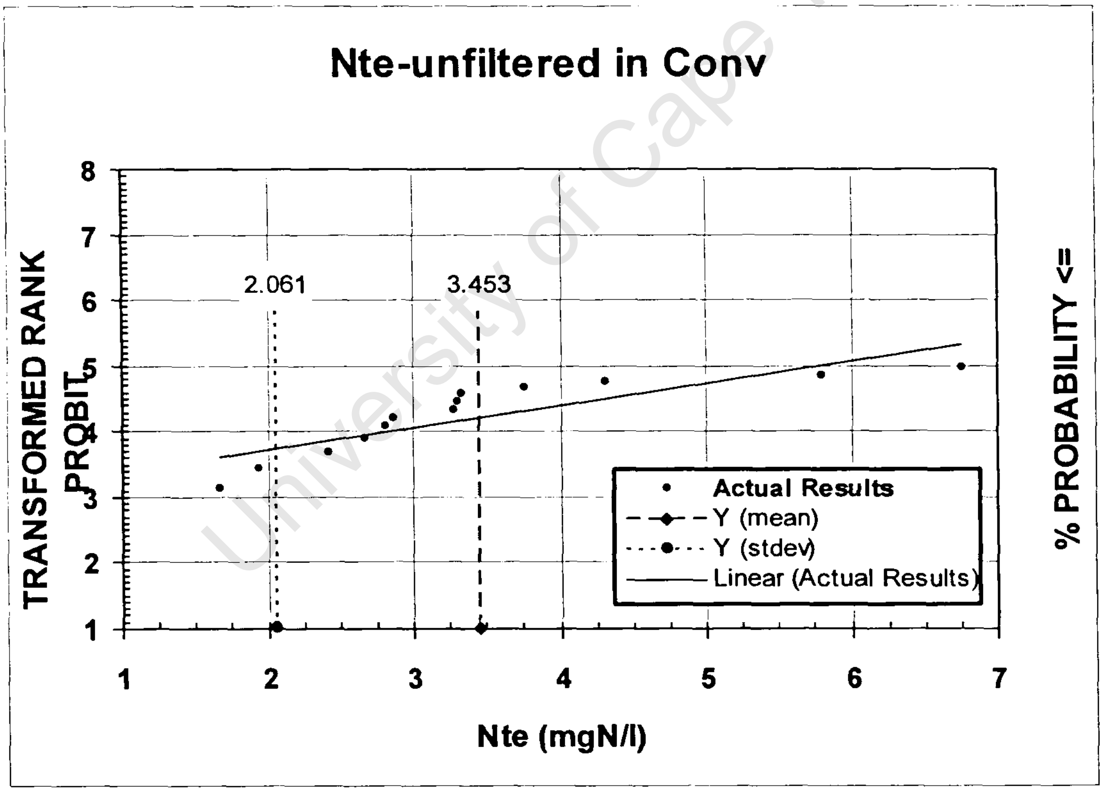


Figure 5.25: *Unfiltered effluent TKN concentrations for sewage batches 15-29.*

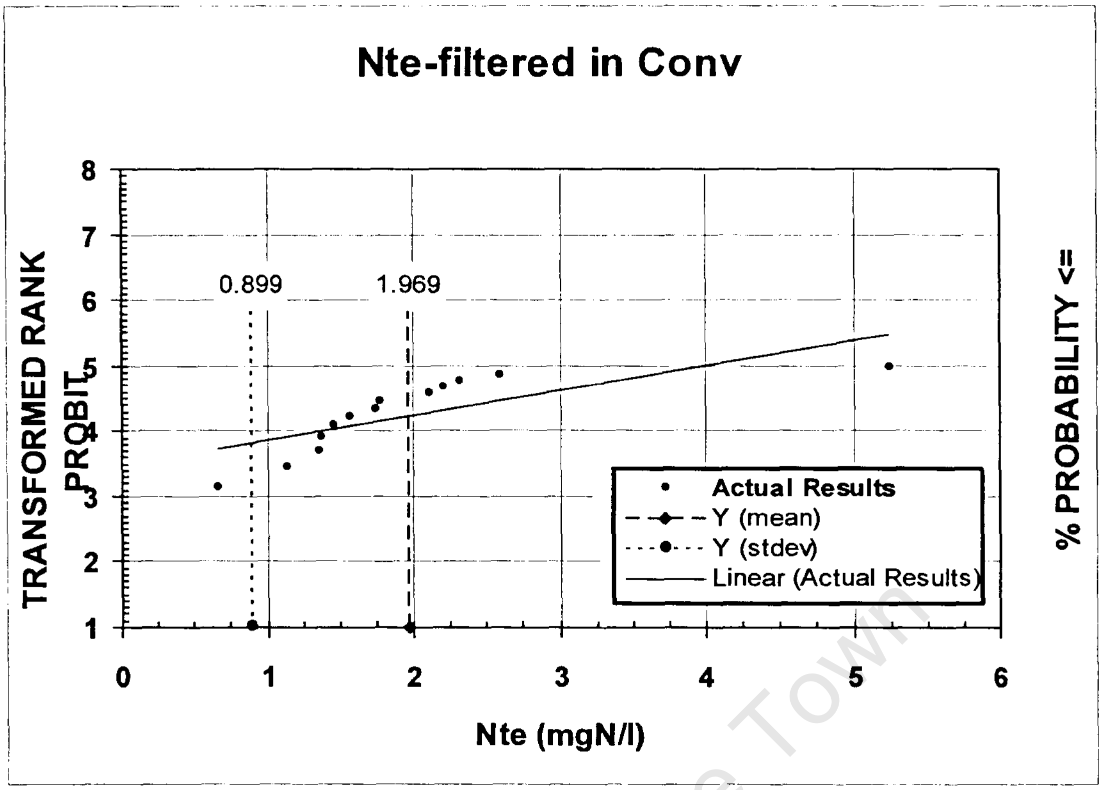


Figure 5.26: *Filtered effluent TKN concentrations for sewage batches 15-29.*

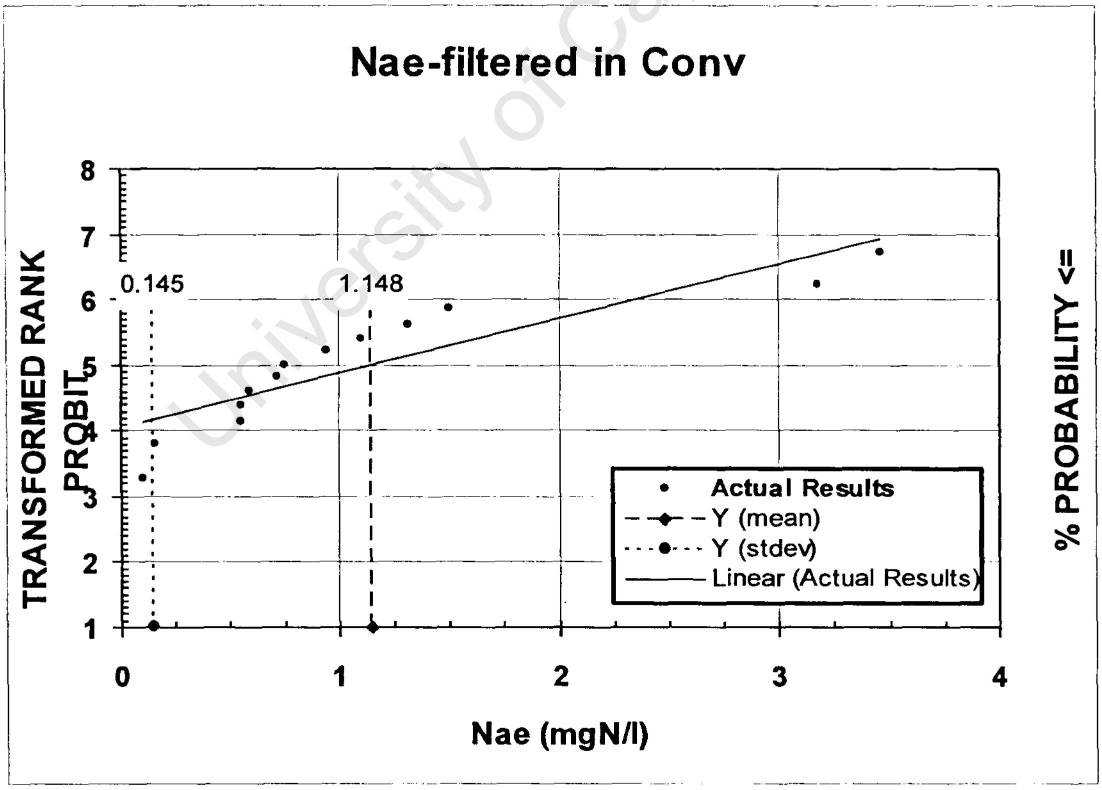


Figure 5.27: *Filtered effluent FSA concentrations for sewage batches 15-29.*

Denitrification

Reactor and effluent NO_3 concentrations are plotted in Figs. 5.27-5.30. Detailed results for all reactors and effluent are listed in Appendix B.

- NO_2 concentrations across the reactors were typically negligible (<1mgN/ℓ) however on a few occasions across all the reactors significant NO_2 concentrations were measured. For ease of assessment these NO_2 concentrations have been added to the nitrate concentrations and the sum termed NO_3.
- In general variations in the TKN/COD ratio were tracked by the effluent nitrate (N_{ne}) concentrations as can be seen in Fig. 5.26. This is expected as in the conventional UCT-type configuration N_{ne} is approximately:

$$N_{ne} = \frac{Nc}{a+s+1} \quad \text{or} \quad N_{ne} > \frac{Nc}{a+s+1} \qquad \text{(5.3a and b)}$$

  Where:

  N_C = the nitrification capacity of the system which is directly dependant on the influent TKN/COD ratio (WRC, 1984).
  a and *s* = the *a*-recycle and *s*-recycles respectively.

  If *a* and *s* in Equation 5.3a are maintained constant as was the case here, and N_C increases due to increased influent TKN, then the N_{ne} must increase. This relationship however accepts that all the NO_3 recycled to the anoxic reactor is denitrified. If this is not true then Equation 5.3b above applies, and N_{ne} increases disproportionately to an increase in N_C.
- The denitrification potential (D_{PP}) as discussed in Chapter 4, Section 4.9.4.4, is the amount of NO_3 an anoxic reactor can denitrify. It is dependant on the anoxic mass fraction, the sludge concentration and the influent COD. The nitrification load (N_{nL}) is the amount of NO_3 loaded on the anoxic reactor and is dependant on the recycles and nitrification capacity of the system. For a fixed underflow *s*-recycle the distribution of NO_3 between the aerobic and anoxic reactors is thus dependant on the *a*-recycle. Ideally the D_{PP} should equal the N_{nL} to denitrify the maximum amount of NO_3, while still protecting BEPR in the anaerobic reactor. If N_{nL} is greater than D_{PP} then NO_3 will be returned to the aerobic reactor.
- The conventional system was designed such that D_{PP} would equal N_{nL}, however in 22 out of the 26 measured sewage batches the anoxic NO_3 was greater than 1mgN/l indicating that the anoxic reactor was overloaded. This was however expected as the solids concentration throughout the system was substantially lower than the expected design solids for the duration of the investigation, and as noted above the D_{PP} is dependant on the solids concentration. Thus the D_{PP} was reduced substantially while the N_{nL} remained the same.
- Clearly high concentrations of NO_3 were recycled to the anaerobic reactor, which had detrimental effects on BEPR. This is examined in Section 5.6.3 (BEPR).

System Nitrogen Removal

The system nitrogen removal is given by the difference between the influent nitrogen (N_{ti}) and the sum of the effluent unfiltered TKN (N_{te}) and NO_3 concentrations (N_{ne}). The influent (N_{ti}) and summed effluent (N_e) for the batch period is presented in Fig. 5.28 below.

The total system N removal ranged from 65 to 87%. For the entire investigation period the system N removal mean was 74.7% (SSD = 7.5%), for the portion of the investigation from sewage batches 15 – 29 the mean was 78.6% (SSD = 5.1%) mgN/ℓ. Thus the higher N_{ae} results in sewage batches 2-14 did influence total system N-removal, and better control of the TKN/COD ratio reduced variation in the removals.

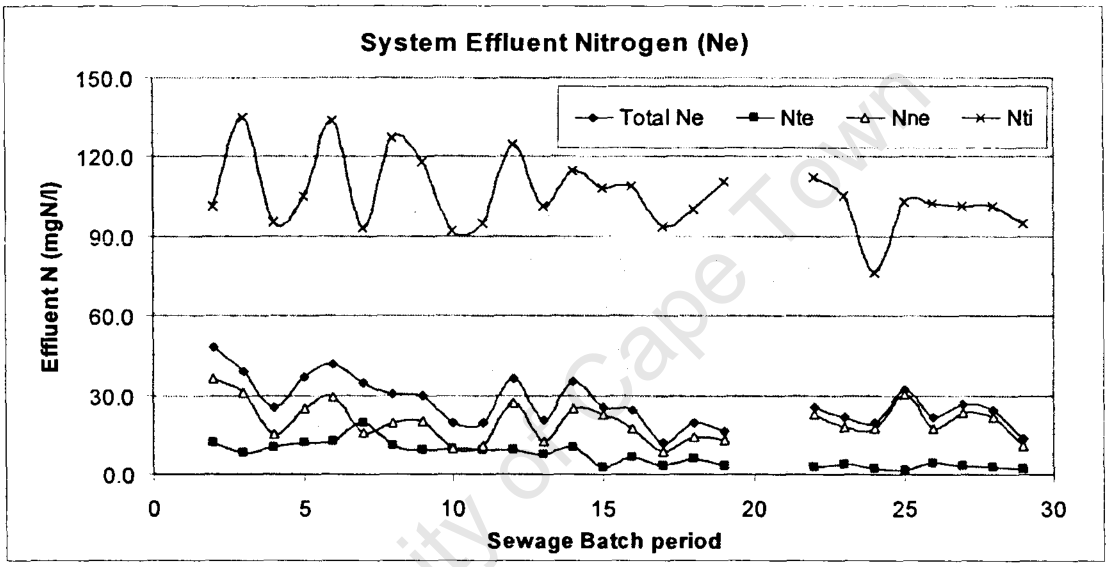


Figure 5.28: *Total system N-removal, comparing the influent TKN (Nti) to the effluent TKN (Nte) and nitrate (Nne), which together give the effluent nitrogen (Ne).*

5.6.3 Biological Excess Phosphorus Removal (BEPR)

Influent, effluent and reactor phosphorus concentrations are shown in Figs. 5.29-5.32. Following the procedures detailed in Chapter 4, Section 4.9.3, Table 5.3 lists the influent P, P release/P uptake across each reactor and the SST, and the overall P removal.

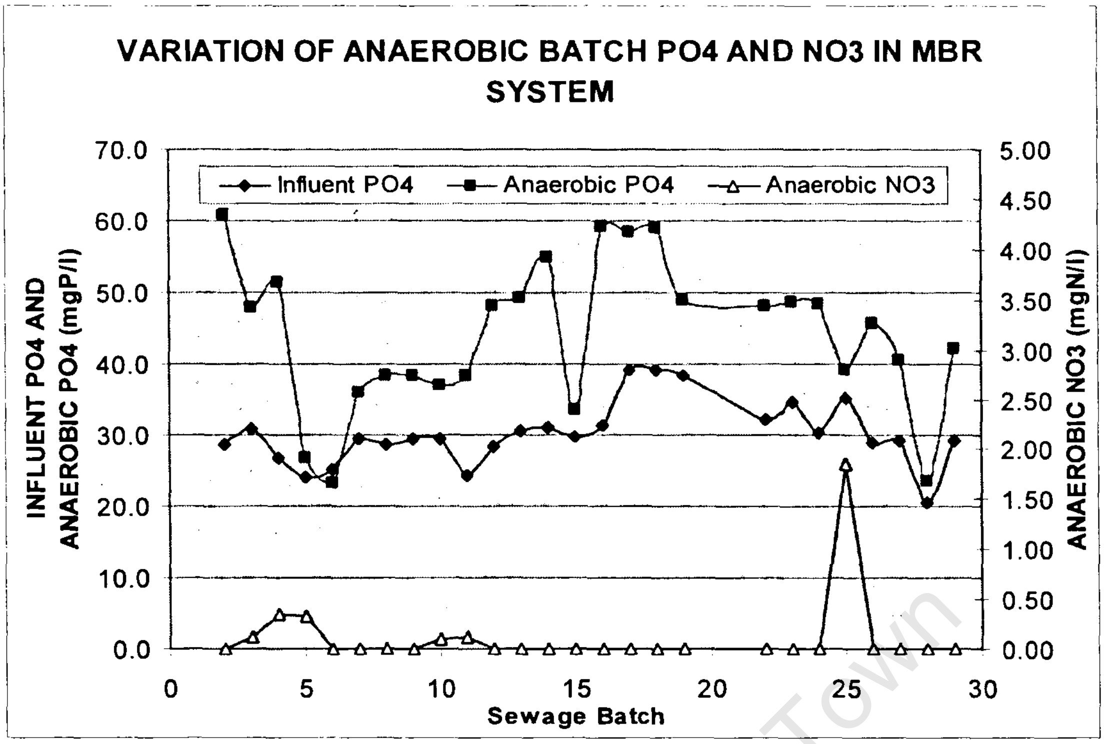


Figure 5.29: *Time dependant variation in anaerobic total soluble phosphorus and anaerobic nitrate concentrations.*

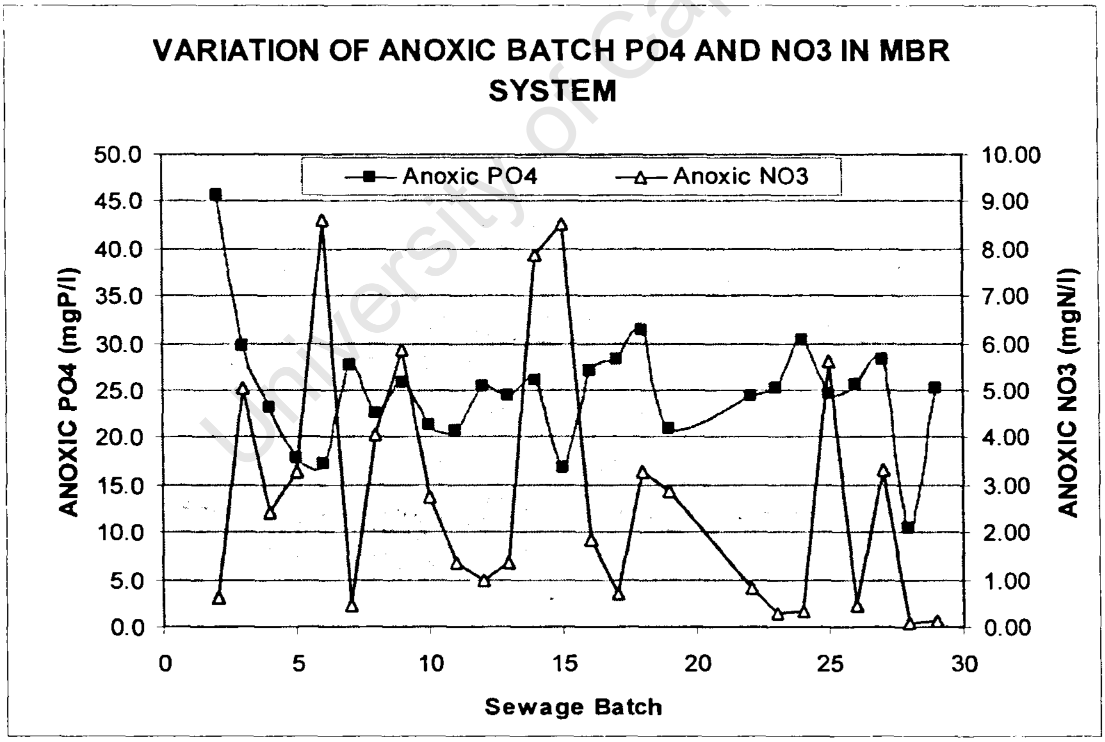


Figure 5.30: *Time dependant variation in anoxic total soluble phosphorus and anoxic nitrate concentrations.*

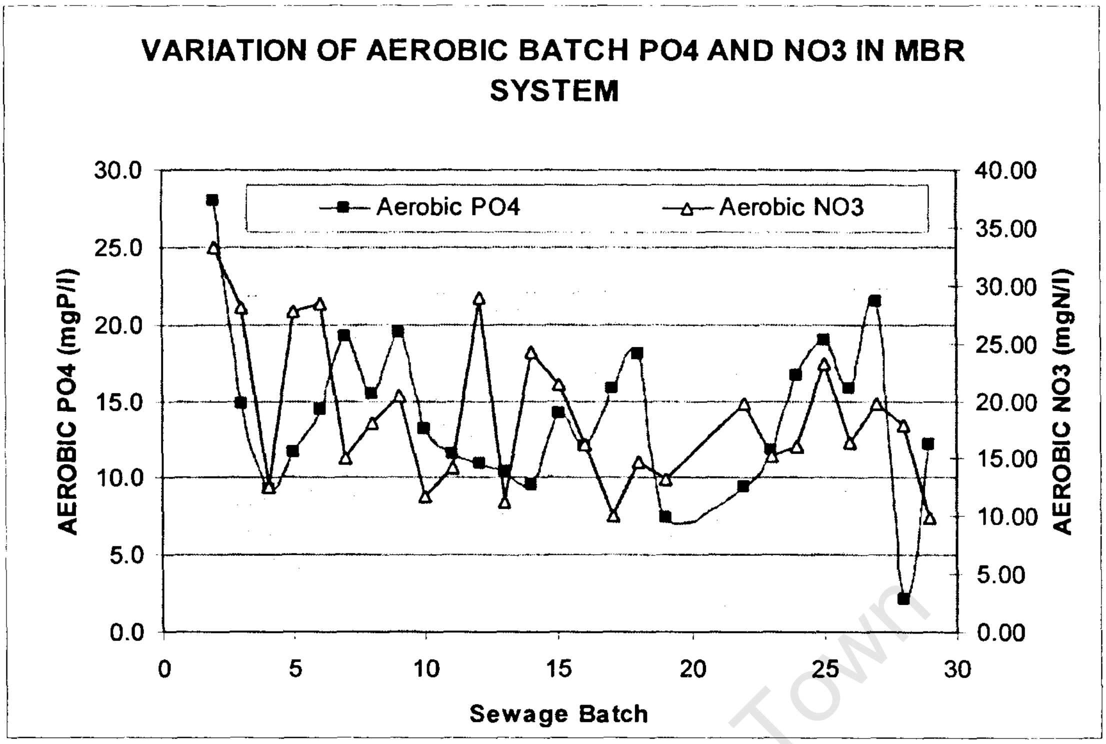


Figure 5.31: *Time dependant variation in aerobic total soluble phosphorus and aerobic nitrate concentrations.*

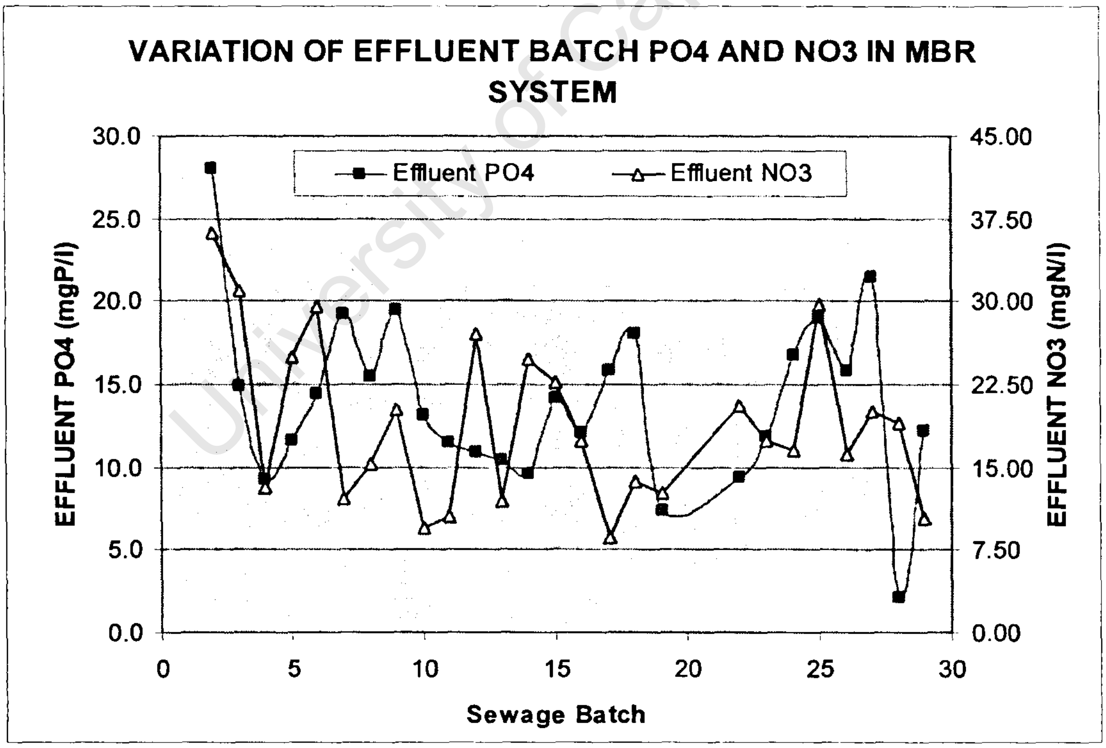


Figure 5.32: *Time dependant variation in effluent total soluble phosphorus and effluent nitrate concentrations.*

Table 5.3: *Sewage batch average P release (-ve) and P uptake (+ve) across the reactors and settling tank for the conventional UCT system.*

Batch Number	Influent	Anaerobic	Anoxic	Aerobic	SST	M Prem
	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf	mgP/linf
2	28.60	-47.28	0.00	68.48	1.63	0.58
3	30.94	-34.79	0.00	56.79	1.91	16.01
4	26.66	-53.11	15.74	54.30	0.76	17.32
5	23.96	-11.75	1.32	21.90	1.51	12.25
6	25.19	-3.75	4.37	9.45	1.16	10.67
7	29.47	-14.69	0.00	20.16	8.42	9.78
8	28.67	-25.70	12.10	26.01	1.43	13.15
9	29.52	-21.42	5.31	26.37	-0.35	10.08
10	29.35	-23.43	8.64	30.28	1.27	16.15
11	24.38	-31.52	9.98	33.16	2.28	12.81
12	28.31	-42.40	8.46	47.95	6.18	17.22
13	30.51	-43.63	10.93	51.18	2.79	19.94
14	30.98	-52.53	10.47	62.21	2.23	21.31
15	29.76	-20.49	22.07	15.78	-3.26	15.67
16	31.36	-60.04	33.06	39.04	12.95	18.78
17	39.06	-49.44	23.88	48.17	1.16	23.22
18	39.10	-47.51	16.70	50.96	1.62	20.99
19	38.43	-38.51	19.39	48.04	3.83	30.91
22	32.04	-39.75	5.22	55.64	2.83	22.57
23	34.72	-37.11	9.27	49.23	2.64	22.77
24	30.16	-36.47	0.00	58.18	-2.23	13.50
25	35.21	-18.46	11.69	26.96	-0.89	16.30
26	28.89	-37.03	11.83	39.27	0.34	13.05
27	29.14	-23.91	7.20	22.80	2.90	7.60
28	20.66	-15.86	3.13	30.06	2.30	18.51
29	29.18	-29.72	3.19	38.84	8.39	16.67
Average	30.16	-33.09	9.77	39.66	2.45	16.07

- The influent P values for sewage batches 2-14 of this investigation were measured independently of the influent to the MBR system, despite both feeds being the same. Hence there is a slight variation between the influent batch averages for the conventional system (Table 5.3) and the MBR system (Chapter 4, Table 4.10).
- The results in the table above show that overall P removal in the conventional UCT system was poor. The average removal was 16.1mgP/ℓ which is substantially less than that measured in Phase 1 of 21.5mgP/ℓ (Ramphao *et al.*, 2004) or in the MBR system for the Phase 2 investigation 22.4mgP/ℓ, but is attributed to the substantially lower TSS concentration in the conventional UCT system due to suspected unaccounted for sludge loss.
- P release predominately occurred in the anaerobic reactor, only 4 out of 26 sewage batches showed net anoxic P release. The P release was generally very poor with an average P uptake of only 33.5mgP/ℓ. Ramphao *et al.* (2004) noted that P releases of at least 100mgP/ℓ should have occurred considering

that 200mgCOD/ℓ was readily biodegradable COD throughout the investigation (0.5mgPreleased/mgCOD is generally sequestered by PAOs).

- Anoxic nitrate concentrations due to overloading the anoxic reactor with nitrate were consistently high. This would have had an adverse effect on P release as for every 1mgN-NO3/ℓ recycled to the anaerobic reactor 8.6mgCOD/ℓ would be lost to the PAOs. However this alone can not justify how low P removal was.
- The majority of P uptake occurred in the aerobic reactor ranging from 9.45 mgP/ℓ to 68.5 mgP/ℓ with an average of 39.7mgP/ℓ.
- Anoxic P uptake occurred in 22 out of 26 sewage batches and in one case, sewage batch 15, it was dominant over aerobic P uptake. The average anoxic P uptake was 9.7 mgP/ℓ.
- P uptake did occur in the SST, though it was negligible for all but four sewage batches, these were sewage batches 7, (8.4mgP/ℓ); batch 12, (6.2mgP/ℓ); batch 16, (13.0 mgP/ℓ) and batch 29, (8.4 mgP/ℓ).
- The total P uptake, on average 51.8mgP/ℓ, was also substantially lower than expected, but is relative to the low P release in the anaerobic reactor.

Thus it is concluded that the low solids concentration, and hence low PAO population, combined with the recycling of NO_3 to the anaerobic reactor are responsible for the poor P removal in the conventional UCT system.

Anoxic P uptake

Significant anoxic P uptake was observed in the conventional system as is illustrated in Figs. 5.33 and 5.34 below. This implies that the PAOs exhibited significant denitrification as has previously been described in Chapter 4, Section 4.9.3. Significantly reduced BEPR has been reported with anoxic P uptake by denitrifying (D)PAOs (Ekama and Wentzel, 1999; Hu *et al.*, 2002). This has been attributed to less efficient utilization of the influent RBCOD (Hu et al., 2002).

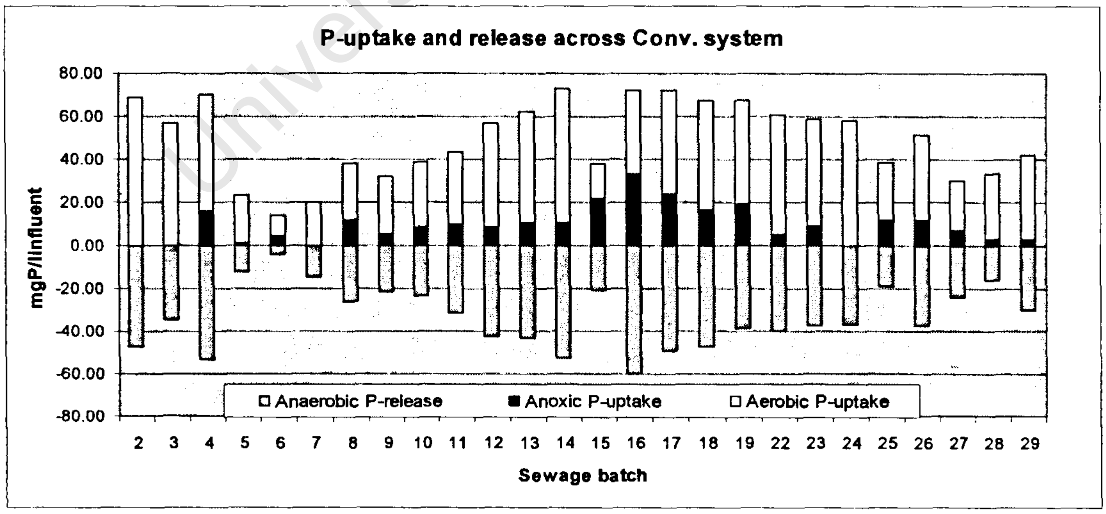


Figure 5.33: *P-release/uptake by the system reactors for each batch period.*

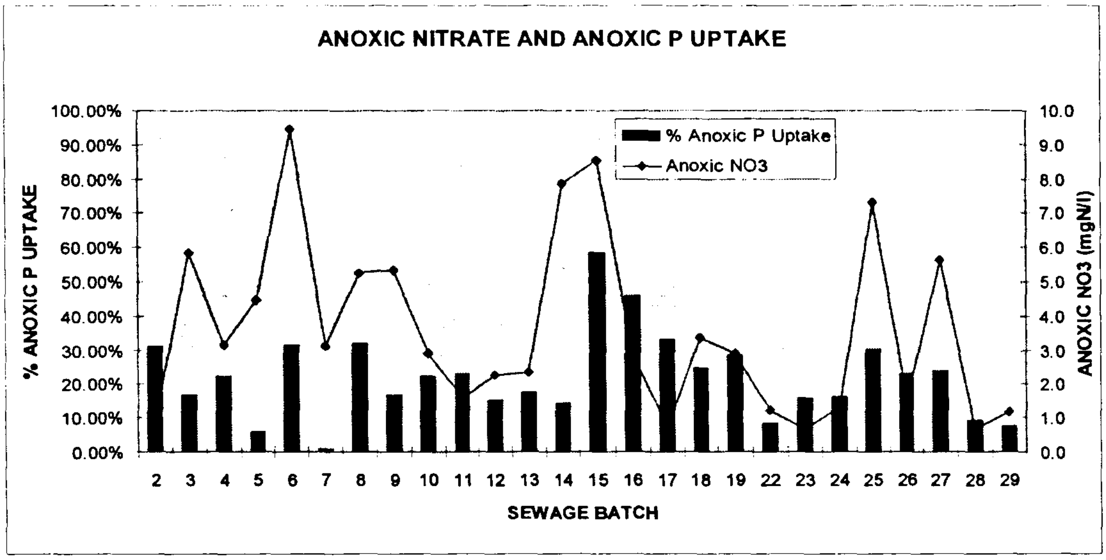


Figure 5.34: *The influence of anoxic nitrate on anoxic P uptake*

- Anoxic P uptake as a percentage of total P uptake ranged from 0.7 – 58.3% with an average of 22.1% thus making it a significant factor in BEPR in the conventional UCT system.
- A link between anoxic NO_3 and anoxic P-uptake is noted in Ramphao *et al.* (2004) citing Hu *et al.*, (2002). This relationship would be illustrated in Fig. 5.34 however in this investigation no clear relationship can be inferred from Fig. 5.34.
- The influence of anoxic P uptake is illustrated in Fig. 5.35 and indicates that higher anoxic P uptake degrades BEPR. However it must be remembered that significant anoxic P uptake is reported throughout the investigation while very poor P removal also occurs throughout the investigation! Hence it is difficult to compare the influence of anoxic P-uptake as at no point in the investigation did it not occur.

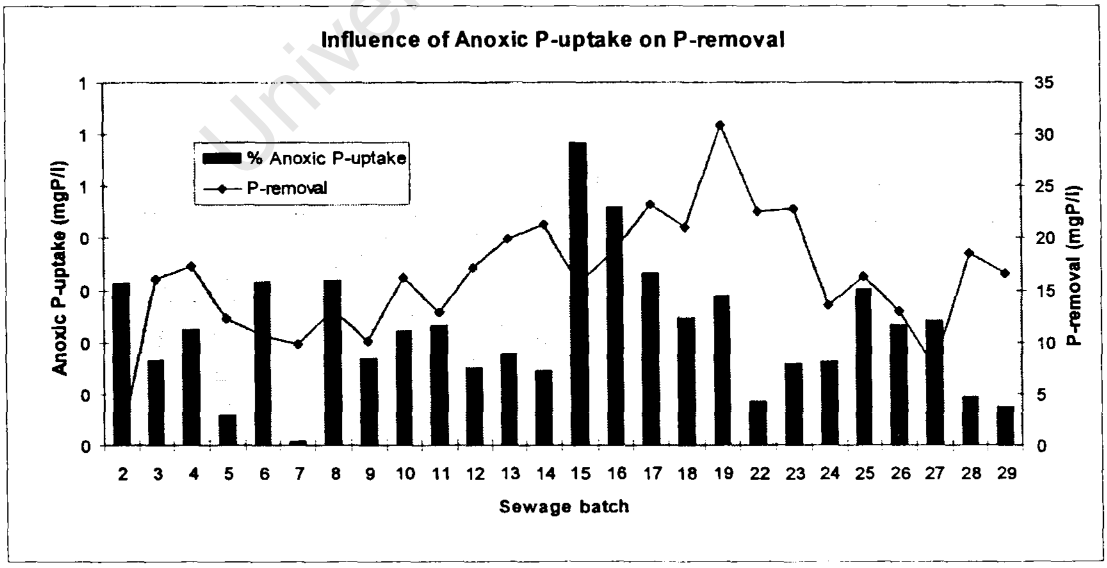


Figure 5.35: *The influence of anoxic P uptake on P removal is not particularly clear in this investigation*

5.7 CLOSURE

Due to the uncertainties in the data gathered from the conventional UCT system, as illustrated by the poor mass balances and variance in solids concentrations, the data has been analysed cautiously in order to assess its performance and to allow as accurate a comparison with the MBR UCT system as possible. Little merit however could be found in conducting a theoretical evaluation of ND and BEPR performance in the conventional system, as was done with the MBR system. This however makes little difference to the outcomes of this investigation as the BNR performance of the MBR system is the focus of this project.

It is concluded that unaccounted for sludge losses resulted in the poor system mass balances. The consequent low solids concentrations resulted in low OUR readings and an overloading of the anoxic reactor with NO_3 as the D_{PP} decreased with decreasing solids concentration. As a consequence the system was not run optimally and nutrient removal was adversely affected.

In Chapter 6 the results from the two UCT systems are compared, as far as possible, to assess the performance of the MBR UCT system.

CHAPTER 6

COMPARISON OF SYSTEM PERFORMANCES

6.1 INTRODUCTION

In Chapters 4 and 5 the performances of the MBR UCT and conventional UCT systems run in Phase 2 of this investigation were evaluated respectfully. In this chapter the performances of both systems are compared with each other and with those observed in Phase 1 of the investigation (Ramphao *et al.*, 2004) in order to assess the advantages and disadvantages of membrane solid-liquid separation in BNR systems, and to evaluate what impact, if any, membranes have on the performance of BNR systems.

6.2 SYSTEM OPERATIONAL PARAMETERS

In order to compare the BNR performance of the two laboratory-scale systems their operational parameters were designed to be the same. In most respects (e.g. sludge age, influent concentrations, mass fractions, temperature) this was achieved. However some differences were apparent:

- The MBR UCT system was run at high MLSS concentrations. The high MLSS concentrations were necessary in order to maintain sufficient scour across the membranes to prevent fouling, and to observe the impact of concentration on BNR performance. In order to achieve the high MLSS concentrations required the COD loading per unit volume in the MBR UCT system was approximately 3.2 times that of the conventional UCT system, at 1801mgCOD/ℓ reactor.d versus 571mgCOD/ℓ reactor.d. Ramphao *et al.* (2004) noted the potential reactor volume savings that could be achieved by an MBR system, but pointed out that the volume savings were strongly influenced by the nature of the influent, particularly the PWWF/ADWF ratio, aerobic mass fraction and COD strength.
- As was observed in Phase 1 (Ramphao *et al.*, 2004), the sludge distribution in the MBR UCT system differed from that in the conventional UCT system, and was linked to the a/as- and r-recycles. In a MBR UCT system the magnitude of the sludge distribution and zone mass fractions is linked to the inter-reactor recycles due to the solids liquid separation step occurring in the aerobic reactor thus concentrating missed liquor in the aerobic reactor as opposed to the SST in a conventional system (Ramphao *et al.*, 2004). Additionally in the MBR UCT system the measured recycles were found to differ from the design recycles resulting in system mass fractions that differed from the design mass fractions: Average mass fractions for the MBR UCT system in Phase 2 were anaerobic:anoxic:aerobic = 0.139:0.277:0.584 versus the original design values of 0.126:0.279:0.595. In the conventional UCT system only the r-recycle influenced the system mass fractions and was found to remain close to the design value, hence the system mass fractions were the same as those

determined in design 0.126:0.279: 0.595. This resulted, as in Phase 1, in slight differences in the system mass fractions of the two systems.

6.3 SYSTEM REMOVALS AND EFFLUENT QUALITY

The average removals of both the MBR and conventional UCT systems for the entire Phase 2 investigation are summarised in Table 6.1.

Table 6.1: *Summary of the influent and effluent qualities, and the resultant removals, of both UCT systems.*

Parameter		Influent	MBR UCT		Conv. UCT	
			Effluent	Efficiency	Effluent	Efficiency
COD	mgCOD/l	951.2	42.0	95.6%	74.6[1] (50.6[2])	92.2%
TKN	mgN/l	106.5	1.7	98.4%	3.7[1] (2.0[2])[3]	96.5%
FSA	mgN/l	81.7	0.7	99.1%	1.3	98.4%
NO3	mgN-NO3/l	0	18.0	-	18.1	-
TN	mgN/l	106.5	19.7	81.5%	21.*	79.5%
TP	mgP/l	30.3	9.0	21.3 mgP/linf	13.6	16.7 mgP/linf
TSS	mgTSS/l	N/A	0.0	-	21.5	-
e. coli	CFU/100ml	N/A	<10	-	2250	-

[1] unfiltered sample; [2] 0.45 filtered sample; [3] System averages for sewage batches 15-29
N/A = value not available

6.3.1 COD Removals

The COD removal efficiency of the MBR system (96%) was superior to that of the conventional system (92% unfiltered, 95% 0.45μm filtered). These results were comparable to those observed in Phase 1 (Ramphao *et al.*, 2004) of 96% COD removal in the MBR UCT system and 93% unfiltered and 94% 0.45μm filtered in the conventional UCT system.

For the purposes of comparison three categories of MBR COD were measured: directly from the effluent line; as 0.45μm filtered effluent from the aerobic reactor; and as unfiltered COD taken as supernatant from the 800ml mark of the DSVI test (Chapter 4, Section 4.9.1). Similarly conventional COD was measured as 0.45μm filtered effluent, and as unfiltered COD taken from the 800ml mark of the DSVI test. The recorded batch average values are presented in Fig. 6.1.

The difference in filtered COD removals from both systems is attributed to the smaller pore size of the membranes which retain organics that would otherwise be considered soluble in a conventional system. However membrane specifications state that the nominal pore size of the Kubota® membranes used in this study were 0.4μm, while the membranes used to filter the conventional system effluent are only marginally larger at 0.45μm, thus the improved filterability of the membrane system is attributed rather to the development of a dynamic gel layer which reduces the effective pore size of the membranes. 0.45μm filtered samples differed substantially for both systems at 70.5 and 50.6mgCOD/ℓ for the MBR and conventional systems respectively. The larger MBR 0.45μm COD is attributed to the retention, and subsequent concentration of COD considered soluble in the conventional system but retained in the MBR system by the membranes.

The MBR unfiltered "effluent" COD values were consistently higher than those in the conventional system which confirmed that the MBR system retains and accumulates unsettleable material which would flow out with the effluent in a conventional system. This was observed in the DSVI test in which the supernatant of the conventional system mixed liquor would become clear in time, whereas the MBR supernatant remained cloudy.

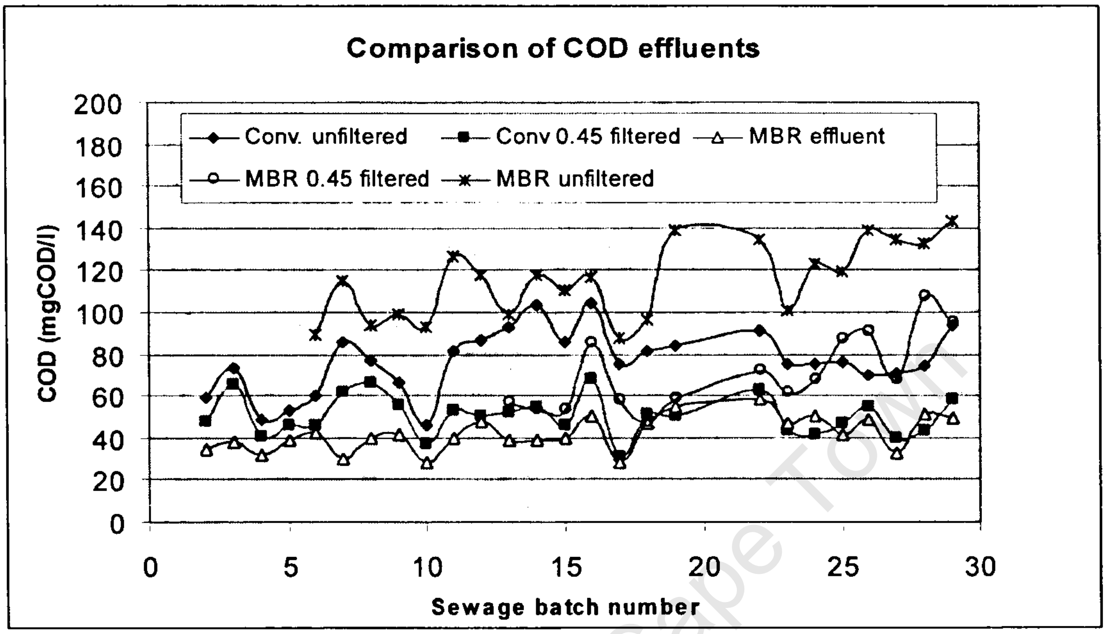


Figure 6.1: *Conventional and MBR effluent filtered and unfiltered COD concentrations.*

The difference between the filtered (50mgCOD/ℓ) and unfiltered (75mgCOD/ℓ) effluent COD measured in the conventional UCT system is attributed to the loss of non-settleable solids through the SST. Approximately 21.5mgTSS/ℓ were lost as COD in the effluent.

After Ramphao *et al.* (2004), differences in the MBR UCT effluent COD and the conventional UCT effluent are accommodated in the steady state design models as differences in the soluble unbiodegradable COD fractions ($f_{S,us}$) which were 0.044 and 0.068 respectively.

6.3.2 N Removals

As was described in Chapter 5, Section 5.6.2.1, the system average TKN and FSA removals in the conventional UCT system were determined from sewage batches 15-29 only.

The TKN removal efficiency of the MBR system (98%) was marginally better than that of the conventional system (97% unfiltered, 98% 0.45μm filtered). This is again attributed to the retention of solids by the membranes that would have been lost in the effluent of the conventional UCT system. FSA removal was also very similar for both systems 99% in the MBR system and 98% in the conventional system. Thus near complete nitrification was achieved in both systems.

Effluent nitrate concentrations were virtually the same for both systems (18.0 and 18.1 mgN-NO_3/ℓ in the MBR and conventional UCT systems respectively) resulting in similar total nitrogen (TN) removals, (81.5% for the MBR system versus 79.5% for the conventional system). These results are higher than those achieved in Phase 1 (74 and 75% respectively), however the effluent nitrate concentrations were lower in Phase 2 than in Phase 1 (23 and 22 mgN-NO_3/ℓ, respectively).

A comparison of N removal behaviour of both systems is presented in Section 6.7.

6.3.3 P removals

In both systems TP was dosed in excess of the amount the system could remove in order to demonstrate BEPR. Thus P removal performance is quantified by the concentration of P removed. Both systems exhibited P removals substantially lower than those observed in Phase 1 however, this is discussed in Chapter 4, Section 4.9.3 and Chapter 5, Section 5.6.3. System average P removals of 21.3mgP/ℓ and 16.7mgP/ℓ were achieved indicating that total P removal would have been possible in both systems with influent P concentrations of up to ~20mgP/ℓ and ~16mgP/ℓ respectively. Clearly however, the P removal performance of the conventional UCT system was inferior to that of the MBR system. Reasons for this are discussed in Section 6.8.

6.3.4 Microbial Removals

Periodic effluent samples were tested from both systems for the indicator micro-organism *e-coli* using the membrane filtration method. Pathogen counts were consistently unobservable in the MBR UCT system whereas in the conventional UCT system pathogen counts ranged from 600 to 5600 cfu/100ml (Appendix E). The measured pathogen counts in the conventional system are still substantially lower than those measured on full scale plants (Sampson K, *pers. com.*). This reduction in pathogen count is attributed to the 4°C sewage storage conditions in the WRL which partially sterilise the wastewater.

Clearly from the removals described above the MBR UCT system produced an effluent that was equal, if not superior in quality to the conventional UCT system. Due to complete retention of solids, and pathogens, the membrane effluent is more viable for reuse purposes.

6.4 MASS BALANCES

N and COD mass balances were conducted on both the MBR and conventional UCT systems. The mass balances differed for both systems with the MBR system producing mass balances close to 100% (96.5 and 103.1% for the N and COD mass balances respectively), while the conventional UCT system mass balances were both low and close to 80% (79.6 and 79.4% respectively). Reasons for the low conventional UCT mass balances are presented in Chapter 5, Section 5.4.

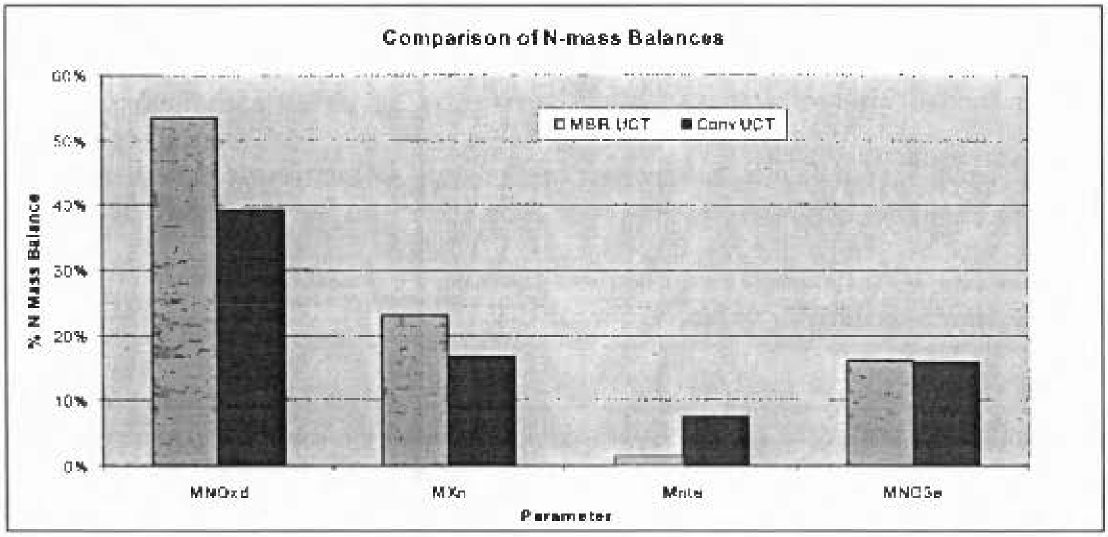


Figure 6.2: *Comparison of % composition in N mass balance: Nitrate/Nitrite denitrified (MNO_d), N incorporated in waste mixed liquor (MX_n), TKN in effluent (MN_{te}), nitrate in effluent (MNO_{3e}).*

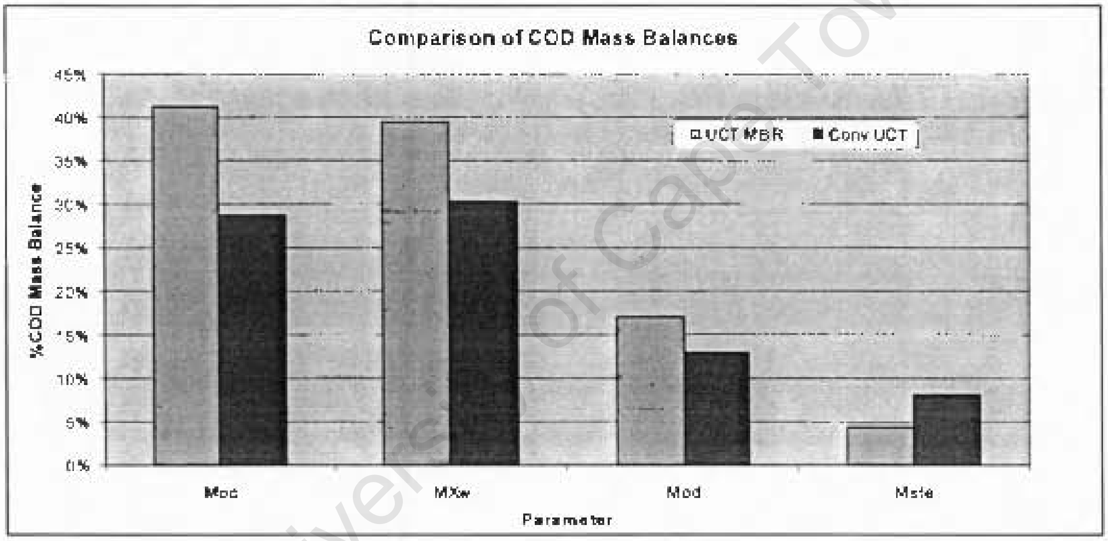


Figure 6.3: *Comparison of % composition in COD mass balance: Carbonaceous oxygen demand (MO_c), COD incorporated in waste mixed liquor (MX_w), oxygen equivalent of nitrite/nitrate denitrified (MO_d), COD in effluent (MS_{te}).*

Figs. 6.2 and 6.3 illustrate the percentile breakdown of the N and COD mass balances respectively for both systems. The breakdown allows a comparison of the routes via which N and COD were removed from the system.

- More nitrogen was removed from the MBR system through denitrification and sludge wasting than in the conventional system. This supports the observation of low sludge concentrations in the conventional UCT system, resulting in lower sludge mass removals and lower denitrification rates.
- N removed as nitrate was very similar for both systems.
- In Chapter 5, Section 5.6.2, it is noted that the effluent TKN concentration was erratic and high up until sewage batch 15 after which it remained low and comparable to that of the MBR system. However for the mass balance average

all sewage batches were used thus producing a very high N_{te}, influenced by the high effluent TKN concentrations up to sewage batch 15.

- In the COD mass balances the MBR removals are consistently higher for all parameters except effluent COD as the membranes produced a low COD effluent. This indicates that the mechanisms of COD removals in both systems are proportionally similar, however little more can be concluded from this comparison due to the low conventional COD mass balance.

6.5 SLUDGE PRODUCTION

In Phase 1 of the investigation sludge production in the two UCT systems differed significantly. A number of explanations were suggested by Ramphao *et al.* (2004), however more data was required in order to validate the observations. Hence one of the objectives for Phase 2 of the investigation was to validate the observed discrepancy in sludge production in the two systems.

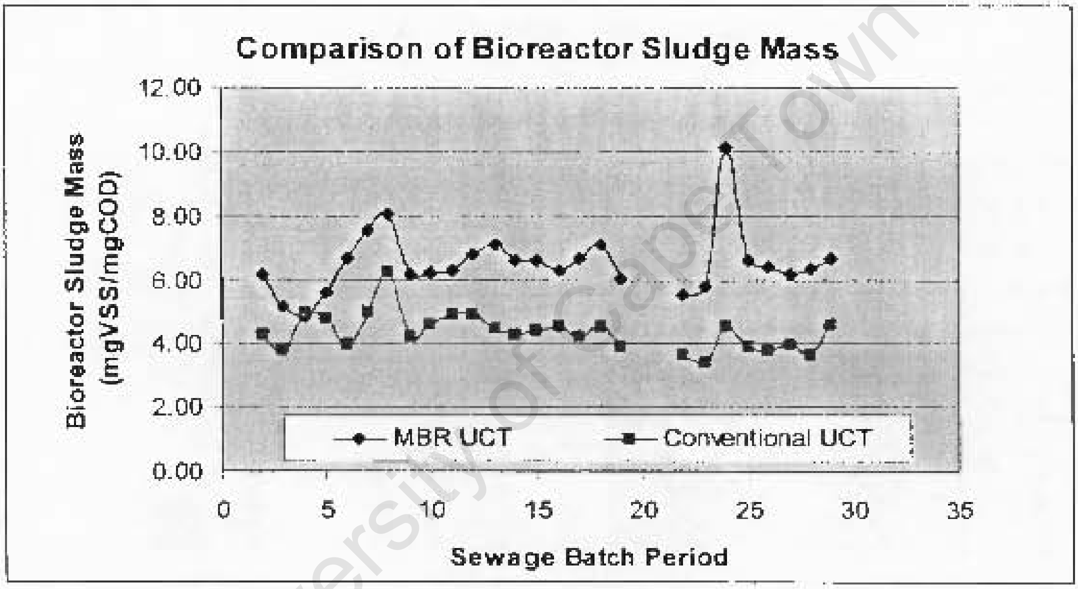


Figure 6.4: *Comparison of bioreactor sludge mass per COD load in MBR and conventional UCT systems.*

The mass of sludge in the reactor systems per unit COD utilized in the influent daily feed is represented in Fig. 6.4.

- With the exception of sewage batch 4 the sludge production in the MBR system was consistently higher than that of the conventional UCT system by on average 50%.
- The MBR system was not at steady state in sewage batch 4 due to substantial loss of mixed liquor through spillages on days 66-69 and 74. Similarly sewage batch 19 experienced substantial mixed liquor losses through spills on days 294, 298 and 305, resulting in a drop in bioreactor sludge mass.
- The spike in both systems in sewage batch 8 is attributed to particularly low influent COD concentrations (785mgCOD/ℓ) that characterised that sewage batch.
- Power failures in sewage batch 24 resulted in some sludge loss and reduced feeding due to the pump not being able to make up backlogs in feeding. As a

result the system was not fed on days 374 and 377, and hence was not at steady state.

- Average sludge productions for the two systems were 0.311 and 0.205 mgVSS/mgCOD for the MBR and conventional UCT systems respectively. In Phase 1 of the project Ramphao *et al.* (2004) reported similar results, 0.32 and 0.22 mgVSS/mgCOD respectively.
- The higher sludge production can be accommodated in the steady state design model by increasing the $f_{S,up}$ fraction. This was demonstrated by the high $f_{S,up}$ values observed in Phase 1 (0.224) (Ramphao *et al.*, 2004) and Phase 2 (0.200) in the MBR system.

As was noted by Ramphao *et al.* (2004) a number of factors contribute to the higher sludge production in the MBR system

- The retention of solids by membranes in the MBR system resulted in approximately 17.2 mgTSS/ℓ accumulating in the MBR system that would have been lost through the SST in the conventional UCT system. This would have "increased" sludge production by 0.018mgVSS/mgCOD.
- In the MBR UCT system, organics that would be considered as soluble in the conventional system are retained. This is demonstrated by the difference in the 0.45 μm filtered effluent COD system averages from the MBR and conventional UCT systems of 8mgCOD/ℓ. This would account for approximately 0.008 in the difference in the $f_{S,up}$ values above.

Additionally Ramphao *et al.* (2004) proposed two other explanations for the difference in sludge production in the two systems.

- The higher P removal in the MBR UCT system suggests a greater PAO population which would produce more sludge per unit influent COD than OHOs due to their lower endogenous respiration rates (Wentzel *et al.*, 1990).
- Particulate organics that are biodegradable in the conventional UCT system are no longer biodegradable in the MBR system due to factors such as high MLSS concentrations, or different floc morphology.

In the literature previous studies comparing conventional and MBR BNR systems run under the same operating conditions have indicated that the sludge production of the two systems were very similar (Masse *et al.*, 2006, Monti *et al.*, 2006), however in both investigations the systems were run at the same COD loading rate per unit reactor volume. Masse *et al.*, (2006) included the sludge lost through the SST in sludge wasting calculations in order to compare sludge productions in the two systems.

Additionally sludge production in ND and NDBEPR systems operated using the same wastewater source, for sludge ages in the region of 10 and 20 days, have produced sludge in comparable magnitudes to those observed in the conventional system. Previous values are listed in Table 6.2. Thus it would appear that there is an increase in sludge production in the MBR system linked to the increased MLSS concentration in the MBR system and the retention by membranes of all solids.

Table 6.2: Comparison of sludge productions in investigations using the same waste water.

Author	System type	SRT	$f_{S,us}$	$f_{S,up}$	Sludge production
units	-	days	-	-	mgVSS/ mgCOD
Sneyders (1995)	UCT	10	0.05	0.045	0.26
	UCT	10	0.06	0.062	0.27
Musvoto	MUCT	20	0.073	0.32	0.31
Beeharry (2001)	MLE	10	0.05	0.161	0.28
Ubisi (1997)	MLE	12	0.095	0.12	0.22
		20	0.095	0.12	0.2
Lee (2002)	MLE	10	0.043	0.165	0.32
		20	0.04	0.148	0.18
Cronje (2000)	MLE	10	0.085	0.103	0.23

6.6 MIXED LIQUOR CHARACTERISTICS

In order to quantify the mixed liquor in both systems the VSS, TSS, COD and TKN concentrations of the mixed liquor were measured. Investigation average ratios between these parameters are listed in Table 6.3.

Table 6.3: Mixed liquor parameters

Parameter	unit	MBR System	Conv. System
VSS/TSS	mgVSS/mgTSS	0.809	0.814
COD/VSS	mgCOD/mgVSS	1.402	1.496
TKN/VSS	mgN/mgVSS	0.085	0.094

- The VSS/TSS and TKN/VSS average ratios were relatively close for both systems.
- Both systems exhibited high VSS/TSS ratios which are not characteristic of BEPR systems. In BEPR systems the development of a PAO population is encouraged. PAO's have internally a low VSS/TSS ratio due to the additional inorganic polyP in their cell mass.
- Although the COD/VSS ratios differ substantially from each other in the two systems, they both fall very close to the expected and theoretical f_{CV} values of 1.48 and 1.42 respectively (WRC., 1984).
- The COD/VSS ratio indicates that the COD incorporated into the mixed liquor was lower in the MBR system than in the conventional system. However the comparison of mass balances showed a greater proportion of COD was removed from the MBR system via the mixed liquor wasted than in the conventional system. In order for this to occur proportionally more mixed liquor would need to be wasted from the MBR system than the conventional system to achieve higher COD removals through wasting, particularly with lower COD incorporated in the mixed liquor. This is only possible, at the same sludge age, if the sludge production in the MBR system was substantially greater than that in the conventional system.

6.7 NITROGEN REMOVAL

As described in Chapter 4, Section 4.9.2 nitrogen is removed from BNR systems either by the incorporation of nitrogen in mixed liquor and its subsequent removal through wasting, or through nitrification/denitrification.

- The influent N incorporated in the mixed liquor was lower in the MBR UCT system than in the conventional UCT system. This corresponds to the observation above of lower COD incorporated in the MLVSS.
- Regardless, N removal through sludge wasting was higher in the MBR UCT system than the conventional UCT system, this is largely due to the higher sludge production in the MBR system, and consequent increased sludge mass wasted per unit influent N.
- The MBR UCT system additionally displayed higher N removals through denitrification. This was achieved despite similar mass fractions and that the conventional UCT system was frequently fully loaded.

6.8 BIOLOGICAL EXCESS PHOSPHORUS REMOVAL (BEPR) BEHAVIOUR

In both systems TP was dosed in excess of the amount the system could remove in order to demonstrate BEPR. Thus P removal performance is represented by P removals. System average P removals of 21.3mgP/ℓ and 16.7mgP/ℓ were achieved indicating that total P removal would have been possible in both systems with influent P concentrations of up to ~20mgP/ℓ and ~16mgP/ℓ respectively. Clearly however, the P removal performance of the conventional UCT system was inferior to that of the MBR system. Reasons for this are discussed below. A comparison of P release, uptake and removal is presented in Fig. 6.4.

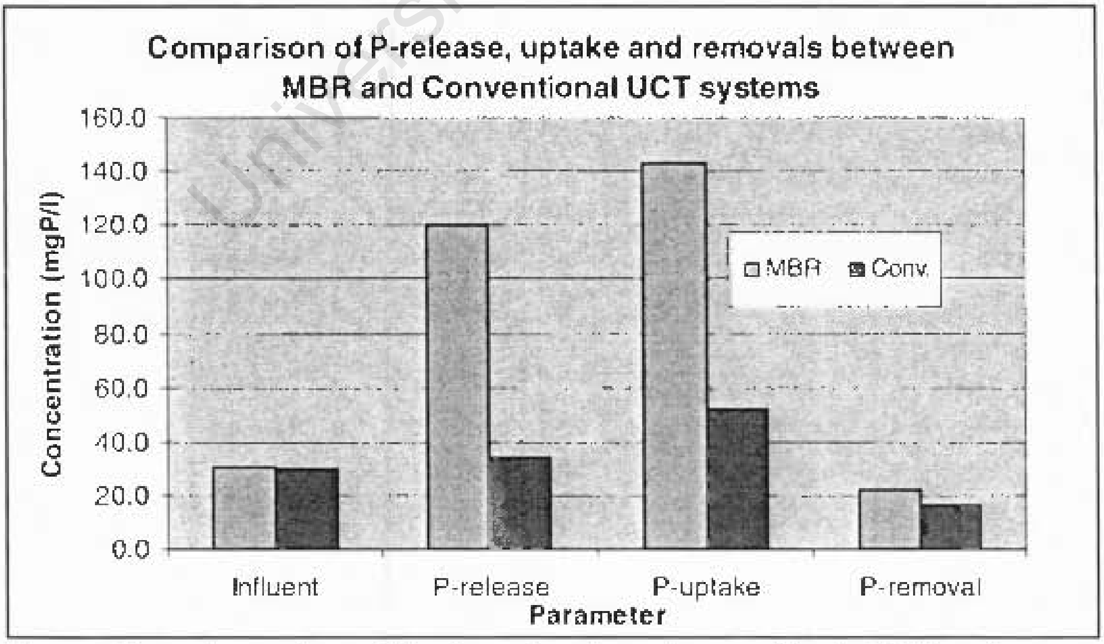


Figure 6.4: *Comparison of P-release/uptake and removal in the MBR and Conventional UCT systems.*

- P-removals differed significantly between the two systems, 22.4 mgP/ℓ and 16.1mgP/ℓ in the MBR and conventional UCT systems respectively.
- Denitrification was complete in the MBR system, but not in the conventional UCT system, evidenced by regular concentrations in the anoxic reactor >1mgN-NO_3/ℓ. This loading of nitrate on the anaerobic reactor in the conventional UCT system would have reduced the RBCOD available for PAOs and consequently reduce P removal.
- the anoxic P uptake was more prevalent in the conventional system with 22.1% of P uptake taking place in the anoxic reactor, in contrast to only 8.5% anoxic P uptake in the MBR system.

The above observations indicate that the conventional system was not being operated optimally (the anoxic reactor was overloaded), hence it is difficult to assess if the presence of membranes does indeed change the P removal efficiency of the MBR system.

6.9 CLOSURE

The behaviour and responses of the UCT activated sludge systems have been compared in this chapter. From the comparison it is clear that the MBR UCT system gave equal or superior quality response and performance in terms of effluent quality and system removals. The MBR system did however produce substantially more mixed liquor per unit COD load than the conventional system, which is in agreement with observations from Phase 1 (Ramphao, *et al.*, 2004). The increased sludge production is explained in part by the retention, by the membranes, of additional COD and non-settleable solids which would otherwise flow through SSTs, however this cannot explain the magnitude of difference in sludge production between the two systems.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

Membranes for solids liquid separation in the activated sludge process are rapidly gaining acceptance internationally and have been implemented in many parts of the world. They have the inherent advantages that they produce a consistently solids free effluent, they reduce the footprint of wastewater treatment plants significantly by allowing AS systems to be run at high solids concentrations and obviating the need for SSTs, additionally experience has shown that membranes retain pathogens and in some cases virus' too which increases the reusability of the wastewater effluent. Stricter international water quality guidelines have stressed the importance of nutrient removal from wastewaters, spurring the development of methods for nutrient removal by chemical or biological means. In South Africa, and more recently internationally, the advantages of biological nutrient removal (BNR) have made it an attractive choice for nutrient removal. Little however is known of the effect of combining the attributes of membranes, namely higher concentration mixed liquors, the retention of all solids and the increased turbulence of aeration for membrane scour, on BNR systems. This investigation set out to add to the limited existing literature on BNR in MBR systems with the following specific objectives:

- Verifying the results obtained by Ramphao *et al.* (2004) with particular emphasis on explaining the phenomena of increased sludge production;
- Gaining a better understanding of the operating conditions and considerations of MBR BNR systems;
- Providing a parent system from which further testing into the kinetics of a MBR BNR system could be performed (Parco *et al.*, 2006).

These objectives were met by running two activated sludge systems in UCT configurations. The first was a MBR UCT system with membranes in the aerobic reactor and the other a conventional UCT system with a SST with which to compare performance. All engineering parameters were monitored in order to assess the BNR performance of the systems. The results of the two systems were presented in Chapters 4 and 5 respectively, with a comparison and discussion of results in Chapter 6.

7.2 CONCLUSIONS

From this investigation, the following conclusions could be drawn:

- Membranes in a BNR system are a feasible nutrient removal solution with excellent organic and nutrient removal performance. The presence of membranes and consequently operating the system at high sludge concentrations did not adversely affect BNR performance, but produced an effluent of equal or superior quality to that produced by a conventional system using SSTs. In addition pathogen counts indicated that all pathogens were retained by the membranes. Thus the membrane effluent is safer and more viable for reuse purposes.

- Higher sludge productions of 0.311 and 0.320 (mgVSS/d)/ (mgCOD/d) were observed in the MBR system in both Phase 1 (Ramphao *et al.,* 2004) and Phase 2 of the investigation respectively. This higher sludge production is accommodated in steady state design theory by increasing the unbiodegradable particulate COD fraction ($f_{S,up}$) fraction, in Phase 1 to 0.224 and in Phase 2 to 0.200. The increased sludge production is justified in part by the retention of all solids. Similarly the unbiodegradable soluble COD fraction ($f_{S,us}$) must be decreased to account for the additional retention of "soluble" COD which is attributed to the finer membrane pore size.
- A theoretical evaluation of the BNR performance of the MBR system indicated that the current BNR theory was able to closely predict the system performance for COD removal and nitrification. However for denitrification the D_{PP} was underpredicted requiring $K_{2'T}$ to be adjusted from 0.145 to 0.216 mgN/mgVSS/d at 20°C in order to match observed and predicted values. The BEPR predictions for aerobic P uptake BEPR were close to those observed when the system PAO population reached a steady state (sewage batches 18 – 25). f_{XBGP} observed in this period (0.376mgP/mgVSS) was close to that determined theoretically of 0.38mgP/mgVSS.
- Aeration testing was performed on the system, in order to determine alpha values for the high concentration sludge. Alpha values of 0.5-0.6 for ~15 000mgTSS/ℓ and 0.2-0.3 for ~20 000mgTSS/ℓ were determined, which are higher than other values reported in the literature. These values are however specific to the laboratory system run in which factors such as reactor geometry and high aeration turbulence would have affected oxygen transfer in the system. Additionally the low sensitivity of the measuring apparatus resulted in substantial variance of results.
- Rheological testing on the sludge confirmed that there is a linear relationship between activated sludge viscosity and oxygen mass transfer.
- The sludge filterability through the membranes can be influenced by fine colloidal material, however observations indicated that the filterability would return to previous levels once colloids are removed from solution by assimilation into the mixed liquor.

7.3 RECOMMENDATIONS FOR FURTHER STUDY

Following from this investigation two recommendations are proposed:

- Accurate knowledge of the oxygen transferability in high concentration sludge is an important design consideration. However in this investigation the difficulty in measuring this parameter at a lab scale was realised. It is recommended that this parameter needs to be quantified on a full scale and be determined at a fully operational BNR MBR WWTP.
- The relationship between Alpha and viscosity of activated sludge needs to be investigated further in order to better understand the influence of high concentration sludges on oxygen mass transfer. This is an important parameter for design and thus accurate prediction of oxygen mass transfer co-efficients such as Alpha is essential.

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APPENDIX A

MBR AND SQW DAILY MEASUREMENTS

TABLE OF CONTENTS

Appendix A-1

Measured COD values for the MBR UCT and SQW systems

COD measurements

Day	Date	SB #	Influent	Aerobic	Eff 0.1	Eff 0.45	Eff unfilt.	Tank	RB-Mbewe*	SQW	SBSi - RBCOD	fts,s	fts,T
-	-	-	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	-	-
21	3-Mar-05	Batch 2											
22	4-Mar-05												
23	5-Mar-05												
24	6-Mar-05												
25	7-Mar-05		1083.7	19514.4	18.7								
26	8-Mar-05		1075.4	20760.0	41.5								
27	9-Mar-05		1054.6	18351.8	62.3								
28	10-Mar-05		1046.3										
29	11-Mar-05		871.9	18517.9	29.1								
30	12-Mar-05												
31	13-Mar-05												
32	14-Mar-05		988.2	13465.9	19.9								
33	15-Mar-05		772.3	19043.5	31.9								
34	16-Mar-05		950.8										
35	17-Mar-05		860.5	17051.5	35.9								
36	18-Mar-05		880.5										
Batch Average		**2**	**958.4**	**18873.2**	**34.2**								
37	19-Mar-05	Batch 3											
38	20-Mar-05												
39	21-Mar-05			16095.4	21.9								
40	22-Mar-05		792.8							460.0	96.0	0.21	0.41
41	23-Mar-05		996.0	18953.0	64.0					460.0	104.5	0.23	0.38
42	24-Mar-05												
43	25-Mar-05		981.9	18009.0	36.4								
44	26-Mar-05												
45	27-Mar-05		1038.0	21497.0	45.0								
46	28-Mar-05												
47	29-Mar-05		1156.0	20361.0	32.4								
48	30-Mar-05		1212.7										
49	31-Mar-05		1249.2	20686.0	34.5					460.0			0.16
50	1-Apr-05		1249.2										
51	2-Apr-05		1131.6	19793.3	32.4								
52	3-Apr-05												
53	4-Apr-05		1314.1	18414.2									
Batch Average		**3**	**1147.7**	**19226.1**	**38.1**					**460.0**	**100.2**	**0.22**	**0.32**
54	5-Apr-05	Batch4	1326.3							460.0	94.2	0.20	0.32
55	6-Apr-05												
56	7-Apr-05												
57	8-Apr-05		880.0	19388.0	46.6								
58	9-Apr-05												
59	10-Apr-05		1155.9	20198.9	44.6								
60	11-Apr-05		1302.0										
61	12-Apr-05		1018.1	20523.4	38.5					460.0	63.9	0.14	0.31
62	13-Apr-05		904.5										
63	14-Apr-05		1257.4	21496.8	14.2					460.0	54.8	0.12	0.26
64	15-Apr-05		1164.1										
65	16-Apr-05		949.1	17765.3	24.3								
66	17-Apr-05												
67	18-Apr-05		851.8	18819.8									
68	19-Apr-05		872.0	15007.2	38.5								
69	20-Apr-05		1105.7										
70	21-Apr-05		1326.0										
71	22-Apr-05		726.2										
72	23-Apr-05		790.9	14114.9	16.2								
73	24-Apr-05												
74	25-Apr-05		681.4	10200.0	30.6								
75	26-Apr-05		1056.7										
Batch Average		**4**	**1021.6**	**18414.3**	**31.7**					**460.0**	**71.0**	**0.15**	**0.30**

76	27-Apr-05	Batch 5											
77	28-Apr-05												
78	29-Apr-05			11995.2	40.8								
79	30-Apr-05												
80	1-May-05		763.0										
81	2-May-05			12484.8	42.8					460.0	79.9	0.17	
82	3-May-05		1130.2										
83	4-May-05		991.4										
84	5-May-05		1224.0	14767.0	39.0					460.0	101.8	0.22	0.35
85	6-May-05		962.8	30110.4	34.7								
86	7-May-05		652.8							460.0	101.2	0.22	0.46
87	8-May-05		895.5										
88	9-May-05		934.5	19747.2	34.7								
89	10-May-05		942.7										
90	11-May-05		1207.2	19747.2	44.9					460.0	58.7	0.13	0.27
91	12-May-05		981.3										
92	13-May-05		881.3	20073.6	36.7					460.0	60.2	0.13	0.33
93	14-May-05												
94	15-May-05												
Batch Average		**5**	**992.2**	**18417.9**	**39.1**					**460.0**	**80.4**	**0.17**	**0.35**
95	16-May-05	Batch 6	947.0	17789.0	30.6								
96	17-May-05												
97	18-May-05												
98	19-May-05		681.4										
99	20-May-05		734.6	18468.0	61.6								
100	21-May-05		759.0										
101	22-May-05		853.0										
102	23-May-05		907.2	20958.0									
103	24-May-05		1153.9							460.0	69.0	0.15	0.30
104	25-May-05		1002.1	19726.0	43.0								
105	26-May-05		969.2										
106	27-May-05		1133.5	19479.5	43.2		65.8						
107	28-May-05		1072.6										
108	29-May-05												
109	30-May-05		741.3	21123.3	34.9		113.0			460.0	50.1	0.11	0.35
110	31-May-05		907.0										
Batch Average		**6**	**912.4**	**19590.6**	**42.7**		**89.4**			**460.0**	**59.6**	**0.13**	**0.32**
111	1-Jun-05	Batch 7											
112	2-Jun-05		904.1										
113	3-Jun-05		830.2	22931.6	41.1		129.5						
114	4-Jun-05												
115	5-Jun-05		678.1										
116	6-Jun-05		905.8	20383.6	20.5		69.9						
117	7-Jun-05		888.4							460.0	81.5	0.18	0.36
118	8-Jun-05		846.6	20159.0	23.9		141.4						
119	9-Jun-05		788.8										
120	10-Jun-05		996.2	18328.8	43.0		76.0						
121	11-Jun-05		813.7										
122	12-Jun-05		669.8										
123	13-Jun-05		742.0	17760.0	24.0		158.0						
124	14-Jun-05		952.0							460.0	57.7	0.13	0.31
Batch Average		**7**	**834.6**	**19912.6**	**30.5**		**115.0**			**460.0**	**69.6**	**0.15**	**0.34**
125	15-Jun-05	Batch 8								460.0	51.2	0.11	0.37
126	16-Jun-05		660.0										
127	17-Jun-05		764.0										
128	18-Jun-05		652.0	18240.0	36.0		170.0						
129	19-Jun-05												
130	20-Jun-05		684.0	20240.0	42.0		82.0						
131	21-Jun-05		966.5										
132	22-Jun-05		986.0	18493.2	41.1		28.8						
Batch Average		**8**	**785.4**	**18991.1**	**39.7**		**93.6**			**460.0**	**51.2**	**0.11**	**0.37**
133	23-Jun-05	9											
134	24-Jun-05		995.0	19232.9	61.6		69.9			460.0	84.9	0.18	0.35
135	25-Jun-05		1052.0										
136	26-Jun-05		580.0										
137	27-Jun-05		648.0	18880.0	30.0		62.0						
138	28-Jun-05		902.0										

139	29-Jun-05	Batch	1004.0	17920.0	52.0		64.0						
140	30-Jun-05		1010.0	18480.0	40.0		76.0						
141	1-Jul-05		960.0	18720.0	40.0		120.0						
142	2-Jul-05		840.0										
143	3-Jul-05		1016.0										
144	4-Jul-05		1144.0	18560.0	28.0		120.0			460.0	85.8	0.19	0.33
145	5-Jul-05		980.0	18320.0	38.0		174.0			460.0	68.6	0.15	0.32
146	6-Jul-05		1136.0	18720.0	46.0		120.0			460.0	76.6	0.17	0.31
147	7-Jul-05		1056.0	18000.0	38.0		84.0						
Batch Average		**9**	**980.2**	**18537.0**	**41.5**		**98.9**			**460.0**	**79.0**	**0.17**	**0.33**
148	8-Jul-05	Batch 10	1072.0	19280.0	36.0		90.0						
149	9-Jul-05												
150	10-Jul-05												
151	11-Jul-05		891.4	18288.0	36.6		85.3						
152	12-Jul-05		901.9	18532.0	24.4		97.5						
153	13-Jul-05		965.1							460.0	80.4	0.17	0.35
154	14-Jul-05		1079.8	18531.8	38.6		121.9			460.0	80.4	0.17	0.33
155	15-Jul-05		1142.0	19263.0	20.3		79.2						
156	16-Jul-05									460.0	77.6	0.17	
157	17-Jul-05												
158	18-Jul-05		1123.7	18369.3	36.6		81.3						
159	19-Jul-05		953.0	19588.5	34.5		97.5						
160	20-Jul-05		1093.2	18856.9	20.3		73.2						
161	21-Jul-05		1060.8	17475.2	24.4		111.8						
162	22-Jul-05		991.6										
163	23-Jul-05												
164	24-Jul-05												
165	25-Jul-05		832.3	19502.4	24.5		79.6						
166	26-Jul-05		1079.2	19992.0	14.9		136.7			460.0	60.9	0.13	0.29
167	27-Jul-05		901.7	18849.6	32.6		102.0						
Batch Average		**10**	**1006.3**	**19004.9**	**28.6**		**92.7**			**460.0**	**74.8**	**0.16**	**0.32**
168	28-Jul-05	Batch 11	824.2										
169	29-Jul-05		1191.4	19176.0	34.7		99.9						
170	30-Jul-05												
171	31-Jul-05												
172	1-Aug-05		838.9	20726.0	40.8		95.9			460.0	52.9	0.12	0.33
173	2-Aug-05		1087.3	19665.6	36.7		104.0			460.0	63.3	0.14	0.30
174	3-Aug-05		1122.0							460.0	72.7	0.16	0.31
175	4-Aug-05		1014.0	18377.9	28.3		170.0						
176	5-Aug-05		1129.4	17730.2	74.9		121.4			460.0	73.4	0.16	0.31
177	6-Aug-05												
178	7-Aug-05												
179	8-Aug-05		935.1	18701.8	42.5		141.7			460.0	60.0	0.13	0.32
180	9-Aug-05		939.1	15625.3	32.4		111.3						
181	10-Aug-05		799.5	18944.6	36.4		151.8						
182	11-Aug-05												
183	12-Aug-05												
184	13-Aug-05												
185	14-Aug-05												
186	15-Aug-05		918.9	19349.4	46.6		111.3						
187	16-Aug-05		900.7	19673.3	38.5		174.1			460.0	37.6	0.08	0.29
188	17-Aug-05		985.7	17649.3	28.3		107.3			460.0	41.4	0.09	0.27
Batch Average		**11**	**975.9**	**18999.4**	**40.0**		**126.2**			**460.0**	**57.3**	**0.12**	**0.30**
189	18-Aug-05	Batch 12	802.4										
190	19-Aug-05		906.8										
191	20-Aug-05												
192	21-Aug-05												
193	22-Aug-05		894.6	17973.1	52.6		107.3						
194	23-Aug-05		1135.2	18539.8	54.6		101.2						
195	24-Aug-05		959.6	17406.4	62.7					460.0	67.8	0.15	0.33
196	25-Aug-05		888.7	18944.6	40.5								
197	26-Aug-05		830.2	18782.7	28.3		137.6						
198	27-Aug-05		866.3										
199	28-Aug-05												
200	29-Aug-05		896.9	16434.9	40.5		119.4						
201	30-Aug-05		870.6										
202	31-Aug-05		862.2	16839.7	52.6		139.1						

203	1-Sep-05		987.5	14977.6	48.6		103.2			460.0	29.6	0.06	0.25
204	2-Sep-05												
Batch Average		**12**	**887.8**	**17487.4**	**47.6**		**118.0**			**460.0**	**48.7**	**0.11**	**0.29**
205	3-Sep-05	Batch 13											
206	4-Sep-05												
207	5-Sep-05		829.5	15868.2	34.4					460.0	93.0	0.20	0.39
208	6-Sep-05		865.9	16093.4	40.6	48.8	101.6		256.0	538.5	75.3	0.14	0.34
209	7-Sep-05		926.4								70.2		
210	8-Sep-05		707.1	16581.1	52.8	60.0	113.8	1081.0	268.2	550.7	77.8	0.14	0.38
211	9-Sep-05		934.7	19019.0	44.7	73.2	97.5	723.4	284.5	532.4	70.0	0.13	0.32
212	10-Sep-05		918.5										
213	11-Sep-05												
214	12-Sep-05		910.3	16938.8	39.4	55.7	92.3	1005.4	222.3	425.5	72.3	0.17	0.35
215	13-Sep-05		827.9										
216	14-Sep-05		735.6	17719.0	20.3	54.9	91.4	1003.8	213.4	404.4	48.2	0.12	0.36
217	15-Sep-05		837.2										
218	16-Sep-05		918.5	16337.3	40.6	48.8	97.5			491.7			
Batch Average		**13**	**855.6**	**16936.7**	**39.0**	**56.9**	**99.0**	**953.4**	**248.9**	**486.2**	**72.4**	**0.15**	**0.36**
219	17-Sep-05	Batch 14	995.7										
220	18-Sep-05												
221	19-Sep-05		866.9	18288.0	26.5		185.5	1175.0	243.0	468.2	77.8	0.17	0.36
222	20-Sep-05		728.9										
223	21-Sep-05		920.4	16581.1	50.8	68.5	134.7	1232.5	315.8	594.1	67.3	0.11	0.31
224	22-Sep-05		926.3										
225	23-Sep-05		939.2	18531.8	46.7	44.7	48.8	1365.5	256.0	654.3	71.7	0.11	0.30
226	24-Sep-05		833.1										
227	25-Sep-05												
228	26-Sep-05		913.9	14467.8	36.6	38.6	111.8	1231.4	262.1	550.7			
229	27-Sep-05		924.7										
230	28-Sep-05		839.2	14711.7	37.5	59.6	139.1	1152.9	258.4	466.0	52.1	0.11	0.32
231	29-Sep-05		728.9								27.1	0.06	0.32
232	30-Sep-05		1175.0								30.3		0.17
233	1-Oct-05												
234	2-Oct-05		793.8										
235	3-Oct-05		897.6	18686.4	35.5		88.7				60.1		0.22
Batch Average		**14**	**869.9**	**16877.8**	**38.9**	**52.9**	**118.1**	**1231.5**	**267.1**	**546.7**	**55.2**	**0.11**	**0.29**
236	4-Oct-05	Batch 15											
237	5-Oct-05			18849.6	42.1	48.8	133.0	2607.7	368.1	634.2	69.6	0.11	
238	6-Oct-05		1224.0										
239	7-Oct-05		1241.7	19665.6	28.8	46.6	122.0	2494.6	37.7	525.5	60.8	0.12	0.26
240	8-Oct-05		767.2										
241	9-Oct-05												
242	10-Oct-05		860.9	17952.0	32.6	53.0	85.7	1362.7	359.0				
243	11-Oct-05		701.8										
244	12-Oct-05		807.8	20726.4	55.1	65.3	102.0	1256.6	273.4	673.2			
Batch Average		**15**	**933.9**	**19298.4**	**39.7**	**53.4**	**110.7**	**1930.4**	**259.5**	**611.0**	**65.2**	**0.11**	**0.26**
245	13-Oct-05	Batch 16											
246	14-Oct-05		979.2	20889.6	28.6	40.8	110.2	1468.8	297.8	971.0			
247	15-Oct-05		942.5										
248	16-Oct-05												
249	17-Oct-05		950.6	17136.0	55.1	95.9	106.1	1240.3	291.7	883.3			
250	18-Oct-05		995.5										
251	19-Oct-05		983.3	16809.6	30.6	79.6	75.5	1244.4	285.6	846.6	89.3	0.11	0.29
252	20-Oct-05										93.0		
253	21-Oct-05		1183.2	17462.4	65.3	130.6	95.9	1334.2	291.7	814.0	84.6	0.10	0.26
254	22-Oct-05												
255	23-Oct-05		938.4										
256	24-Oct-05		930.2	19665.6	61.2	77.5	187.7	1268.9	328.4	846.6			
257	25-Oct-05		967.0										
258	26-Oct-05		840.5	18931.2	61.2	83.6	124.4	1240.3	263.2	785.4	75.4	0.10	0.31
259	27-Oct-05												
Batch Average		**16**	**947.5**	**18482.4**	**50.3**	**84.7**	**116.6**	**1299.5**	**293.1**	**857.8**	**85.6**	**0.10**	**0.28**
260	28-Oct-05	7	599.8	17462.4	12.2	81.6	104.0	1224.0	202.0	911.9			
261	29-Oct-05		1011.8										
262	30-Oct-05												
263	31-Oct-05		869.0	20563.2	46.9	87.7	104.0	1281.1	253.0		68.8		0.23
264	1-Nov-05		1289.3								46.2		0.16

265	2-Nov-05	Batch 1	995.5	20889.6	40.8	55.1	100.0	1146.5	255.0	779.3	95.2	0.12	0.30
266	3-Nov-05		950.6								52.8	0.07	0.27
267	4-Nov-05		869.0	21950.4	4.1	28.6	71.4	1179.1	246.8	728.3			
268	5-Nov-05		954.7										
269	6-Nov-05												
270	7-Nov-05		865.0	18441.6	16.3	14.3	57.1	1150.6	793.6	222.4			
271	8-Nov-05		983.3										
272	9-Nov-05		901.7	19584.0	46.9	79.6	89.8	1252.6	263.2	767.0		0.09	
273	10-Nov-05		860.9								70.2		0.23
Batch Average		**17**	**926.2**	**19815.2**	**27.9**	**57.8**	**87.7**	**1205.6**	**244.0**	**681.8**	**66.6**	**0.10**	**0.24**
274	11-Nov-05	Batch 18	897.6	25622.4	55.1	65.3	106.1	1183.2	297.8	577.3			
275	12-Nov-05		869.0										
276	13-Nov-05												
277	14-Nov-05												
278	15-Nov-05		852.7	19584.0	32.6	40.8	89.8	1273.0			89.3		
279	16-Nov-05		954.7	20155.2	53.0	51.0	100.0	1379.0					
280	17-Nov-05												
281	18-Nov-05		1003.7	26356.8	49.0	51.0	87.7	1150.6	240.7	752.8	85.8	0.11	0.29
282	19-Nov-05		889.4										
283	20-Nov-05												
284	21-Nov-05		848.6										
285	22-Nov-05		909.8	19992.0	61.2	46.9	71.4	1224.0	246.8	707.9	105.8	0.15	0.34
286	23-Nov-05		918.0	20318.4	34.7	34.7	114.2						
287	24-Nov-05		958.8								71.3		
288	25-Nov-05		877.2	20073.6	44.9	26.5	91.8	1142.4	289.7	544.7	85.7	0.16	0.35
289	26-Nov-05										112.2		
290	27-Nov-05		905.8								103.7		
291	28-Nov-05		999.6	20726.4	44.9	61.2	110.2						
Batch Average		**18**	**914.2**	**21603.6**	**46.9**	**47.2**	**96.4**	**1225.4**	**268.8**	**645.7**	**93.4**	**0.14**	**0.33**
292	29-Nov-05	Batch 19	1122.0										
293	30-Nov-05		885.4	21134.4	40.8	63.2	161.2	1554.5	271.3	985.3			
294	1-Dec-05		1020.0							826.2	106.4	0.13	0.30
295	2-Dec-05		1085.3	20726.4	85.7	73.4	130.6	1444.3	344.8	793.6			
296	3-Dec-05												
297	4-Dec-05		975.1							818.0	125.6	0.15	0.33
298	5-Dec-05		1020.0	21950.4	20.4	61.2	128.5	1411.7	304.0	436.6			
299	6-Dec-05												
300	7-Dec-05		767.0							559.0			
301	8-Dec-05		1060.8	23337.6	44.9	59.2	142.8	1419.8	285.6				
302	9-Dec-05		962.9	23011.2	34.7	36.7	138.7	1403.5	308.0	897.6			
303	10-Dec-05												
304	11-Dec-05										72.4	0.08	
305	12-Dec-05		1244.4								78.7	0.09	0.23
306	13-Dec-05		1211.8	23419.2	91.8	44.9	122.4	1685.0	322.3	883.3	85.0	0.10	0.25
307	14-Dec-05		1077.1								147.2	0.17	0.32
308	15-Dec-05		1183.2	18849.6	67.3	71.4	151.0						
309	16-Dec-05												
310	17-Dec-05												
311	18-Dec-05												
312	19-Dec-05												
Batch Average		**19**	**1070.7**	**21775.5**	**55.1**	**58.6**	**139.3**	**1486.5**	**306.0**	**774.9**	**102.5**	**0.12**	**0.29**
313	20-Dec-05	Batch 20											
314	21-Dec-05												
315	22-Dec-05												
316	23-Dec-05												
317	24-Dec-05												
318	25-Dec-05												
319	26-Dec-05												
320	27-Dec-05												
321	28-Dec-05												
322	29-Dec-05												
323	30-Dec-05												
324	31-Dec-05												
325	1-Jan-06												
326	2-Jan-06												
Batch Average		**20**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
327	3-Jan-06												

328	4-Jan-06	Batch 21											
329	5-Jan-06												
330	6-Jan-06												
331	7-Jan-06												
332	8-Jan-06												
333	9-Jan-06												
334	10-Jan-06												
335	11-Jan-06												
336	12-Jan-06												
337	13-Jan-06												
338	14-Jan-06												
339	15-Jan-06												
340	16-Jan-06												
341	17-Jan-06												
Batch Average		**21**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
342	18-Jan-06	Batch 22											
343	19-Jan-06												
344	20-Jan-06		1044.5	16809.6	36.7								
345	21-Jan-06												
346	22-Jan-06		1048.6										
347	23-Jan-06		1064.9	17625.6	71.4	83.6	128.5			983.3	166.5	0.17	0.33
348	24-Jan-06		1044.5							1013.9	83.9	0.08	0.26
349	25-Jan-06			16646.4	71.4	79.6	148.9	1248.5	308.0	1013.9	65.1	0.06	
350	26-Jan-06		869.0										
351	27-Jan-06		942.5	18441.6	55.1	61.2	126.5	1330.1	287.6	807.8			
352	28-Jan-06												
353	29-Jan-06		1113.8										
354	30-Jan-06		942.5	17544.0	57.1	63.2	132.6			836.4	82.6	0.10	0.29
Batch Average		**22**	**1008.8**	**17413.4**	**58.3**	**71.9**	**134.1**	**1289.3**	**297.8**	**931.1**	**99.5**	**0.10**	**0.29**
355	31-Jan-06	Batch 23	987.4							787.4			
356	1-Feb-06		1048.6	19747.2	51.0	85.7	106.1			873.1			
357	2-Feb-06		913.9							703.8			
358	3-Feb-06		820.1	18686.4	42.8	61.2	91.8			665.0			
359	4-Feb-06		652.8										
360	5-Feb-06												
361	6-Feb-06		901.7	13790.4	55.1	44.9	75.5	1117.9	261.1	732.4	101.0	0.14	0.33
362	7-Feb-06		938.4							750.7	75.8	0.10	0.29
363	8-Feb-06		954.7	15177.6	38.8	42.8	89.8	1085.3	257.0	775.2	54.3	0.07	0.26
364	9-Feb-06		946.6								105.6	0.14	0.32
365	10-Feb-06		913.9					1069.0	208.1	754.8	86.6	0.11	0.31
366	11-Feb-06		922.1										
367	12-Feb-06		950.6										
368	13-Feb-06		950.6	9384.0	40.8	61.2	124.4	1040.4	265.2	826.2			
369	14-Feb-06		979.2	18604.8	55.1	69.4	118.3			781.3			
Batch Average		**23**	**940.6**	**15898.4**	**47.3**	**60.9**	**101.0**	**1078.1**	**247.9**	**765.0**	**84.7**	**0.11**	**0.30**
370	15-Feb-06	Batch 24	918.0										
371	16-Feb-06		811.9							442.7	59.1	0.13	0.35
372	17-Feb-06		803.8	20400.0	40.8	65.3	69.4	1154.6	253.0	675.2	59.6	0.09	0.32
373	18-Feb-06										62.0	0.11	
374	19-Feb-06												
375	20-Feb-06		758.9							689.5			
376	21-Feb-06		787.4	20971.2	53.0	55.1	142.8			499.8			
377	22-Feb-06		783.4										
378	23-Feb-06		624.2	16238.4	55.1			1117.9	242.8				
379	24-Feb-06		632.4	20155.2	42.8	71.4	116.3	1138.3	248.9				
380	25-Feb-06		799.7							724.2	93.5	0.13	0.35
381	26-Feb-06		885.4										
382	27-Feb-06		856.8	19502.4	59.2	77.5	163.2	1219.9	344.8	826.2	93.1	0.11	
383	28-Feb-06												
Batch Average		**24**	**787.4**	**19453.4**	**50.2**	**67.3**	**122.9**	**1157.7**	**272.3**	**642.9**	**73.5**	**0.11**	**0.34**
384	1-Mar-06	Batch 25	1028.2	18775.7	32.5	87.4	128.0						
385	2-Mar-06		735.6							495.8			
386	3-Mar-06												
387	4-Mar-06		860.9								194.4		0.23
388	5-Mar-06		901.7							750.7			
389	6-Mar-06		926.2	18033.6	38.8	85.7	126.5	807.8	318.2	736.4	146.3	0.20	0.37
390	7-Mar-06		879.1	18254.8	31.5	75.7	109.4			700.3	307.3		0.23

391	8-Mar-06		1030.5	19012.0	65.2	96.7	113.6	820.2		778.1	284.2		0.19
Batch Average		**25**	**908.9**	**18519.0**	**42.0**	**86.4**	**119.4**	**814.0**	**318.2**	**692.3**	**233.0**	**0.20**	**0.38**
392	9-Mar-06	Batch 26	1179.1	19502.4	44.9	83.6				958.8			
393	10-Mar-06										227.4	0.19	
394	11-Mar-06		1195.4										
395	12-Mar-06		897.6										
396	13-Mar-06		958.8	19176.0	53.0	104.0	120.4						
397	14-Mar-06		1007.8							781.3	148.9	0.19	0.35
398	15-Mar-06		910.3	19751.0	34.5	91.4	107.7	1475.2	278.4	737.6	124.2	0.17	0.35
399	16-Mar-06		1011.9							823.0	123.2	0.15	0.32
400	17-Mar-06		869.7	19588.5	54.9	89.4	132.1	1430.5	274.3	690.9	102.9	0.15	0.34
401	18-Mar-06		910.3							751.8	129.9	0.17	0.35
402	19-Mar-06		1081.0							747.8	148.9	0.20	0.35
403	20-Mar-06		1016.0	19100.8	61.0	89.4	166.6	1398.0	290.6	804.7	123.2	0.15	0.32
404	21-Mar-06										119.1	0.16	
405	22-Mar-06		886.0										
406	23-Mar-06		934.7	19019.5	44.7	85.3	166.6	1341.1	280.4		111.0	0.14	0.33
Batch Average		**26**	**989.1**	**19356.4**	**48.8**	**90.5**	**138.7**	**1411.2**	**280.9**	**762.4**	**125.7**	**0.17**	**0.34**
407	24-Mar-06	Batch 27	1097.3	20238.7	38.6	93.5	158.5	1560.6	323.1	995.7			
408	25-Mar-06		938.8										
409	26-Mar-06		930.7							749.8	132.6	0.18	0.35
410	27-Mar-06		1068.8	19425.9	14.2	0.0	144.3	1434.6	288.5	859.5	108.3	0.13	0.29
411	28-Mar-06		860.9							667.1	86.6	0.13	0.33
412	29-Mar-06		913.9	16809.6	12.2	49.0	114.2	1244.4	242.8	769.1	86.6	0.11	0.31
413	30-Mar-06		811.9							599.8			0.25
414	31-Mar-06		746.6	16646.4	26.5	69.4	126.5	1211.8	193.8				
415	1-Apr-06		799.7							785.4	138.1	0.18	0.38
416	2-Apr-06		950.6							728.3	125.9	0.17	0.35
417	3-Apr-06		1028.2	20236.8	53.0	102.0	122.4	1346.4	259.1	860.9			
418	4-Apr-06		1293.4							897.6	151.6	0.17	0.30
419	5-Apr-06		1040.4	20073.6	51.0	89.8	138.7	1089.4	255.0	799.7			
420	6-Apr-06		1428.0										
421	7-Apr-06		1089.4										
Batch Average		**27**	**969.3**	**18905.2**	**32.6**	**67.3**	**134.1**	**1314.5**	**260.4**	**792.1**	**118.5**	**0.15**	**0.32**
422	8-Apr-06	Batch 28	926.2										
423	9-Apr-06		999.6										
424	10-Apr-06		909.8	35740.8	53.0	104.0	102.0	1097.5	269.3				
425	11-Apr-06									652.8	71.7	0.11	
426	12-Apr-06		1069.0							787.4	117.8	0.15	0.31
427	13-Apr-06			18931.2	30.6		177.5	1093.4	230.5		169.2		
428	14-Apr-06		1024.1							901.7	104.2	0.12	0.29
429	15-Apr-06		1028.2	18686.4	26.5	91.8	128.5	1007.8		787.4	108.3	0.14	0.31
430	16-Apr-06		999.6							767.0			
431	17-Apr-06		1166.9							860.9	141.9	0.16	0.31
432	18-Apr-06		1069.0	19257.6	73.4	126.5	134.6				136.7		0.19
433	19-Apr-06		1317.8							901.7	106.9	0.12	0.25
434	20-Apr-06		1350.5							893.5			
435	21-Apr-06		1383.1	20726.4	73.4	106.1	120.4	1962.5	981.2	885.4			
436	22-Apr-06		1258.9							878.4	150.2		0.16
Batch Average		**28**	**1115.6**	**19400.4**	**51.4**	**107.1**	**132.6**	**1290.3**	**493.7**	**851.5**	**123.0**	**0.13**	**0.26**
437	23-Apr-06	Batch 29	922.9							894.6			
438	24-Apr-06		1226.5	20806.7	52.6	103.2	153.8	1485.6	291.5	1246.8			
439	25-Apr-06		1028.2								197.6	0.21	0.36
440	26-Apr-06		910.8	21373.4	30.4	81.0	115.4	1335.8	271.2	748.9	150.3	0.20	0.38
441	27-Apr-06		632.4										
442	28-Apr-06		999.6	21297.6	53.0	85.7	173.4	1354.6	306.0	799.7			
443	29-Apr-06		820.1							750.7			
444	30-Apr-06		926.2								135.4	0.17	0.35
445	1-May-06		1040.4	20073.6	69.4	100.0	146.9	1342.3	253.0	889.4			
446	2-May-06		962.9										
447	3-May-06		1105.7	18768.0	46.9	93.8	126.5	1256.6	244.8	881.3	94.7	0.11	0.27
448	4-May-06		967.0								89.3		
449	5-May-06		889.4	18360.0	44.9	106.1	144.8	1171.0	236.6	714.0	82.6	0.12	0.31
Batch Average		**29**	**983.3**	**20113.2**	**49.5**	**95.0**	**143.5**	**1324.3**	**267.2**	**811.2**	**131.7**	**0.16**	**0.33**

Appendix A-2

Measured TKN, FSA and solids concentrations in the MBR UCT system

			TKN			FSA		TSS				VSS		
Day	Date	SB #	Infl.	ML	Effl.	Infl.	Effl.	AN	AX	AE	RE	AN	AX	AE
			(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgTSS/l)	(mgTSS/l)	(mgTSS/l)	(mgTSS/l)	(mgVSS/l)	(mgVSS/l)	(mgVSS/l)
19	1-Mar-05							6660	11514	19854			9738	16582
20	2-Mar-05							8226	14256	17822		6836	11658	14500
21	3-Mar-05	Batch 2						9374	15348	19526		7554	12058	15144
22	4-Mar-05							8018	14214	17276		6626	11490	13850
23	5-Mar-05													
24	6-Mar-05													
25	7-Mar-05		104.4	1125.6	2.1	84.1	2.2	7768	12866	15066		6496	10528	12268
26	8-Mar-05		101.9	1192.8	1.8	88.2	0.6	8324	13916	17516		6834	11206	14026
27	9-Mar-05		99.1	952.0	5.5	72.7	1.5	8020	13078	17186		6664	10638	13840
28	10-Mar-05		112.0			86.0								
29	11-Mar-05		89.3	1108.8	2.0	69.1	0.0	7010	12388	15754		5756	10002	12594
30	12-Mar-05													
31	13-Mar-05													
32	14-Mar-05		94.5	940.8	3.8	75.7	1.3	7568	12132	15128		6136	9658	12016
33	15-Mar-05		91.2	1212.4	2.2	69.7	0.9	8402	13890	17438		6804	11108	13888
34	16-Mar-05		96.3	1092.0	4.3	80.7	1.6	8124	13272	17402		6626	10688	13934
35	17-Mar-05		115.0	1092.0	4.3	94.6	1.6	6924	9580	15456		5736	7850	12506
36	18-Mar-05		110.6			89.9		6950	11644	14884		5736	9430	11982
Batch Average		**2**	**101.4**	**1089.6**	**3.3**	**81.1**	**1.2**	**7711**	**13275**	**16311**		**6452**	**10681**	**13277**
37	19-Mar-05	Batch 3												
38	20-Mar-05													
39	21-Mar-05		140.0	1055.6	5.0	102.5	3.6	8800	12010	14144		7380	9890	11686
40	22-Mar-05		89.0			65.7		6636	12020	15212		5474	9870	12442
41	23-Mar-05		123.1	1131.2	3.2	101.7	1.1	7382	12594	15292				
42	24-Mar-05							8222	12598	15540		6896	10528	13002
43	25-Mar-05		141.4	1176.0	2.0	105.0	4.2	7658	12412	15306		6524	10256	12566
44	26-Mar-05													
45	27-Mar-05		114.8	1139.6	2.7	93.0	1.5	9460	13058	14362		8054	10868	11996
46	28-Mar-05													
47	29-Mar-05		111.2	1324.4	4.5	101.6	7.1	6482	15210	17650		5678	12416	14376
48	30-Mar-05		151.8			134.7								
49	31-Mar-05		134.7	1414.0	2.5	102.4	2.4	8034	14192	18604		6792	11592	15208
50	1-Apr-05		150.1			109.9								
51	2-Apr-05		160.4	1274.0		116.2	2.2	7760	13200	16770		6396	10634	13400
52	3-Apr-05													
53	4-Apr-05		166.8	1100.4	7.6	148.1	1.5	11860	14436	15570		9698	11606	12454
Batch Average		**3**	**139.4**	**1201.9**	**3.9**	**107.3**	**2.4**	**7826**	**13173**	**15845**		**6649**	**10851**	**13014**
54	5-Apr-05	Batch4	113.1			83.9		7036	13374	16450		5956	10940	13374
55	6-Apr-05													
56	7-Apr-05													
57	8-Apr-05		97.4	1190.0		64.7	1.1	7906	13178	15692		6538	10578	12446
58	9-Apr-05													
59	10-Apr-05		99.4	1293.6	1.7	68.6	1.8	6334	13040	16776		5484	10694	13624
60	11-Apr-05		105.3			83.7								
61	12-Apr-05		98.0	1313.2	5.0	75.4	1.3	8422	4562	18324		6844	11596	14522
62	13-Apr-05		67.1			51.0								
63	14-Apr-05		108.7	1341.2	3.2	80.0	2.2	8208	14136	19392		6832	11462	15576
64	15-Apr-05		75.9			51.5								
65	16-Apr-05		91.8	1156.4	1.6	60.5	2.2	7514	12710	16124		6322	10250	12964
66	17-Apr-05													
67	18-Apr-05		89.9			77.8		5794	10516	14146		4944	8574	11328
68	19-Apr-05		96.3	1148.0	2.1	62.7	0.0	6038	10764	13510		5038	8694	10748
69	20-Apr-05		105.1			81.2		5338	9706	12922		4430	7806	10250
70	21-Apr-05		105.4			78.1		6158	11316	14272		5018	9076	11380
71	22-Apr-05		90.4			69.6		4198	6642	7968		3636	5564	6390

A-2 MBR TKN FSA / TSS VSS

72	23-Apr-05		86.5	686.0	4.1	59.9	1.0	4270	6866	8340		3670	5640	6672
73	24-Apr-05													
74	25-Apr-05		95.3	624.4	10.2	71.8	1.1	3090	6014	8744		2730	5038	7110
75	26-Apr-05		94.2			71.8								
Batch Average		**4**	**97.0**	**1094.1**	**3.0**	**70.1**	**1.3**	**6177**	**10217**	**14051**		**5188**	**8916**	**11260**
76	27-Apr-05	Batch 5												
77	28-Apr-05													
78	29-Apr-05		105.3	736.4	2.00	81.5	1.0	4686	7804	10350		3972	6384	8282
79	30-Apr-05													
80	1-May-05													
81	2-May-05		12.0	856.8	2.59	12.6	0.8	7024	10490	12184				
82	3-May-05							3658	7534	16382		3122	6204	13106
83	4-May-05		116.2	1500.8	2.80	88.3	1.7	2416	9092	16850		1970	7340	12782
84	5-May-05		115.2			89.9								
85	6-May-05		93.1	1901.2	0.74	78.9	0.8							
86	7-May-05		136.1											
87	8-May-05		95.8											
88	9-May-05		119.4	1307.6	2.70	87.8	1.6	7048	12542	17218		5840	10474	13788
89	10-May-05		99.1			84.3		7770	12730	16156		6516	10408	13148
90	11-May-05		108.2	1226.4	1.89	79.9	1.3	6740	12356	16728		5642	9978	13406
91	12-May-05		123.8			103.5		7636	13654	18604		6282	10976	14888
92	13-May-05		113.1	1341.2	2.87	95.6	1.2	7112	13096	18412		5938	10622	14820
93	14-May-05		125.7			96.0								
94	15-May-05													
Batch Average		**5**	**112.6**	**1267.2**	**2.23**	**88.6**	**1.2**	**6010**	**11033**	**16567**		**4910**	**9048**	**13705**
95	16-May-05	Batch 6	119.6	1248.8	0.8	93.8	0.5	6948	11976	17042		5806	9796	13784
96	17-May-05							5536	12696	18386		4438	10026	14576
97	18-May-05													
98	19-May-05							7592	12766	16940		6170	10170	13450
99	20-May-05		113.0		2.9	88.5	1.3	6974	12100	15856		5640	9668	12678
100	21-May-05							7092	12178	16056		5926	10438	13268
101	22-May-05													
102	23-May-05		148.1	1268.0	1.9	112.6	0.8	7808	13640	18318		6502	11104	14832
103	24-May-05		146.6			117.0		10256	13372	14350		8350	10770	11468
104	25-May-05		138.1	1151.0	0.7	109.2	0.9	7144	12866	17884		5922	10442	14412
105	26-May-05		130.1			101.5		6984	12678	17130		5844	10334	13862
106	27-May-05		143.2	1184.4	1.8	100.3	1.1	7678	13362	17418		6610	10932	14206
107	28-May-05													
108	29-May-05													
109	30-May-05		132.9	1456.0	1.6	103.8	1.4	7604	15654	18724		6194	12512	14860
110	31-May-05		130.8			109.9		8230	15822	18686		6692	12630	14880
Batch Average		**6**	**133.6**	**1261.6**	**1.6**	**104.1**	**1.0**	**7235**	**13026**	**17495**		**5977**	**10563**	**14073**
111	1-Jun-05	Batch 7						8534	15260	19886		7016	12238	15888
112	2-Jun-05							7740	15348	20398		6506	12470	16410
113	3-Jun-05		99.5	1397.2	2.3	79.8	0.9	7456	14464	20310		6220	11624	16202
114	4-Jun-05													
115	5-Jun-05													
116	6-Jun-05		83.4	1288.0	1.1	83.8	0.2	8012	15670	20086		6584	12518	15960
117	7-Jun-05		92.0			74.3		7790	14822	17638		6398	11942	14086
118	8-Jun-05		88.6	1184.4	1.2	71.8	0.0	7118	14294	17790		5828	11382	14062
119	9-Jun-05		86.9			74.8								
120	10-Jun-05		97.3	1159.2	2.1		1.1	7122	14776	17408		5888	11834	13808
121	11-Jun-05							7140	12776	15562		5852	9856	12456
122	12-Jun-05							7134	12916	15578		5872	10068	11830
123	13-Jun-05		95.5	1064.0	0.9	79.5	0.0	7390	14468	15926		6022	11496	12656
124	14-Jun-05		101.8			78.5								
Batch Average		**7**	**93.1**	**1218.6**	**1.5**	**77.5**	**0.4**	**7434**	**14479**	**18058**		**6219**	**11543**	**14336**
125	15-Jun-05	atch 8						7642	14634	17706		6242	11660	13730
126	16-Jun-05							10498	14564	15290		8318	11410	11756
127	17-Jun-05													
128	18-Jun-05		129.1	1209.6	1.9	90.4	0.0	7594	15500	18470		6252	12438	14688
129	19-Jun-05		101.8											

A-2 MBR TKN_FSA / TSS_VSS

130	20-Jun-05	Ba	123.1	1254.4	0.7	77.0	1.2	7896	15424	19078		6500	12332	15122
131	21-Jun-05		137.3			52.6		8530	14300	16704		6904	11388	13166
132	22-Jun-05		145.4	1159.2	0.3	84.0	0.2	7580	14198	19356		6184	11214	13248
Batch Average		**8**	**127.3**	**1207.7**	**1.0**	**76.0**	**0.5**	**8290**	**14770**	**17767**		**6733**	**11740**	**13618**
133	23-Jun-05	Batch 9						9200	14798	19356		7486	11792	15290
134	24-Jun-05		133.3	901.6	1.47	73.3	0.3	6958	12284	16258		5746	9816	12730
135	25-Jun-05													
136	26-Jun-05													
137	27-Jun-05		103.7	1192.8	3.40	67.2	2.6	7158	13298	17490		5870	10608	13806
138	28-Jun-05		115.5	1159.2	1.80	68.3	0.5	7576	13896	18298		6174	11012	14348
139	29-Jun-05		121.5	1173.2	1.20	75.9	0.4	7458	13444	17460		6028	10592	13614
140	30-Jun-05		117.6	1215.2	0.00	69.1	2.1	7652	13730	18280		6192	10806	14236
141	1-Jul-05		112.4	1008.0	0.80	94.4	0.6	7152	13788	18634		5790	10784	14448
142	2-Jul-05													
143	3-Jul-05													
144	4-Jul-05		121.9	1114.4	2.00	102.2	0.9	7176	13726	17996		5808	10764	13894
145	5-Jul-05		124.1	1131.2	1.30	75.1	0.4	7466	13270	17364		5866	10062	12912
146	6-Jul-05		119.4	1122.8	2.30	93.5	0.7	7370	13626	18074		6062	10840	14174
147	7-Jul-05		108.4	1162.0	1.80	67.8	0.0	6896	13142	18328		5632	10428	14492
Batch Average		**9**	**117.8**	**1142.1**	**1.4**	**78.7**	**0.7**	**7286**	**13420**	**18128**		**5917**	**10571**	**13995**
148	8-Jul-05	Batch 10	91.3	1187.2	1.7	71.4	0.4	6830	13078	18574		5532	10256	14492
149	9-Jul-05													
150	10-Jul-05													
151	11-Jul-05		91.7	1229.2	1.8	58.8	0.4	7550	14802	17192		6272	11952	13790
152	12-Jul-05		91.6	1290.8	1.4	56.8	0.4	7450	13890	17348		6212	11246	13870
153	13-Jul-05		93.3			73.6		7492	13790	17052		6272	11166	13650
154	14-Jul-05		100.1	1117.2	2.5	73.2	0.9	7798	14576	17972		6552	11918	14586
155	15-Jul-05		90.9	1226.4	0.8	73.9	0.4	6882	14406	18120		5760	11696	14576
156	16-Jul-05													
157	17-Jul-05													
158	18-Jul-05		99.7	1162.0	1.8	69.2	0.7	7428	14908	16610		6230	12200	13450
159	19-Jul-05		92.0	1125.6	1.6	62.1	0.1	6990	13886	16980		5976	11462	13930
160	20-Jul-05		87.5	1150.8	1.4	62.9	0.5	6986	13394	17082		5928	11058	14028
161	21-Jul-05		95.1	1178.8	1.5	67.0	0.6	7324	14556	18674		6352	12252	15596
162	22-Jul-05		87.9			70.1								
163	23-Jul-05							8096	14148	17590		6750	11614	14322
164	24-Jul-05													
165	25-Jul-05		90.9	1240.4	1.4	72.9	1.2	7778	15484	18180		6736	12972	15052
166	26-Jul-05		87.5	1243.2	1.4	69.6	0.1	7944	13912	17922		6632	11396	14606
167	27-Jul-05		89.5	1204.0	2.1	64.6	0.2	7658	15818	17602		6422	12958	14318
Batch Average		**10**	**91.5**	**1196.3**	**1.5**	**67.6**	**0.4**	**7443**	**14332**	**17636**		**6315**	**11838**	**14205**
168	28-Jul-05	Batch 11						7830	14388	19344		6660	11828	15776
169	29-Jul-05		90.7	1232.0	1.1	59.1	0.7	7188	14482	17474		6112	11930	14242
170	30-Jul-05							6802	12308	16090		5744	10078	13088
171	31-Jul-05													
172	1-Aug-05		88.8	1285.2	0.3	75.4	0.5	8018	14040	19264		6666	11470	15634
173	2-Aug-05		95.3	1302.0	0.4	73.2	0.7	6812	14244	17754		5706	11538	14332
174	3-Aug-05		102.5			80.9		6812	14244	17754		5706	11538	14332
175	4-Aug-05		93.7	1120.0	1.1	70.4	0.2	6864	12932	17668		5834	10650	14444
176	5-Aug-05		108.8	1111.6	1.1	82.2		7140	13054	15810		6080	10720	12908
177	6-Aug-05													
178	7-Aug-05													
179	8-Aug-05		95.3	1128.4	0.6	75.7	0.2	6642	15644	16910		5664	12768	13796
180	9-Aug-05		94.9	1058.4	1.3	82.0	0.2	6526	12296	16064		5488	10006	13026
181	10-Aug-05		97.1	1226.4	1.2	73.9	0.2	7030	13036	17368		5832	10560	14022
182	11-Aug-05							8290	14294	15880		6972	11698	12928
183	12-Aug-05							7214	13238	15492		6070	10800	12584
184	13-Aug-05													
185	14-Aug-05													
186	15-Aug-05		89.2	1120.0	0.7	74.9	0.0	7668	15722	16800		6388	12814	13614
187	16-Aug-05		89.6	1128.4	0.8	78.0	0.4	7644	14266	17330		6290	11508	14022
188	17-Aug-05		89.5	1106.0	1.1	73.7	0.0	7474	13468	17400		6144	10894	13950

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Batch Average		**11**	**93.3**	**1165.3**	**0.9**	**76.4**	**0.3**	**7178**	**13854**	**17150**		**6026**	**11300**	**13795**
189	18-Aug-05	Batch 12	69.2			54.9		7564	12710	16894		6280	10324	13672
190	19-Aug-05							7402	12730	16146		6118	10274	12930
191	20-Aug-05													
192	21-Aug-05													
193	22-Aug-05							6760	13432	15800		5674	10878	12666
194	23-Aug-05		138.5			111.2		8724	12646	15710		7200	10254	12670
195	24-Aug-05		144.3			107.4		10660	14932	15938		8684	12082	12744
196	25-Aug-05		110.3	1190.0	0.6	86.8	1.0	8038	13800	17608		6704	11270	14192
197	26-Aug-05		110.0	1181.6	1.5	87.4		7370	12824	17518		6026	10224	13910
198	27-Aug-05							7378	13330	16752		6146	10772	13450
199	28-Aug-05													
200	29-Aug-05		142.1	994.0	0.0	107.1	0.8	10778	14886	15280		8722	11866	12128
201	30-Aug-05		128.1			98.3		7786	13014	16718		6374	10328	13268
202	31-Aug-05		137.5	1089.2	1.5	97.4	0.4	6262	14054	14960		5164	11142	13176
203	1-Sep-05		142.9	996.8	1.8	101.4	0.4	7564	12582	15280		6410	10098	12104
204	2-Sep-05							7696	12194	15086		6330	9654	13868
Batch Average		**12**	**131.7**	**1090.3**	**1.1**	**99.6**	**0.6**	**7504**	**13318**	**16130**		**6221**	**10705**	**13137**
205	3-Sep-05	Batch 13												
206	4-Sep-05													
207	5-Sep-05		87.4	910.0	0.8	75.1	0.4	11644	14108	14912		9302	11196	11780
208	6-Sep-05		99.5	870.8	0.5	69.4	0.4	7606	13556	18050		6484	11032	14496
209	7-Sep-05		103.5			68.2		7542	13792	18458		6296	11118	14700
210	8-Sep-05		111.6	1069.6	1.8	112.3	0.7	7274	13128	17302		5968	10520	13692
211	9-Sep-05		101.5	1142.4	1.4	82.1	0.0	9246	14814	17970		7402	11654	14042
212	10-Sep-05													
213	11-Sep-05													
214	12-Sep-05		101.9	1075.2	1.6	86.4	0.6	7160	12472	17118		5796	9804	13352
215	13-Sep-05		101.5			78.0		7002	12362	15252		5836	9860	12056
216	14-Sep-05		99.3	1100.4	1.7	91.1	0.3	6756	12904	17080		5572	10268	13422
217	15-Sep-05							6622	14436	16782		5368	11368	13114
218	16-Sep-05		105.7	1229.6	2.3	83.1	0.6	6756	13768	15878		5550	10840	12302
Batch Average		**13**	**101.3**	**1056.9**	**1.4**	**79.2**	**0.4**	**7329**	**13534**	**16880**		**6030**	**10766**	**13296**
219	17-Sep-05	Batch 14												
220	18-Sep-05													
221	19-Sep-05		113.1	1278.3	1.6	94.0	0.5							
222	20-Sep-05							8084	12834	16836		6508	10076	13150
223	21-Sep-05		114.8	1168.7	1.8	92.3	0.4	7496	12528	16008		5992	9774	12448
224	22-Sep-05		102.3			85.1		7088	12618	16158		5750	9956	12662
225	23-Sep-05		106.3	966.0	1.7	84.1	1.2	6840	11740	15774		5522	9158	12204
226	24-Sep-05													
227	25-Sep-05													
228	26-Sep-05		106.3	775.6	0.8	89.3	0.4	6844	11350	14286		5508	8900	11068
229	27-Sep-05		122.9			104.9		7588	12310	15584		6284	9846	12322
230	28-Sep-05		109.6	856.8	1.1	94.2	0.0	9484	12556	13808		7526	9784	10714
231	29-Sep-05		117.6			97.3		8476	13958	17666		6850	10974	13832
232	30-Sep-05		135.2			109.2		8152	13842	17414		6686	10926	13748
233	1-Oct-05													
234	2-Oct-05													
235	3-Oct-05		118.7	1279.6	0.6	96.6	0.0	8326	13614	17084		6628	10612	13246
Batch Average		**14**	**112.4**	**1054.2**	**1.3**	**94.7**	**0.4**	**7838**	**12735**	**16062**		**6325**	**10001**	**12539**
236	4-Oct-05	Batch 15						8716	13510	16628		6994	10614	12966
237	5-Oct-05		106.1	1220.8	1.0	76.2	0.9	8768	13740	17294		7056	10844	13564
238	6-Oct-05													
239	7-Oct-05		109.5	1254.4	1.5	83.2	0.2	8432	13898	18212		6808	11008	14316
240	8-Oct-05													
241	9-Oct-05													
242	10-Oct-05		120.4	1033.2	2.4	90.2	3.9	8402	13472	17104		6866	10704	13488
243	11-Oct-05							6943	11153	16947	12308	5697	8872	13373
244	12-Oct-05		98.3	1380.4	0.4	80.4	0.0	7032	13152	18884		5856	10564	15032
Batch Average		**15**	**108.6**	**1222.2**	**1.3**	**82.5**	**1.3**	**8049**	**13554**	**17512**	**12308**	**6546**	**10747**	**13790**
245	13-Oct-05							6942	13326	18108		5728	10618	14310

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246	14-Oct-05	Batch 16	94.4	1316.0	1.9	77.0	0.0	6958	12960	18024	13366	5798	10374	14316
247	15-Oct-05													
248	16-Oct-05													
249	17-Oct-05		105.3	1047.2	3.7	83.4	1.0	6966	12876	17208		5790	10286	13534
250	18-Oct-05							6756	12496	16656		5608	9956	13138
251	19-Oct-05		105.8	1027.6	3.4	84.0	0.2	8342	12938	15898		8710	10158	12418
252	20-Oct-05							7880	12820	15852	12862	6442	10178	12474
253	21-Oct-05		137.8	1187.2	1.5	79.2	0.9	7088	12548	16256	12370	5770	9888	12702
254	22-Oct-05													
255	23-Oct-05													
256	24-Oct-05		108.9	1503.6	0.0	73.9	0.5	7148	13178	17180	13354	5820	10378	13382
257	25-Oct-05							6980	12864	17508	12716	5654	10108	13648
258	26-Oct-05		101.1	1055.6	0.5	76.4	0.0	7406	13174	17956	13030	6020	10386	14012
259	27-Oct-05							7448	13262	17620	13358	7082	10420	13744
Batch Average		**16**	**108.9**	**1189.5**	**1.8**	**79.0**	**0.4**	**7157**	**12949**	**17115**	**13008**	**5971**	**10250**	**13425**
260	28-Oct-05	Batch 17	96.6	1092.0	4.0	83.4	1.8	6784	12696	17398	13026	5568	10066	13562
261	29-Oct-05													
262	30-Oct-05													
263	31-Oct-05		92.4	1268.4	1.3	64.7	0.8	6996	13296	18124	13148	5710	10488	14188
264	1-Nov-05							8262	14022	17904	13838	6698	11092	14036
265	2-Nov-05		97.4	1327.2	1.7	100.5	1.5	7176	13910	18346	13384	5878	11020	14426
266	3-Nov-05													
267	4-Nov-05		84.8	1506.4	2.6	75.9	1.2	6844	13162	19954	13180	5786	10452	15620
268	5-Nov-05													
269	6-Nov-05													
270	7-Nov-05		98.8	1302.0	2.6	76.2	1.5	8510	14142	17618	14250	6918	11228	13892
271	8-Nov-05							8442	14130	18548	12866	6950	11298	14740
272	9-Nov-05		90.4	1366.4	1.6	67.5	1.1	7650	13726	18290	13772	6238	10900	14412
273	10-Nov-05							7240	13814	19242	11870	5980	11030	15244
Batch Average		**17**	**93.4**	**1310.4**	**2.3**	**78.0**	**1.3**	**7545**	**13655**	**18184**	**13433**	**6192**	**10842**	**14458**
274	11-Nov-05	Batch 18	101.9	1243.2	1.5	72.2	0.8	7436	13682	18880	13726	6096	10884	14914
275	12-Nov-05													
276	13-Nov-05													
277	14-Nov-05							6926	12984	17950	12984	5702	10384	14292
278	15-Nov-05		97.4	1386.0	1.9	81.8	0.8	8050	14132	18796	13946	6646	11326	
279	16-Nov-05		94.9	1405.6	3.5	97.2	1.2	10254	15050	16624	14728	8272	11946	13196
280	17-Nov-05							7946	12972	17968	13924	6542	10300	14394
281	18-Nov-05		88.2	1330.0	1.8	79.0	1.1	7774	13150	18104	13614	6298	10224	13962
282	19-Nov-05													
283	20-Nov-05													
284	21-Nov-05							7898	13824	19242	13788	6330	10970	14766
285	22-Nov-05		101.1	1341.2	2.7	81.5	1.3	13998	16214	17350	15726	11184	12908	13808
286	23-Nov-05		105.6	1472.8	1.8	84.0	1.1	7848	13988	19834	14166	6490	11250	15822
287	24-Nov-05							7894	13598	16916	13262	6460	10904	13464
288	25-Nov-05		107.2	1204.0	1.6	80.6	1.2	8144	14232	18814	14244	6532	11036	14444
289	26-Nov-05													
290	27-Nov-05													
291	28-Nov-05		104.2	1355.2	1.6	86.8	0.7	8056	14058	18716	14058	6564	11240	14792
Batch Average		**18**	**100.1**	**1342.3**	**1.8**	**80.8**	**1.0**	**8021**	**13788**	**18266**	**14014**	**6926**	**11114**	**14350**
292	29-Nov-05	Batch 19						8794	14742	19068	14840	7378	11788	15176
293	30-Nov-05		96.9	1456.0	2.4	73.6	1.3	8126	14722	18972	14652	6484	11526	14598
294	1-Dec-05							7896	14118	18378	14038	6438	11236	14540
295	2-Dec-05		139.7	1327.2	1.9	103.0	1.2	7844	13568	18850	13936	6400	10760	14950
296	3-Dec-05													
297	4-Dec-05													
298	5-Dec-05		90.7	1125.6	0.3	70.6	0.0	5840	15052	19450	14824	4878	11982	15468
299	6-Dec-05							6392	15840	20098	15200	5242	12646	15994
300	7-Dec-05							5158	14486	19242	13598	4262	11078	14412
301	8-Dec-05		73.6	1271.2	2.0	70.8	0.0	5920	15292	19354	15064	4850	11768	14820
302	9-Dec-05		114.8	1276.8	1.9	82.9	0.0	5614	14890	20514	14752	4606	11814	16190
303	10-Dec-05													
304	11-Dec-05													

305	12-Dec-05							7380	13248	18354	13162	6074	10628	14682
306	13-Dec-05		104.2	1358.0	1.9	85.7	0.5	7276	13710	18090	13734	6004	11014	14444
307	14-Dec-05							8948	14922	18196	14100	7314	11972	14558
308	15-Dec-05		151.8	1092.0	0.8	77.3	0.2	8854	14498	17622	13706	7242	11574	14000
309	16-Dec-05													
310	17-Dec-05													
311	18-Dec-05													
312	19-Dec-05													
Batch Average		**19**	**110.2**	**1272.4**	**1.6**	**80.6**	**0.5**	**7234**	**14545**	**18938**	**14277**	**5936**	**11428**	**14804**
313	20-Dec-05	Batch 20												
314	21-Dec-05													
315	22-Dec-05													
316	23-Dec-05													
317	24-Dec-05													
318	25-Dec-05													
319	26-Dec-05													
320	27-Dec-05													
321	28-Dec-05													
322	29-Dec-05													
323	30-Dec-05													
324	31-Dec-05													
325	1-Jan-06													
326	2-Jan-06													
Batch Average		**20**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
327	3-Jan-06	Batch 21												
328	4-Jan-06													
329	5-Jan-06													
330	6-Jan-06													
331	7-Jan-06													
332	8-Jan-06													
333	9-Jan-06													
334	10-Jan-06													
335	11-Jan-06													
336	12-Jan-06													
337	13-Jan-06													
338	14-Jan-06													
339	15-Jan-06													
340	16-Jan-06													
341	17-Jan-06													
Batch Average		**21**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
342	18-Jan-06	Batch 22						9734	12740	13742	12748	7750	10024	10730
343	19-Jan-06													
344	20-Jan-06		100.2	949.2	0.2	70.3	0.0	8596	12458	14868	12344	6714	9670	11510
345	21-Jan-06													
346	22-Jan-06													
347	23-Jan-06		125.2	1061.2	2.0	103.0	1.2	7210	12024	15564	12582	5878	9512	12178
348	24-Jan-06							6684	12166	15526	12210	5456	9616	12162
349	25-Jan-06		103.3	817.6	1.3	82.9	0.0	6890	12678	16346	12128	5542	9860	12688
350	26-Jan-06							6570	12812	15902	11880	5336	10088	12384
351	27-Jan-06		117.0		1.3	91.3	0.7	6748	12240	16214	12366	5456	9588	12590
352	28-Jan-06													
353	29-Jan-06													
354	30-Jan-06		114.2	907.2		92.7	0.6	6432	12414	15152	11770	5210	9706	11762
Batch Average		**22**	**112.0**	**933.8**	**1.2**	**88.0**	**0.5**	**7019**	**12442**	**15414**	**12254**	**5656**	**9758**	**12182**
355	31-Jan-06	ch 23						6160	11862	15722	11906	5240	9346	12268
356	1-Feb-06							6850	12374	16264	12692	5570	9632	12636
357	2-Feb-06							6484	12014	16120	12212	5280	9456	12534
358	3-Feb-06					70.3	0.2	6472	12410	15840	12328	5200	9656	12192
359	4-Feb-06													
360	5-Feb-06							4610	8230	11216	8316	3798	6566	8754
361	6-Feb-06					41.2	0.2	5298	9532	12662	9822	4368	7550	9930
362	7-Feb-06							5626	10534	14160	10468	4660	8376	11118

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363	8-Feb-06	Bat	102.8	781.2	1.5	85.7	0.3	6010	11062	14396	11056	4956	8798	11342
364	9-Feb-06							5958	11436	16098	11076	4930	9070	12686
365	10-Feb-06					78.4	0.0	5676	10814	15274	10502	4682	8566	11978
366	11-Feb-06													
367	12-Feb-06							9096	13256	15382		7418	10592	12064
368	13-Feb-06		109.2		1.7	80.4	0.6	7356	13142	16860	13184	6040	10476	13374
369	14-Feb-06		102.8	1153.6	2.4	79.2	0.5	7098	13232	17676	13500	5806	10464	13840
Batch Average		**23**	**104.9**	**967.4**	**1.9**	**72.5**	**0.3**	**6133**	**11806**	**15538**	**11704**	**5044**	**9332**	**12164**
370	15-Feb-06	Batch 24						7690	14586	18210	13864	6304	11598	14394
371	16-Feb-06							7344	14464	19940	13570	5996	11470	15708
372	17-Feb-06		65.0	1038.8	2.0	93.5	0.0	7606	13880	19426	13646	6076	10712	14822
373	18-Feb-06													
374	19-Feb-06													
375	20-Feb-06													
376	21-Feb-06		85.7	1260.0	0.4	59.1	0.0	8222	15840	17526	16028	6634	12672	13582
377	22-Feb-06							7558	15986	20370	20704	6304	13272	16752
378	23-Feb-06							5816	10926	13870	11238	4828	8676	10808
379	24-Feb-06		71.4			47.9		7606	13498	17560	13732	6154	10650	13778
380	25-Feb-06							8206	14728	19504	14606	6634	11640	15288
381	26-Feb-06							7860	13898	18168	13996	6408	11028	14312
382	27-Feb-06		86.0			54.3	0.0	9756	14104	16898	14236	7820	11102	13194
383	28-Feb-06		74.8	747.6	1.0			6950	11398	14210	11638	5682	9028	11138
Batch Average		**24**	**76.6**	**1015.5**	**1.1**	**63.7**	**0.0**	**7486**	**13937**	**17789**	**13655**	**6244**	**11077**	**13980**
384	1-Mar-06	Batch 25	92.1	1036.0		72.5	0.1	7252	12836	16538	12722	5864	10104	12948
385	2-Mar-06							7382	13596	17728	13502	6016	10702	13898
386	3-Mar-06													
387	4-Mar-06							6590	13444	17218	13598	5408	10616	13528
388	5-Mar-06													
389	6-Mar-06		98.0	988.4	1.4	82.3	1.1	7466	13142	17022	13326	6020	10270	13224
390	7-Mar-06		118.2	946.4	0.4	82.9	0.2	7302	12846	16444	12884	5846	10020	12718
391	8-Mar-06			1103.2	1.3	98.0	0.0	7492	12708	15494	12616	5994	9890	12016
Batch Average		**25**	**102.8**	**1018.5**	**1.0**	**83.9**	**0.4**	**7379**	**13095**	**16741**	**13108**	**5858**	**10267**	**13055**
392	9-Mar-06	Batch 26				96.9	0.4	7078	12670	16422	12828	5648	9814	12622
393	10-Mar-06													
394	11-Mar-06													
395	12-Mar-06							9168	13626	19382	14170	7298	10608	15012
396	13-Mar-06		91.3	890.4		74.8	0.2	7594	13234	17798	13202	5994	10494	
397	14-Mar-06							7660	13498	18506	13706	6138	10550	14428
398	15-Mar-06		132.7	1204.0	0.6	102.8		7646	14066	18770	14118	6144	10994	14578
399	16-Mar-06							7900	14266	18950	14366	6174	11212	14778
400	17-Mar-06		90.7	1271.2	1.2	70.0	0.5	7108	13746	18074	13996	5716	10734	14020
401	18-Mar-06													
402	19-Mar-06													
403	20-Mar-06		98.3	1162.0	1.4	84.6	0.5	7290	13246	18002	13682	5878	10404	14054
404	21-Mar-06													
405	22-Mar-06							7054	12534	16170		5734	9852	12636
406	23-Mar-06		98.0	1176.0		82.0	0.8	7268	13254	17556	13050	5916	10440	13728
Batch Average		**26**	**102.2**	**1140.7**	**1.1**	**85.2**	**0.5**	**7400**	**13414**	**17963**	**13680**	**5927**	**10510**	**13984**
407	24-Mar-06	Batch 27	107.0	1209.6	1.3	76.7	0.3	7242	13190	17874	13252	5844	10310	13850
408	25-Mar-06													
409	26-Mar-06													
410	27-Mar-06		101.9	1248.8	1.6	93.2	0.3	7344	13124	17602	12962	5788	10246	13688
411	28-Mar-06							6948	12992	17272	12418	5648	10210	13554
412	29-Mar-06		98.6	1097.6	0.7	72.5	1.1	7346	12970	16210	13146	5976	10234	12726
413	30-Mar-06													
414	31-Mar-06		84.6	1204.0	1.6	75.0	0.3	8450	13958	17474	13470	6886	11052	13736
415	1-Apr-06													
416	2-Apr-06													
417	3-Apr-06		108.6	1187.2	1.5	82.3	0.3	7668	13492	17968	13126	6232	10578	14032
418	4-Apr-06								13316	16890	13530		10498	13148
419	5-Apr-06		106.4	1428.0	1.2	78.1	0.2	7406	13632	17576	13542	6020	10688	13696
420	6-Apr-06							7550	12956	16978	13248	6112	10174	13246

421	7-Apr-06													
Batch Average		**27**	**101.2**	**1229.2**	**1.3**	**79.7**	**0.3**	**7358**	**13292**	**17454**	**13285**	**5946**	**10367**	**13520**
422	8-Apr-06	Batch 28												
423	9-Apr-06							7564	13682	18248	17412	6072	10748	14360
424	10-Apr-06		80.6	905.8	1.1	58.8	0.3	7164	13006	17166	13232	5852	10288	13428
425	11-Apr-06							7214	13168	16020	13426	5858	10428	13064
426	12-Apr-06							7692	13806	18450	13796	6350	11078	14640
427	13-Apr-06		100.2	1184.4	1.3	83.7	0.6	6960	12734	16990	13070	5726	10176	13424
428	14-Apr-06		94.9					7454	13212	17130	13094	6176	10570	13634
429	15-Apr-06		100.0	1198.4	0.8	81.8	0.8	7474	12848	15474	13308	6130	10244	12258
430	16-Apr-06		98.0											
431	17-Apr-06		101.9											
432	18-Apr-06		117.0	1136.8	1.9	80.4	0.2	7074	11678	15828	11240	5880	9464	12702
433	19-Apr-06							7276	12892	17290	12872	6124	10496	13936
434	20-Apr-06							6902	12062	16226	12002	5872	9876	13208
435	21-Apr-06		118.2	1240.4	2.1	86.8	1.8	7352	13354	17898	13272	6174	10858	14462
436	22-Apr-06													
Batch Average		**28**	**101.4**	**1133.2**	**1.5**	**78.3**	**0.8**	**7284**	**13076**	**16975**	**12931**	**6019**	**10476**	**13556**
437	23-Apr-06	Batch 29												
438	24-Apr-06		105.8	1204.0	1.2	77.0	0.1	6900	13166	17508	13048	5902	10914	14436
439	25-Apr-06							7254	13733	18664	13992	6184	11418	15400
440	26-Apr-06		94.4	1316.0	1.6	76.7	0.0	6786	12874	17772	13098	5770	10636	14966
441	27-Apr-06							7102	13362	17980	13652	6034	11014	14744
442	28-Apr-06		88.2	1377.6	1.7	69.7	0.0	6460	12500	17580	16190			
443	29-Apr-06													
444	30-Apr-06							7222	12820	18118	13012	5894	10210	14364
445	1-May-06					79.5	2.0	7250	13042	17456	13412	5934	10416	13838
446	2-May-06													
447	3-May-06		96.9	1128.4	2.2	64.1	0.9	8300	14484	18520	14862	6766	11608	14734
448	4-May-06													
449	5-May-06		89.6	1150.8	0.9	63.0	0.3	7482	12798	16778	12838			
Batch Average		**29**	**95.0**	**1235.4**	**1.5**	**71.7**	**0.6**	**7057**	**13037**	**17820**	**13489**	**5953**	**10888**	**14640**

Appendix A-3

Measured NO3, NO2 and soluble P in the MBR UCT system

			NO3				NO2				Ortho-P				
Day	Date	SB #	AN	AX	AE	E	AN	AX	AE	E	I	AN	AX	AE	E
			(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgN/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)
21	3-Mar-05	Batch 2													
22	4-Mar-05														
23	5-Mar-05														
24	6-Mar-05														
25	7-Mar-05														
26	8-Mar-05														
27	9-Mar-05														
28	10-Mar-05														
29	11-Mar-05														
30	12-Mar-05														
31	13-Mar-05														
32	14-Mar-05		0.00	0.00	17.57	20.55	0.00	0.00	0.00	0.00	49.3	71.6	46.5	31.1	35.7
33	15-Mar-05		0.00	0.00	20.86	21.86	0.00	0.00	0.00	0.00	17.8	48.4	77.5	30.2	33.6
34	16-Mar-05														
35	17-Mar-05		0.00	0.00	19.61	32.14	0.00	0.00	0.00	0.00	18.7	43.8	31.7	11.6	
36	18-Mar-05														
Batch Average		**2**	**0.00**	**0.00**	**19.35**	**24.85**	**0.00**	**0.00**	**0.00**	**0.00**	**28.6**	**54.6**	**51.9**	**24.3**	**34.6**
37	19-Mar-05	Batch 3													
38	20-Mar-05														
39	21-Mar-05		0.00	0.92	13.30	28.75					18.0	44.2	16.9	4.3	13.6
40	22-Mar-05										18.0				
41	23-Mar-05		1.41	1.23	31.00	32.71					25.8	20.1	22.1	33.4	16.0
42	24-Mar-05														
43	25-Mar-05		0.00	2.19	14.15	13.32					18.3	90.5	48.3	30.2	26.5
44	26-Mar-05														
45	27-Mar-05		0.00	0.41		26.08					39.3	98.2	69.6	93.4	8.1
46	28-Mar-05														
47	29-Mar-05		0.00	0.00	7.90	22.64					34.8	101.1	33.9	10.4	12.0
48	30-Mar-05														
49	31-Mar-05		0.00	0.00	15.34	18.43	0.00	0.00	0.00	0.00	34.5	97.3	42.2	9.7	9.7
50	1-Apr-05														
51	2-Apr-05		1.64	0.16	12.40	16.90	0.00	0.00	0.00	0.00	36.7	95.8	39.3	23.4	24.6
52	3-Apr-05														
53	4-Apr-05		0.00	0.00	30.50	31.60	0.00	0.00	0.00	0.00	35.9	63.7	51.7	12.6	12.8
Batch Average		**3**	**0.38**	**0.39**	**17.80**	**23.81**	**0.00**	**0.00**	**0.00**	**0.00**	**36.2**	**91.2**	**47.3**	**14.0**	**13.4**
54	5-Apr-05	Batch4													
55	6-Apr-05														
56	7-Apr-05														
57	8-Apr-05		0.00	0.00	8.02	8.76					27.5	92.2	43.8	19.7	12.0
58	9-Apr-05														
59	10-Apr-05		0.00	0.00	0.97	9.58					27.8	146.4	103.7	61.6	12.9
60	11-Apr-05														
61	12-Apr-05		0.85	0.97		9.17					26.9	81.1	5.1	16.9	11.1
62	13-Apr-05														
63	14-Apr-05		0.00	0.00	11.38	13.27					32.3	86.5	45.2	8.3	11.7
64	15-Apr-05														
65	16-Apr-05		0.00	0.00	10.01	14.50					34.6	83.4	38.6	8.5	10.3
66	17-Apr-05														
67	18-Apr-05														
68	19-Apr-05		0.00	0.00	8.63	26.00					27.5		37.7	6.6	7.8
69	20-Apr-05														
70	21-Apr-05														

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71	22-Apr-05														
72	23-Apr-05		0.00	0.00	7.59	10.14	0.00	0.00	0.00	0.00	28.2	73.4	33.0	10.4	11.9
73	24-Apr-05														
74	25-Apr-05		0.00	1.18	11.84	9.46	0.00	0.00	0.00	0.00	22.7	62.5	28.5	10.1	11.6
75	26-Apr-05														
Batch Average		**4**	**0.00**	**0.27**	**9.58**	**10.70**	**0.00**	**0.00**	**0.00**	**0.00**	**28.4**	**79.9**	**33.1**	**11.5**	**11.2**
76	27-Apr-05	Batch 5													
77	28-Apr-05														
78	29-Apr-05			0.13	11.94	17.04					28.8	81.8	39.6	13.1	27.0
79	30-Apr-05		0.00												
80	1-May-05														
81	2-May-05		0.00	0.00	8.86	12.12					31.5	67.6	28.5	6.6	10.3
82	3-May-05														
83	4-May-05		0.00	2.76	21.14	21.51					29.0	60.1	55.8	17.0	10.6
84	5-May-05			0.00	9.14	16.02	0.00	2.09	0.00	0.00	29.3	90.4	28.2	3.9	11.8
85	6-May-05		0.00	0.00	13.61	14.63					25.5	56.1	44.0	10.0	2.7
86	7-May-05														
87	8-May-05														
88	9-May-05		0.15		10.54	15.16	0.26	0.10	0.00	0.00	19.0	78.2	33.0	5.8	4.0
89	10-May-05										19.2				
90	11-May-05		0.00	0.00	11.42	14.94					19.6	80.0	33.6	5.2	4.3
91	12-May-05										17.3				
92	13-May-05		0.00	0.00	11.42	15.49					20.5	75.6	32.7	6.1	3.2
93	14-May-05														
94	15-May-05														
Batch Average		**5**	**0.00**	**0.02**	**10.99**	**15.06**	**0.13**	**1.09**	**0.00**	**0.00**	**24.0**	**73.7**	**34.2**	**8.5**	**6.7**
95	16-May-05	Batch 6	0.00	0.00	11.75	14.83	0.00	0.00	0.00	0.00	21.7	75.3	31.6	8.4	3.5
96	17-May-05														
97	18-May-05														
98	19-May-05														
99	20-May-05		0.00	0.31	13.57	17.55	0.00	0.22	0.00	0.00	18.9	56.9	21.1	0.0	1.5
100	21-May-05														
101	22-May-05														
102	23-May-05		0.00	0.50	14.13	17.46	0.00	0.46	0.00	0.00	22.2	65.3	29.2	2.1	0.1
103	24-May-05		0.00	0.50	12.60	19.80	0.00	0.46	0.00	0.00	23.3	43.2	13.8	0.0	0.0
104	25-May-05		0.00	0.41	18.81	21.78	0.00	0.30	0.00	0.00	22.1	65.8	30.0	1.5	1.5
105	26-May-05		0.00	0.53	18.18	20.79	0.00	0.43	0.00	0.00	25.3	72.0	30.6	0.4	0.4
106	27-May-05		0.00	0.15	14.58	20.16	0.00	0.19	0.00	0.00	31.6	82.9	35.4	4.9	2.9
107	28-May-05														
108	29-May-05														
109	30-May-05			0.46	13.97	18.44	0.00	0.40	0.00	0.00	30.8	63.4	34.1	4.0	7.4
110	31-May-05			0.76	13.55	17.50	0.00	0.60	0.00	0.00	30.1	62.0	29.6	4.0	7.7
Batch Average		**6**	**0.00**	**0.40**	**14.57**	**18.70**	**0.00**	**0.34**	**0.00**	**0.00**	**25.1**	**65.2**	**30.2**	**2.1**	**2.8**
111	1-Jun-05	Batch 7	0.00	0.00	10.74	14.49	0.00	0.00	0.00	0.00	28.8	83.1	36.1	3.2	3.5
112	2-Jun-05		0.00	0.00	10.43	12.61	0.00	0.00	0.00	0.00	26.5	86.8	42.0	4.9	5.7
113	3-Jun-05		0.00	0.00	12.72	14.59	0.00	0.00	0.00	0.00	26.3	86.2	41.7	4.6	5.2
114	4-Jun-05														
115	5-Jun-05														
116	6-Jun-05		0.02	0.17	7.24	12.70	0.27	0.00	0.00	0.00	28.0	91.4	48.7	14.8	12.9
117	7-Jun-05		0.00	0.18	9.84	13.09	0.27	0.00	0.00	0.00	30.4	82.2	43.0	14.8	13.2
118	8-Jun-05		0.00	0.26	9.45	15.04	0.31	0.00	0.00	0.00	30.9	88.4	46.2	13.2	13.2
119	9-Jun-05										30.3				
120	10-Jun-05		0.01	0.05	12.31	16.54	0.18	0.00	0.00	0.00	34.1	93.3	45.2	14.0	11.8
121	11-Jun-05														
122	12-Jun-05														
123	13-Jun-05		0.00	0.16	5.38	10.90					26.9	74.4	55.0	16.9	18.3
124	14-Jun-05														
Batch Average		**7**	**0.00**	**0.10**	**10.39**	**13.75**	**0.15**	**0.00**	**0.00**	**0.00**	**29.1**	**85.7**	**44.7**	**10.8**	**10.5**

125	15-Jun-05	Batch 8													
126	16-Jun-05														
127	17-Jun-05														
128	18-Jun-05		0.00	0.15	9.97	16.09	0.00	0.00	0.00	0.00	25.8	87.8	42.8	15.8	15.3
129	19-Jun-05														
130	20-Jun-05		0.00	0.11	10.48	16.94	0.00	0.00	0.00	0.00	28.3	87.2	41.7	9.7	9.4
131	21-Jun-05		0.00	0.24	13.79	17.19	0.00	0.00	0.00	0.00	28.9	61.7	28.1	5.8	7.2
132	22-Jun-05		0.00	0.21	16.34	18.89					30.8	80.8	41.9	8.9	8.1
Batch Average		**8**	**0.00**	**0.18**	**12.64**	**17.28**	**0.00**	**0.00**	**0.00**	**0.00**	**28.5**	**79.4**	**38.6**	**10.1**	**10.0**
133	23-Jun-05	Batch 9	0.00	0.15	14.73	18.89					33.6	73.6	36.1	3.6	9.4
134	24-Jun-05		0.00	0.00		10.48					33.1	96.7	64.7	16.4	6.9
135	25-Jun-05														
136	26-Jun-05														
137	27-Jun-05		0.36	0.47	7.41	12.32					26.5	83.6	43.5		8.9
138	28-Jun-05		0.11	0.11	7.55	13.42					26.5	76.6	38.7	10.5	
139	29-Jun-05		0.60	0.44	9.05	14.24					29.5	88.5	42.7	13.2	8.9
140	30-Jun-05		0.11	0.09	7.68	17.10					28.6	85.5	41.9	7.5	6.7
141	1-Jul-05		0.36	0.30	12.32	16.42					28.9	91.0	41.9	8.1	10.0
142	2-Jul-05														
143	3-Jul-05														
144	4-Jul-05		0.00	1.74	19.53	21.42	0.00	0.00	0.00	0.00	35.7	92.6	43.8	11.8	11.8
145	5-Jul-05		0.00	0.00	10.23	26.26	0.00	0.00	0.00	0.00	31.5	81.2	40.5	12.5	15.5
146	6-Jul-05		0.00	1.71	17.77	20.42	0.00	0.00	0.00	0.00	18.7	75.5	29.3	1.9	2.4
147	7-Jul-05						0.00	0.00	0.00	0.00	12.5	76.6	33.2	2.2	1.6
Batch Average		**9**	**0.10**	**0.50**	**11.81**	**17.10**	**0.00**	**0.00**	**0.00**	**0.00**	**29.3**	**84.5**	**39.8**	**9.5**	**9.0**
148	8-Jul-05	Batch 10	0.00	0.00	16.44	19.92	0.00	0.00	0.00	0.00	10.9	69.8	31.5	1.6	1.4
149	9-Jul-05		0.00	0.00	13.81	16.18									
150	10-Jul-05														
151	11-Jul-05		0.00	0.00	11.59	13.10	0.00	0.00	0.00	0.00	9.6	74.2	36.7	1.3	1.0
152	12-Jul-05		0.00	0.00	11.15	14.93	0.00	0.00	0.00	0.00	10.1	73.3	31.9	1.8	1.0
153	13-Jul-05										13.2				
154	14-Jul-05		0.00	0.00	12.23	14.93	0.00	0.00	0.00	0.00	12.7	68.2	27.4	3.0	1.3
155	15-Jul-05		0.00	0.00	11.48	16.45	0.00	0.00	0.00	0.00	15.2	76.7	32.5	3.0	1.8
156	16-Jul-05														
157	17-Jul-05														
158	18-Jul-05		0.00	0.00	11.96	12.41	0.00	0.03	0.00	0.00	11.2	68.7	29.2	1.0	1.0
159	19-Jul-05		0.00	0.00	12.23	13.63	0.00	0.03	0.00	0.00	12.2	63.4	25.6	1.5	0.5
160	20-Jul-05		0.00	0.00	11.84	13.77	0.00	0.03	0.00	0.00		61.4	25.6	1.5	0.2
161	21-Jul-05		0.00	0.00	12.28	13.87	0.00	0.05	0.00	0.00	11.7	71.8	26.3	1.5	0.5
162	22-Jul-05										12.5				
163	23-Jul-05				6.48	11.54	0.08	0.12	0.00	0.00	9.6	68.6	27.0	3.3	1.3
164	24-Jul-05														
165	25-Jul-05				11.89	14.31	0.08	0.05	0.00	0.00	28.7	71.4	37.4	5.7	8.0
166	26-Jul-05			0.17	10.80	13.43	0.04	0.05	0.00	0.00	30.2	71.9	33.9	9.3	9.3
167	27-Jul-05				12.89	14.49	0.04	0.05	0.00	0.00	29.2	96.2	37.7	8.8	9.3
Batch Average		**10**	**0.00**	**0.00**	**12.01**	**14.08**	**0.02**	**0.03**	**0.00**	**0.00**	**29.3**	**79.8**	**36.3**	**8.0**	**8.9**
168	28-Jul-05	atch 11	0.00	0.00	17.90	16.61	0.03	0.08	0.00	0.00		80.7	46.0	11.8	11.0
169	29-Jul-05						0.06	0.06	0.00	0.00	27.8	73.6	36.9	8.5	11.8
170	30-Jul-05														
171	31-Jul-05														
172	1-Aug-05		0.00	0.00	11.93	14.69	0.04	0.04	0.00	0.00	23.3	51.7	32.4	3.0	7.1
173	2-Aug-05				13.17	14.45	0.04	0.07	0.00	0.00	22.0	78.2	38.5	8.5	8.7
174	3-Aug-05		0.00	0.00	12.95	14.37		0.09	0.00	0.00	23.3	82.9	40.7	10.9	12.9
175	4-Aug-05		0.00	0.00	12.43	15.08			0.00	0.00	23.3	73.0	34.6	9.3	15.6
176	5-Aug-05										25.3	76.0	43.7	10.9	10.9
177	6-Aug-05														
178	7-Aug-05														
179	8-Aug-05		0.00	0.00	12.94	14.31			0.00	0.00					

180	9-Aug-05	B	0.00	0.00	11.88	12.01			0.00	0.00	23.3	71.3	31.6	7.8	8.4
181	10-Aug-05		0.00	0.00	16.76	17.03			0.00	0.00	22.8	70.3	31.0	8.4	8.6
182	11-Aug-05										20.6	60.7	28.1	8.1	6.8
183	12-Aug-05		0.00	0.00	18.20	18.67			0.00	0.00					
184	13-Aug-05														
185	14-Aug-05														
186	15-Aug-05		1.60	1.01	14.20	16.08		0.00	0.00	0.00	31.0	63.9	38.0	6.5	7.8
187	16-Aug-05										20.6	60.1	32.1	7.3	6.8
188	17-Aug-05		0.00	0.00	17.07	20.39		0.00	0.00		24.4	56.9	26.0	6.0	6.5
Batch Average		**11**	**0.00**	**0.00**	**14.49**	**15.33**	**0.04**	**0.05**	**0.00**	**0.00**	**24.0**	**69.2**	**35.4**	**8.7**	**8.9**
189	18-Aug-05	Batch 12	0.96	0.00	15.52	19.07	0.00	0.00	0.00	0.00					
190	19-Aug-05														
191	20-Aug-05														
192	21-Aug-05														
193	22-Aug-05		0.00	0.00	17.38	21.48			0.00	0.00	27.4	77.5	40.3	12.7	10.0
194	23-Aug-05		0.00	0.00	20.67	19.77			0.00	0.00	28.7	59.8	20.7	5.4	5.7
195	24-Aug-05		0.00	0.00	14.97	15.74			0.00	0.00	30.9	60.1	23.9	6.3	6.0
196	25-Aug-05		0.19	0.96	21.22	22.68	0.00	0.00	0.00	0.00	27.4	76.2	28.7	5.7	4.9
197	26-Aug-05		0.00	0.00	23.18	24.48			0.00	0.00	27.7	80.4	34.1	7.3	6.3
198	27-Aug-05														
199	28-Aug-05														
200	29-Aug-05		0.00	5.87	27.66	28.47			0.00	0.00	26.6	50.4	20.2	2.1	1.2
201	30-Aug-05		0.00	5.41	25.44	24.04						76.3	27.7	8.2	5.4
202	31-Aug-05											90.9	31.9	8.8	8.5
203	1-Sep-05		0.00	6.39	27.20	28.33					28.3	124.1	57.6	24.1	23.6
204	2-Sep-05		0.00	6.03	22.54	26.32					29.4	99.8	37.2	2.1	10.2
Batch Average		**12**	**0.02**	**2.47**	**21.58**	**23.04**	**0.00**	**0.00**	**0.00**	**0.00**	**28.3**	**74.6**	**29.4**	**6.5**	**6.5**
205	3-Sep-05	Batch 13													
206	4-Sep-05														
207	5-Sep-05														
208	6-Sep-05		0.00	0.41	9.20	9.39					27.7	96.7	44.6	3.8	5.0
209	7-Sep-05														
210	8-Sep-05		0.00	0.36	12.72	12.79					29.9	99.9	45.9	7.3	8.5
211	9-Sep-05				9.50	11.72					30.3	81.7	25.1	1.2	0.6
212	10-Sep-05										31.2				
213	11-Sep-05														
214	12-Sep-05		0.00	0.36	10.63	11.50					28.9	93.4	37.1	6.4	4.8
215	13-Sep-05				12.37	11.82					29.3	93.8	39.6	9.5	10.2
216	14-Sep-05		0.00	0.41	12.47	12.80						95.3	39.9	6.1	4.2
217	15-Sep-05				17.69	18.16					29.3	96.6	40.2	8.6	8.3
218	16-Sep-05		0.00	0.27	15.80	17.21					30.2	110.0	44.3	4.8	4.8
Batch Average		**13**	**0.00**	**0.36**	**12.55**	**13.17**	**0.00**	**0.00**	**0.00**	**0.00**	**29.6**	**95.9**	**41.7**	**6.0**	**5.8**
219	17-Sep-05	Batch 14													
220	18-Sep-05														
221	19-Sep-05														
222	20-Sep-05		0.00	4.52	26.05	25.04					45.9	74.3	31.9	6.1	2.0
223	21-Sep-05				19.65	20.41					29.1	88.3	36.0	9.8	10.4
224	22-Sep-05		0.00	1.07	19.60	20.87		0.00	0.00	0.00	27.9	91.1	40.6	15.4	11.3
225	23-Sep-05		0.00	1.80	20.86	22.95		0.00	0.00	0.00	29.7	97.6	40.9	9.2	9.2
226	24-Sep-05														
227	25-Sep-05														
228	26-Sep-05		0.00	4.76	21.28	21.87		0.00	0.00	0.00	33.2	79.6	31.6	8.2	8.9
229	27-Sep-05		0.00	5.45	24.25	24.71		0.00	0.00	0.00	34.1	74.9	31.6	8.2	6.4
230	28-Sep-05										34.1	69.0	22.9	5.4	3.2
231	29-Sep-05		0.00	0.46	8.60	9.21		0.00	0.00	0.00		71.4	30.1	4.7	6.3
232	30-Sep-05		0.00	0.58	18.07	20.03		0.00	0.00	0.00	31.3	83.2	34.8	9.1	7.5
233	1-Oct-05														
234	2-Oct-05														

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235	3-Oct-05		0.00	0.42	17.47	19.55		0.00	0.00	0.00	30.4	77.0	32.6	9.1	9.7
Batch Average		**14**	**0.00**	**2.38**	**20.90**	**21.93**	**0.00**	**0.00**	**0.00**	**0.00**	**31.2**	**80.6**	**33.3**	**7.8**	**7.5**
236	4-Oct-05	Batch 15	0.00	0.42	15.43	17.92		0.00	0.00	0.00	29.1	91.1	40.4	16.9	20.4
237	5-Oct-05		0.00	0.66	15.80			0.00	0.00	0.00	23.5	68.2	27.3	6.3	6.3
238	6-Oct-05														
239	7-Oct-05		0.00	0.60	16.29	16.36		0.00	0.00	0.00	26.9	92.3	40.1	11.0	11.6
240	8-Oct-05														
241	9-Oct-05														
242	10-Oct-05		0.00	0.03	13.36	14.77		0.00	0.00	0.00	30.1	86.8	37.8	10.3	11.5
243	11-Oct-05		0.00	0.17	18.50	20.97		0.00	0.36	0.00	26.9	95.8	51.0	17.0	12.8
244	12-Oct-05				21.06	22.45		0.00	0.00	0.00	42.0	99.3	44.1	9.5	9.5
Batch Average		**15**	**0.00**	**0.37**	**16.74**	**18.49**	**0.00**	**0.00**	**0.00**	**0.00**	**29.8**	**88.9**	**40.1**	**11.8**	**10.3**
245	13-Oct-05	Batch 16	0.00	0.00	16.94	18.65		0.00	0.00	0.00	33.4	104.8	45.9	8.9	8.9
246	14-Oct-05		0.00	0.05	17.14	17.73		0.00	0.00	0.00	33.4	105.4	46.2	9.8	9.8
247	15-Oct-05														
248	16-Oct-05														
249	17-Oct-05		0.00	1.78	20.12	21.14		0.00	0.00	0.00	30.3	91.8	34.4	0.0	0.0
250	18-Oct-05			0.00	19.88	20.38		0.00	0.00	0.00	29.7	97.8	39.1	3.8	0.7
251	19-Oct-05		0.00	0.96	14.65	15.19	0.00	0.00	0.00	0.00	33.5	83.9	32.5	3.2	1.9
252	20-Oct-05		0.00	1.75	17.75	19.04	0.00	0.00	0.00	0.00	29.3	87.4	32.2	7.3	8.5
253	21-Oct-05		0.00	7.25	24.62	25.60	0.00	0.00	0.00	0.00		89.6	35.7	9.2	7.3
254	22-Oct-05		0.00												
255	23-Oct-05														
256	24-Oct-05		0.00	2.86	19.66	21.00	0.00	0.00	0.00	0.00	26.9	99.1	37.9	9.8	6.5
257	25-Oct-05		0.00	4.32	22.80	23.65		0.00	0.00	0.00	35.8	91.7	40.1	6.5	5.9
258	26-Oct-05		0.00	1.02	18.51	19.92		0.00	0.00	0.00	30.0	102.7	43.1	7.1	8.3
259	27-Oct-05		0.00	0.57	16.62	16.89		0.00	0.00	0.00	31.4	90.0	38.0	10.5	11.8
Batch Average		**16**	**0.00**	**1.33**	**18.41**	**19.93**	**0.00**	**0.00**	**0.00**	**0.00**	**31.4**	**94.9**	**38.7**	**7.6**	**6.3**
260	28-Oct-05	Batch 17	0.00	0.44	14.13	14.29		0.00	0.00	0.00	38.0	103.0	46.2	11.1	11.1
261	29-Oct-05														
262	30-Oct-05														
263	31-Oct-05		0.00	0.40	12.58	12.12	0.00	0.00	0.00	0.00	38.9	100.5	45.8	11.1	11.4
264	1-Nov-05		0.00	0.27	11.72	11.39	0.00	0.00	0.00	0.00	41.3	94.7	44.0	12.6	15.0
265	2-Nov-05		0.00	0.00	12.26	12.53	0.00	0.00	0.00	0.00	39.2	105.6	48.8	12.0	13.2
266	3-Nov-05														
267	4-Nov-05		0.00	0.47	13.83	14.18	0.00	0.00	0.00	0.00	39.6	106.2	57.0	17.1	16.2
268	5-Nov-05														
269	6-Nov-05														
270	7-Nov-05		0.00	0.56	9.81	10.06	0.00	0.00	0.00	0.00	31.4	90.0	38.0	10.5	11.8
271	8-Nov-05		0.00	0.48	10.94	11.45	0.00	0.00	0.00	0.00	38.0	103.0	46.2	11.1	11.1
272	9-Nov-05		0.00	0.35	10.61	9.17	0.00	0.00	0.00	0.00					
273	10-Nov-05			0.00	10.86	11.56	0.00	0.00	0.00	0.00	38.4	101.4	49.6	11.6	11.6
Batch Average		**17**	**0.00**	**0.33**	**11.86**	**11.86**	**0.00**	**0.00**	**0.00**	**0.00**	**39.1**	**100.5**	**47.0**	**12.2**	**12.7**
274	11-Nov-05	Batch 18	0.00	0.36	13.07	13.01		0.00	0.00	0.00	34.6	112.6	53.4	14.8	14.8
275	12-Nov-05														
276	13-Nov-05														
277	14-Nov-05		0.00	4.52	20.39	22.79	0.00	0.41	0.00	0.00	36.3	97.6	54.0	24.3	24.3
278	15-Nov-05		0.00	3.07	19.37	19.09	0.00	0.34	0.00	0.00		83.4	38.4	14.0	14.0
279	16-Nov-05		0.00	0.91	14.22	14.40	0.00	0.17	0.00	0.00		75.5	24.6	7.2	7.2
280	17-Nov-05			0.00	15.16	15.70	0.00	0.00	0.00	0.00	36.1	96.6	44.0	9.1	8.8
281	18-Nov-05		0.00	0.30	13.11	14.00	0.00	0.00	0.00	0.00	37.1	99.0	43.7	12.4	10.3
282	19-Nov-05														
283	20-Nov-05														
284	21-Nov-05		0.00	0.66	16.53	16.61	0.00	0.00	0.00	0.00	41.6	89.9	41.6	7.0	7.0
285	22-Nov-05		0.00	0.33	9.30	3.588	0.00	0.00	0.00	0.00	32.2	48.3	17.6	3.0	7.0
286	23-Nov-05		0.00	0.29	18.01	18.17	0.00	0.00	0.00	0.00	38.6	84.5	40.7	10.9	10.0
287	24-Nov-05		0.00	4.54	21.25		0.00	0.23	0.00	0.00	56.3	85.2	42.2	12.4	13.4
288	25-Nov-05		0.00	0.34	15.66	16.73	0.00	0.00	0.00	0.00	55.7	92.4	37.5	7.1	9.3

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289	26-Nov-05														
290	27-Nov-05														
291	28-Nov-05		0.00	0.50	15.01	15.30	0.00	0.00	0.00	0.00	56.0	96.8	42.2	11.8	11.5
Batch Average		**18**	**0.00**	**1.32**	**15.92**	**15.40**	**0.00**	**0.07**	**0.00**	**0.00**	**36.6**	**87.5**	**39.8**	**9.8**	**9.9**
292	29-Nov-05	Batch 19	0.00	0.42	12.71	13.34		0.00	0.00	0.00	57.9	88.9	40.0	15.3	5.9
293	30-Nov-05		0.00	0.23	13.78	14.06		0.00	0.00	0.00	51.9	90.8	34.1	9.3	9.9
294	1-Dec-05		0.00	0.04	11.39	13.09		0.00	0.00	0.00	29.3	81.3	38.5	10.8	10.2
295	2-Dec-05		0.00	0.01	12.91	13.16		0.00	0.00	0.00	35.7	83.7	37.6	9.6	9.9
296	3-Dec-05														
297	4-Dec-05														
298	5-Dec-05		0.00	0.18	14.07	13.70		0.00	0.00	0.00	35.4	87.1	33.9	11.7	10.5
299	6-Dec-05		0.00	0.04	12.98	12.05		0.00	0.00	0.00	41.9	86.8	28.6	7.1	6.5
300	7-Dec-05										44.4	114.1	41.6	5.8	6.4
301	8-Dec-05		0.00	0.23	12.05	12.68		0.00	0.00	0.00	36.9	92.5	34.1	5.8	7.0
302	9-Dec-05		0.00	0.16	13.64	12.71		0.00	0.00	0.00	33.7	88.7	30.6	6.4	3.0
303	10-Dec-05														
304	11-Dec-05														
305	12-Dec-05														
306	13-Dec-05		0.00	0.18	12.66	13.01		0.00	0.00	0.00	33.4	79.0	31.9	1.7	1.4
307	14-Dec-05		0.00	0.19	11.56	11.90		0.00	0.00	0.00	39.1	74.6	25.6	6.4	1.7
308	15-Dec-05		0.00	0.18	12.12	12.72		0.00	0.00	0.00	41.0	82.7	31.5	3.6	1.4
309	16-Dec-05										34.4	89.1	37.8	8.9	8.5
310	17-Dec-05														
311	18-Dec-05														
312	19-Dec-05														
Batch Average		**19**	**0.00**	**0.14**	**12.72**	**12.95**	**0.00**	**0.00**	**0.00**	**0.00**	**36.8**	**84.5**	**33.8**	**7.1**	**6.0**
313	20-Dec-05	Batch 20													
314	21-Dec-05														
315	22-Dec-05														
316	23-Dec-05														
317	24-Dec-05														
318	25-Dec-05														
319	26-Dec-05														
320	27-Dec-05														
321	28-Dec-05														
322	29-Dec-05														
323	30-Dec-05														
324	31-Dec-05														
325	1-Jan-06														
326	2-Jan-06														
Batch Average		**20**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
327	3-Jan-06	Batch 21													
328	4-Jan-06														
329	5-Jan-06														
330	6-Jan-06														
331	7-Jan-06														
332	8-Jan-06														
333	9-Jan-06														
334	10-Jan-06														
335	11-Jan-06														
336	12-Jan-06														
337	13-Jan-06														
338	14-Jan-06														
339	15-Jan-06														
340	16-Jan-06														
341	17-Jan-06														
Batch Average		**21**	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
342	18-Jan-06														

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343	19-Jan-06	Batch 22													
344	20-Jan-06		0.03	0.00		23.87	0.00	0.00	0.00	0.00	36.2	30.8			7.1
345	21-Jan-06														
346	22-Jan-06														
347	23-Jan-06		0.00	0.99	25.12	24.50	0.00	0.66	0.00	0.00	32.4	29.8	8.5	8.9	4.3
348	24-Jan-06		0.00	0.00	17.17	17.17	0.00	0.00	0.00	0.00	32.0	94.4	37.1	6.6	5.3
349	25-Jan-06		0.00	0.00	19.89	17.17	0.00	0.09	0.00	0.00	32.4	96.0	34.3	5.0	3.7
350	26-Jan-06		0.00	0.00	19.68	18.21	0.00	0.00	0.00	0.00	30.1	95.1	34.3	6.5	5.3
351	27-Jan-06		0.00	0.00	19.05	19.05	0.00	0.00	0.00	0.00		65.8	38.4	5.0	5.9
352	28-Jan-06														
353	29-Jan-06														
354	30-Jan-06		0.00	0.00	20.73	18.84	0.00	0.14	3.47	0.00	29.2	98.6	49.5	6.6	5.9
Batch Average		**22**	**0.00**	**0.00**	**20.27**	**19.83**	**0.00**	**0.04**	**0.00**	**0.00**	**32.0**	**72.9**	**33.7**	**6.4**	**5.4**
355	31-Jan-06	Batch 23													
356	1-Feb-06		0.00	0.02	6.43	21.68	0.05	0.13	2.71	3.39	32.4	95.7	42.1	10.6	7.1
357	2-Feb-06		0.00	0.57	9.06	12.26	0.05	0.10	0.00	4.19	33.9	106.1	47.2	9.9	10.6
358	3-Feb-06		0.00	0.70	12.64	11.13	0.05	0.11	0.00	0.00	33.6	104.9	46.8	11.2	11.5
359	4-Feb-06														
360	5-Feb-06														
361	6-Feb-06		0.00	0.74	18.85	16.40	0.04	0.21	0.00	0.00	33.0	94.2	48.7	9.3	9.9
362	7-Feb-06		0.00	0.36	14.34	17.54	0.00	0.41	0.00	0.00	34.2	98.3	40.1	11.0	11.6
363	8-Feb-06		0.00	0.00	15.14	17.74	0.00	0.00	0.00	0.00	35.1	91.8	40.4	11.3	11.9
364	9-Feb-06		0.00	0.00	14.14	18.74	0.00	0.00	0.00	0.00	36.1	98.3	41.6	12.5	12.2
365	10-Feb-06										37.6				
366	11-Feb-06														
367	12-Feb-06														
368	13-Feb-06		0.00	0.00	15.94	15.74	0.00	0.00	0.00	0.00	36.4	94.9	41.0	10.4	9.8
369	14-Feb-06		0.00	0.00	14.40	17.04	0.00	0.00	0.00	0.00	34.8	105.8	42.0	12.2	12.2
Batch Average		**23**	**0.00**	**0.27**	**13.44**	**16.48**	**0.02**	**0.07**	**0.00**	**0.42**	**34.7**	**98.9**	**43.3**	**10.9**	**11.2**
370	15-Feb-06	Batch 24													
371	16-Feb-06		0.00	0.00	10.88	15.72	0.00	0.18	0.00	0.00	30.1	96.5	36.3	10.1	5.9
372	17-Feb-06		0.00	0.00	13.96	15.50	0.00	0.00	0.00	0.00	32.5	105.8	46.2	6.8	7.4
373	18-Feb-06														
374	19-Feb-06														
375	20-Feb-06														
376	21-Feb-06		0.00	0.00	12.20	14.40	0.00	0.00	0.00	0.00	27.2	92.3	44.3	10.0	8.8
377	22-Feb-06		0.00	0.09	19.24	20.56	0.00	0.81	0.00	0.00	40.1	100.1	41.9	8.5	9.7
378	23-Feb-06		0.00	0.00	11.54	13.30	0.00	0.00	0.00	0.00	30.2	103.7	50.4	8.2	6.7
379	24-Feb-06		0.00	0.68	18.14	19.68	0.11	0.81	0.00	0.00	27.8	87.4	37.4	5.8	5.5
380	25-Feb-06														
381	26-Feb-06														
382	27-Feb-06		0.00	0.00	11.22	11.85	0.00	0.00	0.00	0.00	31.0	70.2	28.0	4.6	1.9
383	28-Feb-06		0.00	0.00	16.47	16.89	0.00	0.19	0.00	0.00	32.5	98.7	43.6	11.2	12.4
Batch Average		**24**	**0.00**	**0.01**	**14.21**	**15.99**	**0.00**	**0.25**	**0.00**	**0.00**	**30.2**	**97.8**	**41.0**	**8.1**	**7.3**
384	1-Mar-06	Batch 25	0.00	1.02	20.67	21.72	0.00	1.60	0.00	0.00	34.6	77.7	30.4	7.3	5.5
385	2-Mar-06														
386	3-Mar-06														
387	4-Mar-06														
388	5-Mar-06														
389	6-Mar-06		0.00	0.91	27.39	29.49	0.00	0.44	0.00	0.00	40.0	104.0	44.8	13.3	10.6
390	7-Mar-06		0.00	1.79	33.90	35.58	0.00	0.82	0.00	0.00	37.0	85.5	34.0	7.3	7.3
391	8-Mar-06		0.00	0.39	34.15	37.04	0.00	1.19	0.00	0.00	29.3	85.7	35.1	3.7	6.1
Batch Average		**25**	**0.00**	**1.03**	**29.03**	**30.96**	**0.00**	**1.01**	**0.00**	**0.00**	**35.2**	**88.2**	**36.0**	**7.9**	**7.4**
392	9-Mar-06		0.00	0.45	32.82	34.37	0.00	1.30	0.00	0.00	32.0	89.4	33.2	5.8	5.2
393	10-Mar-06														
394	11-Mar-06														
395	12-Mar-06														
396	13-Mar-06		0.00	0.08	15.06	18.83	0.00	0.56	0.00	0.00	27.8	96.9	38.1		6.4

397	14-Mar-06	Batch 2	0.00	0.00	15.28	16.84	0.00	0.02	0.00	0.00	26.0	90.6	38.4	7.3	4.0
398	15-Mar-06		0.00	0.00	12.00	15.42	0.04	0.05	0.00	0.00	25.4	104.7	41.2	9.8	10.4
399	16-Mar-06		0.00	0.00	14.56	21.20	0.04	0.05	0.00	0.00	32.4	103.8	45.2	7.4	8.6
400	17-Mar-06		0.00	0.00	14.99	16.92	0.04	0.14	0.00	0.00	25.4	93.4	41.8	8.9	9.8
401	18-Mar-06														
402	19-Mar-06														
403	20-Mar-06		0.00	0.00	19.49	22.48	0.06	0.77	0.00	0.00	34.5	111.4	43.1		6.7
404	21-Mar-06		0.00	0.00	6.43	7.07	0.03	0.05	0.00	0.00	29.9	79.4	33.6	9.8	8.9
405	22-Mar-06														
406	23-Mar-06		0.00	0.00	13.70	17.27	0.05	0.00	0.00	0.00	27.0	92.8	38.2	8.3	7.2
Batch Average		**26**	**0.00**	**0.01**	**13.94**	**17.00**	**0.03**	**0.21**	**0.00**	**0.00**	**28.9**	**95.8**	**39.2**	**8.2**	**7.5**
407	24-Mar-06	Batch 27	0.00	0.00	19.64	21.82	0.04	0.00	0.00	0.00	29.3	95.7	38.2	7.8	7.5
408	25-Mar-06														
409	26-Mar-06														
410	27-Mar-06		0.00	1.10	21.03	23.41	0.05	0.00	0.00	0.00	33.9	53.4	29.0	17.0	17.8
411	28-Mar-06		0.00	6.50	14.69	17.07	0.00	0.00	0.00	0.00	29.6	98.6	37.6	7.5	8.0
412	29-Mar-06														
413	30-Mar-06		0.04	0.51	8.16	16.23	0.20	0.51	0.00	0.00	25.4	63.8	69.6	19.0	5.9
414	31-Mar-06		0.00	0.58	13.09	14.88	0.08	0.54	0.00	0.00	27.7	80.1	33.1	15.5	7.8
415	1-Apr-06		0.00	0.08	9.96	18.24	0.13	0.22	0.00	0.00	27.7	110.5	48.1	16.8	9.4
416	2-Apr-06		0.00	0.00	13.09	18.69	0.06	0.08	0.00	0.00	30.5	105.1	49.4	17.1	10.7
417	3-Apr-06		0.00	0.30	16.90	20.04	0.08	0.38	0.00	0.00	27.7	99.9	39.5	10.7	5.6
418	4-Apr-06		0.00	1.73	17.80	22.28	0.08	1.19	0.00	0.00	31.8	104.4	41.4	15.2	8.5
419	5-Apr-06		0.00	0.00	14.66	23.00	0.11	0.86	0.73	0.31	24.5	91.4	37.9	9.8	7.7
420	6-Apr-06		0.00	0.00	15.03	20.86	0.08	0.12	0.79	0.31	30.0	88.3	43.1	13.8	8.0
421	7-Apr-06		0.00	0.00	17.02	21.50	0.05	0.25	0.73	0.31	32.4	94.4	37.0	12.3	8.0
Batch Average		**27**	**0.00**	**0.39**	**15.09**	**19.84**	**0.07**	**0.27**	**0.19**	**0.08**	**29.2**	**93.8**	**39.5**	**13.5**	**7.9**
422	8-Apr-06	Batch 28													
423	9-Apr-06														
424	10-Apr-06		0.00	0.00	16.10	19.36	0.06	0.09	0.79	0.31	28.2	91.4	38.8	5.6	1.9
425	11-Apr-06		0.00	0.00	17.60	21.29	0.04	0.08	0.79	0.31	14.4	92.6	36.4	2.2	0.4
426	12-Apr-06		0.00	0.00	17.13	24.09	0.11	0.08	0.00	0.00	17.7	115.6	39.2		
427	13-Apr-06		0.00	1.38	20.61	25.95	0.10	1.16	0.00	0.00		97.5	35.2		
428	14-Apr-06		0.00	0.00	17.83	21.08	0.05	0.20	0.00	0.00	18.4	96.5	30.1		
429	15-Apr-06		0.00	0.00	16.67	21.31	0.05	0.08	0.00	0.00	18.1	95.1	33.8	5.7	
430	16-Apr-06														
431	17-Apr-06														
432	18-Apr-06		0.00	0.69	19.22	21.50	0.07	1.79	0.00	0.00	25.6	75.2	31.1	3.6	0.7
433	19-Apr-06		0.00	11.22	17.89	19.79	0.10	0.11	0.00	0.00	19.5	98.1	41.3	2.7	1.3
434	20-Apr-06		0.00	0.00	16.56	18.84	0.09	0.08	0.00	0.00	20.1	94.6	39.5	9.7	0.4
435	21-Apr-06		0.00	0.00	15.99	19.03	0.06	0.11	0.00	0.00	23.9	98.1	39.8	1.9	0.4
436	22-Apr-06														
Batch Average		**28**	**0.00**	**0.23**	**17.22**	**20.70**	**0.07**	**0.22**	**0.16**	**0.06**	**20.7**	**95.5**	**36.5**	**4.5**	**0.8**
437	23-Apr-06	Batch 29													
438	24-Apr-06					12.89	0.11	0.05	0.64	0.07	9.1	81.6	32.4	1.4	1.7
439	25-Apr-06					11.03	0.05	0.05	0.75	0.07	10.3	88.0	33.7	1.7	1.4
440	26-Apr-06		0.00	0.00	8.03	12.19	0.04	0.06	0.75	0.07	27.8	81.3	31.8	1.1	2.6
441	27-Apr-06		0.00	0.00	8.60	13.12	0.04	0.04	0.64	0.07	18.7	76.7	28.7	1.4	1.1
442	28-Apr-06		0.00	0.00	12.55	14.28	0.05	0.05	0.64	0.07	34.9	91.7	37.6	2.3	1.4
443	29-Apr-06						0.03	0.11	0.00	0.00	45.8	117.0	62.2	8.0	7.1
444	30-Apr-06		0.00	0.04	10.45	13.87	0.05	0.35	0.00	0.00	36.3	84.1	35.7	7.7	8.6
445	1-May-06		0.00	0.19	8.63	14.10	0.04	0.57	0.00	0.00	35.1	85.6	36.9	6.5	6.2
446	2-May-06														
447	3-May-06		0.00	0.00	8.40	9.31	0.03	0.11	0.00	0.00	54.0	82.6	31.7	2.2	8.0
448	4-May-06														
449	5-May-06		0.00	2.28	13.87	15.01	0.03	1.50	0.00	0.00	37.8	85.6	36.6	8.0	8.6
Batch Average		**29**	**0.00**	**0.04**	**10.08**	**13.31**	**0.05**	**0.15**	**0.34**	**0.04**	**31.0**	**84.1**	**33.9**	**4.0**	**4.7**

Appendix A-4

Miscellaneous measurements on the MBR UCT system

			DSVI		Vol Flow		OUR		Recycles		Trans-Membrane Head	Reactor Vol			
Day	Date	SB #	msrd.	adj.	Qi	Qw	meas.	revised	as	r		AN	AX	AE	RE
-	-	-	(mm/gTSS/L)		(l)		mgO/l/hr		-		(mm)	(l)			
19	1-Mar-05				140	2.85						19.0	21.0	34.0	
20	2-Mar-05				140	2.85						19.0	21.0	34.0	
21	3-Mar-05	Batch 2			140	2.85						19.0	21.0	34.0	
22	4-Mar-05				140	2.85						19.0	21.0	34.0	
23	5-Mar-05				140							19.0	21.0	34.0	
24	6-Mar-05				140							19.0	21.0	34.0	
25	7-Mar-05				140	2.85						18.0	20.0	34.0	
26	8-Mar-05				140	2.30					95.0	19.0	21.0	34.0	
27	9-Mar-05		105.0	122.2	140	2.85					120.0	19.0	20.0	32.0	
28	10-Mar-05				140	3.60					39.0	19.0	21.0	32.0	
29	11-Mar-05				140	2.85						19.0	21.0	34.0	
30	12-Mar-05				140							19.0	21.0	34.0	
31	13-Mar-05				140							19.0	21.0	34.0	
32	14-Mar-05		85.0	112.4	140	1.00					130.0	19.0	21.0	36.0	
33	15-Mar-05		90.0	103.2	140	4.80					130.0	19.0	21.0	34.0	
34	16-Mar-05				140	2.85					130.0	19.0	21.0	34.0	
35	17-Mar-05		90.0	116.5	140	2.85						19.0	21.0	34.0	
36	18-Mar-05				140	2.85					130.0	19.0	21.0	34.0	
Batch Average		**2**	**92.5**	**113.4**	**140**	**2.88**			**4.00**	**1.00**	**122.5**	**18.9**	**20.9**	**33.9**	
37	19-Mar-05	Batch 3			140							19.0	21.0	34.0	
38	20-Mar-05				140							19.0	21.0	34.0	
39	21-Mar-05		75.0	106.1	140	2.85						19.0	21.0	34.0	
40	22-Mar-05				140	2.85					130.0	19.0	21.0	34.0	
41	23-Mar-05				140	2.85						19.0	21.0	34.0	
42	24-Mar-05				140	2.85					130.0	18.0	21.0	34.0	
43	25-Mar-05		75.0	98.0	140	2.85						19.0	21.0	34.0	
44	26-Mar-05				140							19.0	21.0	34.0	
45	27-Mar-05				140	2.85						19.0	21.0	34.0	
46	28-Mar-05				140							19.0	21.0	34.0	
47	29-Mar-05		90.0	102.0	140	2.85					130.0	19.0	21.0	34.0	
48	30-Mar-05				140							19.0	21.0	34.0	
49	31-Mar-05		90.0	96.8	140	2.85						19.0	21.0	34.0	
50	1-Apr-05				140							19.0	21.0	34.0	
51	2-Apr-05		85.0	101.4	140	2.85						19.0	21.0	34.0	
52	3-Apr-05				140							19.0	21.0	34.0	
53	4-Apr-05				140	2.85						19.0	21.0	34.0	
Batch Average		**3**	**83.0**	**104.8**	**140**	**2.85**			**4.00**	**1.00**	**130.0**	**18.9**	**21.0**	**34.0**	
54	5-Apr-05	Batch4			140	3.35						19.0	21.0	34.0	
55	6-Apr-05				140							19.0	21.0	34.0	
56	7-Apr-05				140							19.0	21.0	34.0	
57	8-Apr-05		80.0	102.0	140	2.85					19.0	19.0	21.0	34.0	
58	9-Apr-05				140							19.0	21.0	34.0	
59	10-Apr-05				140	2.85						19.0	21.0	34.0	
60	11-Apr-05				140						30.0	19.0	21.0	34.0	
61	12-Apr-05				140	2.85						19.0	21.0	34.0	
62	13-Apr-05				140					0.95		19.0	21.0	34.0	
63	14-Apr-05		85.0	87.7	140	2.85					20.0	19.0	21.0	34.0	
64	15-Apr-05				140					1.30		19.0	21.0	34.0	
65	16-Apr-05				140	2.85						19.0	21.0	34.0	
66	17-Apr-05				140							19.0	21.0	34.0	
67	18-Apr-05				140	2.85						19.0	21.0	34.0	
68	19-Apr-05		55.0	81.4	140	2.85				1.75	45.0	19.0	21.0	34.0	
69	20-Apr-05				140	2.85						19.0	21.0	34.0	
70	21-Apr-05				140	2.85						19.0	21.0	34.0	
71	22-Apr-05				140				4.00	1.74		19.0	21.0	34.0	
72	23-Apr-05		45.0	107.9	140		36.1					19.0	21.0	34.0	
73	24-Apr-05				140							19.0	21.0	34.0	
74	25-Apr-05		40.0	91.5	140		32.5				35.0	19.0	21.0	34.0	
75	26-Apr-05				140							19.0	21.0	34.0	

Batch Average		**4**	**61.0**	**86.8**	**140**	**2.85**	**34.3**		**4.00**	**1.00**	**29.8**	**19.0**	**21.0**	**34.0**	
76	27-Apr-05	Batch 5			140							19.0	21.0	34.0	
77	28-Apr-05				140							19.0	21.0	34.0	
78	29-Apr-05		40.0	77.3	140		58.7		4.08	1.67		19.0	21.0	34.0	
79	30-Apr-05				140							19.0	21.0	34.0	
80	1-May-05				140		25.1					19.0	21.0	34.0	
81	2-May-05		55.0	90.3	140	2.85						19.0	21.0	34.0	
82	3-May-05				140	2.85	51.7				25.0	19.0	21.0	34.0	
83	4-May-05		95.0	112.8	140	2.85						19.0	21.0	34.0	
84	5-May-05				140	2.85					30.0	19.0	21.0	34.0	
85	6-May-05				140	2.85			2.78	1.29		19.0	21.0	34.0	
86	7-May-05				140							19.0	21.0	34.0	
87	8-May-05				140							19.0	21.0	34.0	
88	9-May-05		85.0	98.7	140	2.85						19.0	21.0	34.0	
89	10-May-05				140	2.85						19.0	21.0	34.0	
90	11-May-05		80.0	95.6	140	2.85	64.5					19.0	21.0	34.0	
91	12-May-05				140	2.85					35.0	19.0	21.0	34.0	
92	13-May-05		85.0	92.3	140	2.85	48.5		2.91	1.29		19.0	21.0	34.0	
93	14-May-05				140							19.0	21.0	34.0	
94	15-May-05				140							19.0	21.0	34.0	
Batch Average		**5**	**73.3**	**88.5**	**140**	**2.85**	**49.7**		**4.00**	**1.00**	**30.0**	**19.0**	**21.0**	**34.0**	
95	16-May-05	Batch 6			140	1.50	51.7					19.0	21.0	34.0	
96	17-May-05				140	6.20					40.0	19.0	21.0	34.0	
97	18-May-05				140	0.00					40.0	19.0	21.0	34.0	
98	19-May-05				140	6.30					45.0	19.0	21.0	34.0	
99	20-May-05				140	0.80			3.13	1.31		19.0	21.0	34.0	
100	21-May-05				140	4.80						19.0	21.0	34.0	
101	22-May-05				140	2.80						19.0	21.0	34.0	
102	23-May-05				140	3.00					45.0	19.0	21.0	34.0	
103	24-May-05		60.0	83.6	140	4.20						19.0	21.0	34.0	
104	25-May-05		80.0	89.5	140	3.00					25.0	19.0	21.0	34.0	
105	26-May-05				140	1.40						19.0	21.0	34.0	
106	27-May-05		80.0	91.9	140	2.80			3.09	1.26		19.0	21.0	34.0	
107	28-May-05				140	2.80						19.0	21.0	34.0	
108	29-May-05				140	2.80						19.0	21.0	34.0	
109	30-May-05		80.0	85.5	140	2.80						19.0	21.0	34.0	
110	31-May-05				140	2.80					55.0	19.0	21.0	34.0	
Batch Average		**6**	**75.0**	**85.7**	**140**	**3.00**	**51.7**		**3.11**	**1.29**	**41.7**	**19.0**	**21.0**	**34.0**	
111	1-Jun-05	Batch 7			140	0.30			3.00	1.12	10.0	19.0	21.0	34.0	
112	2-Jun-05				140	5.70						19.0	21.0	34.0	
113	3-Jun-05				140	1.80					65.0	19.0	21.0	34.0	
114	4-Jun-05				140							19.0	21.0	34.0	
115	5-Jun-05				140	2.80						19.0	21.0	34.0	
116	6-Jun-05		100.0	99.6	140	2.80					45.0	19.0	21.0	34.0	
117	7-Jun-05				140	5.60						19.0	21.0	34.0	
118	8-Jun-05		95.0	106.8	140	2.80						19.0	21.0	34.0	
119	9-Jun-05				140	2.85						19.0	21.0	34.0	
120	10-Jun-05				140	2.80			2.93	1.16		19.0	21.0	34.0	
121	11-Jun-05				140	2.80						19.0	21.0	34.0	
122	12-Jun-05		90.0	115.5	140	2.80					35.0	19.0	21.0	34.0	
123	13-Jun-05				140	2.80					25.0	19.0	21.0	34.0	
124	14-Jun-05				140	0.00						19.0	21.0	34.0	
Batch Average		**7**	**95.0**	**105.2**	**140**	**2.76**			**2.96**	**1.14**	**36.0**	**19.0**	**21.0**	**34.0**	
125	15-Jun-05	Batch 8			140	2.95						19.0	21.0	34.0	
126	16-Jun-05				140	2.95						19.0	21.0	34.0	
127	17-Jun-05				140	2.80						19.0	21.0	34.0	
128	18-Jun-05		95.0	102.9	140	2.85						19.0	21.0	34.0	
129	19-Jun-05				140	2.85						19.0	21.0	34.0	
130	20-Jun-05		100.0	104.8	140	2.80			2.99	1.28	30.0	19.0	21.0	34.0	
131	21-Jun-05				140		140.9	140.9				19.0	21.0	34.0	
132	22-Jun-05		80.0	82.7	140							19.0	21.0	34.0	
Batch Average		**8**	**91.7**	**103.2**	**140**	**2.87**	**140.9**	**140.9**	**2.99**	**1.28**	**30.0**	**19.0**	**21.0**	**34.0**	
133	23-Jun-05				140	3.60	138.2	138.2	2.99	1.28		19.0	21.0	34.0	
134	24-Jun-05		80.0	98.4	140	2.85					75.0	19.0	21.0	34.0	
135	25-Jun-05				140	2.85					35.0	19.0	21.0	34.0	
136	26-Jun-05				140	2.85						19.0	21.0	34.0	
137	27-Jun-05		90.0	102.9	140	2.85					35.0	19.0	21.0	34.0	

138	28-Jun-05	Batch 9	95.0	103.8	140	2.85						19.0	21.0	34.0	
139	29-Jun-05		90.0	103.1	140	2.85						19.0	21.0	34.0	
140	30-Jun-05		90.0	98.5	140	3.05	139.6	139.6			50.0	19.0	21.0	34.0	
141	1-Jul-05				140	2.85	116.2	116.2				19.0	21.0	34.0	
142	2-Jul-05				140	2.85						19.0	21.0	34.0	
143	3-Jul-05				140	2.85						19.0	21.0	34.0	
144	4-Jul-05		85.0	94.5	140	2.85						19.0	21.0	34.0	
145	5-Jul-05				140	2.85						19.0	21.0	34.0	
146	6-Jul-05		85.0	94.1	140	2.95	132.1	132.1			40.0	19.0	21.0	34.0	
147	7-Jul-05		85.0	92.8	140	2.85			3.17	1.15		19.0	21.0	34.0	
Batch Average		**9**	**87.5**	**96.5**	**140**	**2.92**	**131.5**	**131.5**	**3.08**	**1.22**	**47.0**	**19.0**	**21.0**	**34.0**	
148	8-Jul-05	Batch 10			140	2.85			3.17	1.15		19.0	21.0	34.0	
149	9-Jul-05				140	2.85						19.0	21.0	34.0	
150	10-Jul-05				140	2.85						19.0	21.0	34.0	
151	11-Jul-05		70.0	81.4	140	2.90						19.0	21.0	34.0	
152	12-Jul-05		80.0	92.2	140	2.85	123.2	123.2			35.0	19.0	21.0	34.0	
153	13-Jul-05				140	2.80	120.0	120.0				19.0	21.0	34.0	
154	14-Jul-05		90.0	100.2	140	2.85	105.0	105.0				19.0	21.0	34.0	
155	15-Jul-05				140	2.85						19.0	21.0	34.0	
156	16-Jul-05				140	2.85					45.0	19.0	21.0	34.0	
157	17-Jul-05				140	2.85						19.0	21.0	34.0	
158	18-Jul-05		80.0	96.3	140	2.90					45.0	19.0	21.0	34.0	
159	19-Jul-05		80.0	94.2	140	2.85	140.0	140.0				19.0	21.0	34.0	
160	20-Jul-05		80.0	93.7	140	3.00	126.0	126.0				19.0	21.0	34.0	
161	21-Jul-05				140	2.85						19.0	21.0	34.0	
162	22-Jul-05				140	2.85						19.0	21.0	34.0	
163	23-Jul-05				140	2.85	118.0	118.0			50.0	19.0	21.0	34.0	
164	24-Jul-05				140	2.85	116.0	116.0				19.0	21.0	34.0	
165	25-Jul-05		110.0	121.0	140	2.85					70.0	19.0	21.0	34.0	
166	26-Jul-05		110.0	122.8	140	2.85					70.0	19.0	21.0	34.0	
167	27-Jul-05		110.0	125.0	140	2.85						19.0	21.0	34.0	
Batch Average		**10**	**90.0**	**102.1**	**140**	**2.86**	**121.2**	**121.2**	**3.17**	**1.15**	**52.5**	**19.0**	**21.0**	**34.0**	
168	28-Jul-05	Batch 11			140	2.85			3.17	1.15		19.0	21.0	34.0	
169	29-Jul-05		110.0	125.9	140	2.90					70.0	19.0	21.0	34.0	
170	30-Jul-05				140	2.85						19.0	21.0	34.0	
171	31-Jul-05				140	2.85						19.0	21.0	34.0	
172	1-Aug-05		110.0	114.2	140	3.00	111.0	111.0			45.0	19.0	21.0	34.0	
173	2-Aug-05		100.0	112.7	140	2.85	120.0	120.0				19.0	21.0	34.0	
174	3-Aug-05				140	2.80					120.0	19.0	21.0	34.0	
175	4-Aug-05		100.0	113.2	140	2.85						19.0	21.0	34.0	
176	5-Aug-05				140	2.85					10.0	19.0	21.0	34.0	
177	6-Aug-05				140	2.85						19.0	21.0	34.0	
178	7-Aug-05				140	2.85						19.0	21.0	34.0	
179	8-Aug-05		90.0	106.4	140	2.90	102.0	102.0				19.0	21.0	34.0	
180	9-Aug-05				140	2.85					70.0	19.0	21.0	34.0	
181	10-Aug-05		90.0	103.6	140	2.85	126.0	126.0	3.63	1.71	70.0	19.0	21.0	34.0	
182	11-Aug-05				140	2.85	111.0	111.0			70.0	19.0	21.0	34.0	
183	12-Aug-05		85.0	109.7	140	2.85	112.0	131.1				19.0	21.0	34.0	
184	13-Aug-05				140	2.85						19.0	21.0	34.0	
185	14-Aug-05				140	2.85						19.0	21.0	34.0	
186	15-Aug-05				140	2.85	107.0	114.3				19.0	21.0	34.0	
187	16-Aug-05				140	2.70						19.0	21.0	34.0	
188	17-Aug-05				140	2.85						19.0	21.0	34.0	
Batch Average		**11**	**97.9**	**114.1**	**140**	**2.85**	**112.7**	**116.5**	**3.40**	**1.43**	**65.0**	**19.0**	**21.0**	**34.0**	
189	18-Aug-05	Batch 12			140	2.85	114.0	151.5	3.38	1.56		19.0	21.0	34.0	
190	19-Aug-05				140	2.85	119.0	150.9				19.0	21.0	34.0	
191	20-Aug-05				140	2.85						19.0	21.0	34.0	
192	21-Aug-05				140	2.85						19.0	21.0	34.0	
193	22-Aug-05				140	2.85	96.0	119.3				19.0	21.0	35.0	
194	23-Aug-05				140	2.85	99.0	105.7				19.0	21.0	34.0	
195	24-Aug-05				140	2.85									
196	25-Aug-05		95.0	107.9	140	2.85	100.0	136.6				19.0	21.0	34.0	
197	26-Aug-05				140	2.85	106.0	133.2				19.0	21.0	34.0	
198	27-Aug-05				140	2.85						21.0	23.0	36.0	
199	28-Aug-05				140	2.85									
200	29-Aug-05				140	2.85						19.0	21.0	35.0	
201	30-Aug-05				140	2.35	108.0	115.0	3.24	1.31		19.0	21.0	35.0	

202	31-Aug-05				140	4.20	102.0	123.9			85.0				
203	1-Sep-05				140	2.80	109.0	134.9			35.0	20.0	22.0	35.0	
204	2-Sep-05				140	2.85	117.0	141.7							
Batch Average		**12**	**95.0**	**117.8**	**140**	**2.90**	**107.0**	**131.3**	**3.31**	**1.44**	**60.0**	**19.3**	**21.3**	**34.5**	
205	3-Sep-05	Batch 13			140										
206	4-Sep-05				140										
207	5-Sep-05				140	2.35	102.0	135.8			85.0	19.0	21.0	35.0	
208	6-Sep-05				140	3.50					100.0	19.0	21.0	35.0	
209	7-Sep-05				140	2.85					75.0	20.0	22.0	34.0	
210	8-Sep-05		90.0	104.0	140	2.85			3.59	1.33	85.0	19.0	21.0	36.0	
211	9-Sep-05				140	3.35					95.0	19.0	21.0	35.0	
212	10-Sep-05				140	2.35									
213	11-Sep-05				140	2.85	102.0	140.0	3.83	1.56		19.0	21.0	35.0	
214	12-Sep-05		90.0	105.2	140	2.85	110.0	151.0	3.37	1.23	110.0	19.0	22.0	35.0	
215	13-Sep-05				140	2.35	102.0	125.8			100.0	19.0	21.0	35.0	
216	14-Sep-05		90.0	105.4	140	3.00	111.0	146.9			95.0	19.0	21.0	35.0	
217	15-Sep-05				140	3.05			2.50	0.95	90.0	19.0	21.0	35.0	
218	16-Sep-05		80.0	100.8	140	3.15	113.0	130.3			80.0	19.0	23.0	36.0	
Batch Average		**13**	**87.5**	**103.7**	**140**	**2.88**	**106.7**	**138.3**	**3.32**	**1.27**	**91.5**	**19.1**	**21.4**	**35.1**	
219	17-Sep-05	Batch 14			140	2.85									
220	18-Sep-05				140	2.85									
221	19-Sep-05		90.0		140	2.85	104.0	136.4	3.12	1.24	45.0	19.0	21.0	35.0	
222	20-Sep-05		85.0	101.0	140	2.85	107.0	140.4			80.0	19.0	21.0	35.0	
223	21-Sep-05		80.0	100.0	140	2.85	112.0	143.1			83.0	19.0	21.0	35.0	
224	22-Sep-05		70.0	86.6	140	2.85	99.0	126.8			100.0	19.0	21.0	36.0	
225	23-Sep-05				140	2.50	109.0	146.5			83.0	19.0	21.0	35.0	
226	24-Sep-05				140	3.00			2.87	1.11					
227	25-Sep-05				140	2.85									
228	26-Sep-05		70.0	98.0	140	2.85	96.0	120.8				19.0	21.0	35.0	
229	27-Sep-05				140	2.85					95.0				
230	28-Sep-05				140	3.10	69.0	75.9	2.90	1.07		19.0	21.0	35.0	
231	29-Sep-05				140	2.70						19.0	21.0	35.0	
232	30-Sep-05				140	3.00									
233	1-Oct-05				140	2.85									
234	2-Oct-05				140	2.85									
235	3-Oct-05		90.0	105.4	140	2.85					65.0				
Batch Average		**14**	**80.8**	**100.7**	**140**	**2.85**	**104.5**	**135.7**	**2.96**	**1.14**	**78.7**	**19.0**	**21.0**	**35.1**	
236	4-Oct-05	Batch 15	90.0	108.3	140	2.85					57.0	19.0	21.0	35.0	0.0
237	5-Oct-05		90.0	104.1	140	2.85					57.0	19.0	21.0	35.0	0.0
238	6-Oct-05				140	2.85					57.0				0.0
239	7-Oct-05		110.0	120.8	140	2.85	69.0	90.4	3.15	1.25	56.0	19.0	21.0	35.0	0.0
240	8-Oct-05				140	2.85									0.0
241	9-Oct-05				140	2.85	82.0	107.4							0.0
242	10-Oct-05		90.0	105.2	140	2.85	104.0	132.0	2.97	1.14	100.0	19.0	21.0	35.0	0.0
243	11-Oct-05				140	2.85	104.0	143.2				19.0	21.0	32.0	3.0
244	12-Oct-05		100.0	105.9	140	2.85	105.0	150.8			52.0	19.0	21.0	35.0	0.0
Batch Average		**15**	**96.0**	**109.6**	**140**	**2.85**	**92.8**	**124.8**	**3.06**	**1.20**	**63.2**	**19.0**	**21.0**	**34.5**	**0.3**
245	13-Oct-05	Batch 16			140	2.85									
246	14-Oct-05		100.0	111.0	140	2.85	104.0	140.2	2.87	1.08	63.0	19.0	21.0	32.0	3.0
247	15-Oct-05				140	2.85									
248	16-Oct-05				140	2.85									
249	17-Oct-05		100.0	116.2	140	2.85	105.0	129.4			50.0	19.0	21.0	32.0	3.0
250	18-Oct-05				140	2.85					56.0	19.0	21.0	32.0	3.0
251	19-Oct-05		80.0	100.6	140	2.85	111.0	136.8	2.75	1.13		19.0	21.0	32.0	3.0
252	20-Oct-05				140	2.85	107.0	131.9			52.0	19.0	21.0	32.0	3.0
253	21-Oct-05		70.0	86.1	140	2.85	117.0	153.8			68.0	19.0	21.0	32.0	3.0
254	22-Oct-05				140	2.85						19.0	21.0	32.0	3.0
255	23-Oct-05				140	2.85									
256	24-Oct-05		80.0	93.1	140	2.85	97.0	124.8				19.0	21.0	32.0	3.0
257	25-Oct-05				140	2.85	97.0	133.6				19.0	21.0	32.0	3.0
258	26-Oct-05		90.0	100.2	140	2.85	94.0	129.5			52.0	19.0	21.0	32.0	3.0
259	27-Oct-05				140	2.85	91.6	120.8	2.89	0.99		19.0	21.0	32.0	3.0
Batch Average		**16**	**86.7**	**101.3**	**140**	**2.85**	**102.6**	**130.9**	**2.84**	**1.07**	**56.8**	**19.0**	**21.0**	**32.0**	**3.0**
260	28-Oct-05		80.0	92.0	140	2.90	84.9	113.4			52.0	19.0	21.0	32.0	3.0
261	29-Oct-05				140	2.85	78.4	104.7				19.0	21.0	32.0	3.0
262	30-Oct-05				140	2.85									
263	31-Oct-05		80.0	88.3	140	2.85	82.8	114.1				19.0	21.0	32.0	3.0

64	1-Nov-05	Batch 17			140	2.85	74.5	96.4				19.0	21.0	32.0	3.0
65	2-Nov-05		100.0	109.0	140	2.85	75.0	102.8			70.0	19.0	21.0	32.0	3.0
66	3-Nov-05				140	0.00									
67	4-Nov-05		105.0	105.2	140	3.85			3.00	1.00		19.0	21.0	31.0	3.0
68	5-Nov-05				140	3.60									
69	6-Nov-05				140	2.85					72.0	19.0	21.0	32.0	3.0
70	7-Nov-05				140	2.85	83.0	102.6			54.0	19.0	22.0	31.0	3.0
71	8-Nov-05				140	2.85						19.0	21.0	32.0	3.0
72	9-Nov-05		100.0	109.3	140	2.85	86.0	114.2				19.0	21.0	32.0	3.0
73	10-Nov-05				140	2.85					92.0	19.0	21.0	32.0	3.0
Batch Average		**17**	**93.0**	**102.3**	**140**	**2.78**	**80.7**	**106.9**	**3.00**	**1.00**	**68.0**	**19.0**	**21.1**	**31.8**	**3.0**
274	11-Nov-05	Batch 18	110.0	116.5	140	2.85					84.0	19.0	21.0	32.0	3.0
275	12-Nov-05				140	2.85									
276	13-Nov-05				140	2.85									
277	14-Nov-05				140	2.85									
278	15-Nov-05		90.0	95.8	140	2.85	84.0	113.2			86.0	19.0	21.0	32.0	3.0
279	16-Nov-05		95.0	114.3	140	2.85	82.1	92.7			75.0	19.0	21.0	33.0	3.0
280	17-Nov-05				140	2.85	98.6	127.2				19.0	21.0	33.0	3.0
281	18-Nov-05		80.0	88.4	140	2.85	89.6	119.2			69.0	19.0	21.0	32.0	3.0
282	19-Nov-05				140	2.80						19.0	21.0	34.0	
283	20-Nov-05				140	2.85			3.38	1.27	63.0	19.0	21.0	34.0	
284	21-Nov-05		80.0	83.2	140	2.85	97.0	135.4			95.0	19.0	21.0	32.0	3.0
285	22-Nov-05		75.0	86.5	140	2.85	95.5	105.4				19.0	21.0	32.0	3.0
286	23-Nov-05		90.0	90.8	140	2.85	67.5	94.5				19.0	21.0	32.0	3.0
287	24-Nov-05		85.0	100.5	140	2.85	83.5	106.5				19.0	21.0	32.0	3.0
288	25-Nov-05		80.0	85.0	140	2.85	90.5	119.5			76.0	19.0	21.0	32.0	3.0
289	26-Nov-05				140	2.85									
290	27-Nov-05				140	2.85	94.9	126.3							
291	28-Nov-05		90.0	96.2	140	2.85	90.6	120.6				19.0	21.0	32.0	3.0
Batch Average		**18**	**87.5**	**95.8**	**140**	**2.85**	**90.6**	**114.6**	**3.38**	**1.27**	**78.3**	**19.0**	**21.0**	**32.5**	**3.0**
292	29-Nov-05	Batch 19			140	2.85	91.8	118.0			58.0	19.0	21.0	32.0	3.0
293	30-Nov-05		80.0	84.3	140	2.85					73.0	19.0	21.0	32.0	3.0
294	1-Dec-05				140	2.85	90.5	118.5				19.0	21.0	32.0	3.0
295	2-Dec-05		80.0	84.9	140	2.85	89.9	121.6			78.0	19.0	21.0	32.0	3.0
296	3-Dec-05				140	2.85									
297	4-Dec-05				140	2.85									
298	5-Dec-05		80.0	82.3	140	2.85					60.0	19.0	21.0	32.0	3.0
299	6-Dec-05				140	2.85	92.6	122.4				19.0	21.0	32.0	3.0
300	7-Dec-05				140	2.85	93.9	132.9			90.0	19.0	21.0	32.0	3.0
301	8-Dec-05		75.0	77.5	140	2.85	95.3	122.4				19.0	21.0	32.0	3.0
302	9-Dec-05				140	2.85	97.4	135.4				19.0	21.0	32.0	3.0
303	10-Dec-05				140	2.85									
304	11-Dec-05				140	2.85									
305	12-Dec-05				140	2.85	101.1	141.0	3.23	1.13		19.0	21.0	32.0	3.0
306	13-Dec-05		80.0	88.4	140	2.85	96.2	126.7				19.0	21.0	32.0	3.0
307	14-Dec-05				140	2.85	94.0	121.3				19.0	21.0	32.0	3.0
308	15-Dec-05				140	2.85	93.5	120.2				19.0	21.0	32.0	3.0
309	16-Dec-05				140										
310	17-Dec-05				140										
311	18-Dec-05				140										
312	19-Dec-05				140										
Batch Average		**19**	**79.0**	**83.5**	**140**	**2.85**	**93.5**	**123.9**	**3.23**	**1.13**	**71.8**	**19.0**	**21.0**	**32.0**	**3.0**
313	20-Dec-05	Batch 20			140										
314	21-Dec-05				140				3.35	1.16					
315	22-Dec-05				140										
316	23-Dec-05				140										
317	24-Dec-05				140										
318	25-Dec-05				140										
319	26-Dec-05				140										
320	27-Dec-05				140										
321	28-Dec-05				140										
322	29-Dec-05				140										
323	30-Dec-05				140										
324	31-Dec-05				140										
325	1-Jan-06				140										
326	2-Jan-06				140										
Batch Average		**20**			**140**										

90	7-Mar-06	B	100.0	121.6	140	2.20	103.1	131.6	3.40	1.21	129.0	20.0	21.0	32.0	3.5
91	8-Mar-06		95.0	122.6	140	2.85	99.1	121.7			130.3	19.0	21.0	32.0	3.5
Batch Average		**25**	**96.3**	**117.7**	**140**	**2.83**	**110.8**	**139.8**	**3.45**	**1.17**	**130.8**	**19.7**	**21.3**	**32.8**	**3.5**
92	9-Mar-06	Batch 26			140	2.95	116.5	149.1			126.9	19.0	21.0	33.0	3.5
93	10-Mar-06				140	2.85					125.2				
94	11-Mar-06				140	2.85									
95	12-Mar-06				140	2.00						20.0	22.0	29.0	3.5
396	13-Mar-06		100.0	112.4	140	2.85	75.5	101.8				21.0	23.0	34.0	3.5
397	14-Mar-06			0.0	140	3.25	61.2	82.6				20.0	22.0	35.0	3.5
398	15-Mar-06		95.0	101.2	140	2.45						20.0	21.0	32.0	3.5
399	16-Mar-06			0.0	140	3.05	84.0	110.8			146.9	20.0	22.0	33.0	3.5
400	17-Mar-06		95.0	105.1	140	2.65	82.3	106.3				20.0	22.0	33.0	3.5
401	18-Mar-06				140	2.85									
402	19-Mar-06				140	2.85	69.3	89.5			140.1				
403	20-Mar-06		90.0	100.0	140	2.85	88.6	116.6			147.1	19.0	21.0	33.0	3.5
404	21-Mar-06				140	2.85	81.1	104.7	3.91	1.23	143.3				
405	22-Mar-06				140	2.85	87.0	114.5				20.0	22.0	33.0	3.5
406	23-Mar-06		95.0	108.2	140	2.85	99.2	133.5			154.8	19.0	21.0	34.0	3.5
Batch Average		**26**	**95.0**	**75.3**	**140**	**2.80**	**80.9**	**110.9**	**3.91**	**1.23**	**140.6**	**19.8**	**21.7**	**32.9**	**3.5**
407	24-Mar-06	Batch 27	100.0	111.9	140	2.85	87.7	118.3			142.4	19.0	21.0	32.0	3.5
408	25-Mar-06				140	2.85					148.3				
409	26-Mar-06				140	2.85									
410	27-Mar-06		80.0	90.9	140	2.85	77.1	104.7				19.0	21.0	32.0	3.5
411	28-Mar-06				140	2.85	71.9	100.0			157.5	21.0	23.0	34.0	3.5
412	29-Mar-06		85.0	104.9	140	2.85					154.1	19.0	21.0	32.0	3.5
413	30-Mar-06				140	2.85					156.4				
414	31-Mar-06		100.0	114.5	140	2.85			3.52	1.12	157.7	19.0	21.0	32.0	3.5
415	1-Apr-06				140	2.85									
416	2-Apr-06				140	2.85									
417	3-Apr-06		90.0	100.2	140	2.85	90.2	123.5			152.0	19.0	21.0	32.0	3.5
418	4-Apr-06				140	2.25	85.9	107.2	3.52	1.12	164.0	19.0	21.0	32.0	3.5
419	5-Apr-06		90.0	102.4	140	3.25	73.1	94.9			164.6	19.0	21.0	32.0	3.5
420	6-Apr-06				140	2.85						19.0	21.0	32.0	3.5
421	7-Apr-06				140	2.85					173.9				
Batch Average		**27**	**90.8**	**104.1**	**140**	**2.84**	**81.0**	**108.1**	**3.52**	**1.12**	**157.1**	**19.2**	**21.2**	**32.2**	**3.5**
422	8-Apr-06	Batch 28			140	2.85									
423	9-Apr-06				140	2.85						19.0	21.0	32.0	3.5
424	10-Apr-06		95.0	110.7	140	2.85			3.22	1.10	179.9	19.0	21.0	32.0	3.5
425	11-Apr-06				140	2.85	95.8	114.3				20.0	22.0	32.0	3.5
426	12-Apr-06				140	2.85	58.8	78.6			173.6	19.0	21.0	33.0	3.5
427	13-Apr-06		90.0	105.9	140	2.85	63.3	82.3				19.0	21.0	32.0	3.5
428	14-Apr-06				140	2.85	67.9	88.8			181.6	19.0	21.0	34.0	3.5
429	15-Apr-06		110.0	142.2	140	2.85	63.7	74.1	3.54	1.22	185.9	19.0	21.0	32.0	3.5
430	16-Apr-06				140	2.85	65.5	76.2			197.8				
431	17-Apr-06				140	2.85									
432	18-Apr-06		100.0	126.4	140	5.90	73.6	103.6			195.1	19.0	21.0	38.0	3.5
433	19-Apr-06				140	2.85	82.5	110.8	2.69	0.97	202.5	19.0	21.0	32.0	3.5
434	20-Apr-06				0	0.00					194.8	19.0	21.0	32.0	
435	21-Apr-06		100.0	111.7	140	2.90	81.5	109.9				19.0	21.0	32.0	3.5
436	22-Apr-06				0	2.85									
Batch Average		**28**	**99.0**	**119.4**	**121**	**2.87**	**72.5**	**93.2**	**3.15**	**1.10**	**188.9**	**19.1**	**21.1**	**32.8**	**3.5**
437	23-Apr-06	Batch 29			140	2.85					166.4				
438	24-Apr-06		95.0	108.5	140	2.85	69.9	93.8			151.8	19.0	22.0	34.0	3.5
439	25-Apr-06				140	2.85	66.3	88.4			150.3	20.0	23.0	33.0	3.5
440	26-Apr-06		100.0	112.5	140	2.85	88.5	120.1			142.2	19.0	21.0	33.0	3.5
441	27-Apr-06				140	2.85	88.6	116.7			136.3	19.0	21.0	33.0	3.5
442	28-Apr-06		110.0	125.1	140	2.85	93.7	101.7	3.21	1.20	138.2	19.0	23.0	34.0	3.5
443	29-Apr-06				140	2.85						19.0	23.0	32.0	4.0
444	30-Apr-06				140	2.85	71.0	98.9			151.4	19.0	22.0	33.0	3.5
445	1-May-06		95.0	108.8	140	2.85	68.9	89.7			150.4	19.0	21.0	32.0	3.5
446	2-May-06				140	3.10	68.5	89.2			154.2				
447	3-May-06		90.0	97.2	140	2.95	62.7	78.1			149.2	19.0	21.0	32.0	3.5
448	4-May-06				140	2.86					158.6				
449	5-May-06		90.0	107.3	140	2.85					148.5	19.0	22.0	32.5	3.5
Batch Average		**29**	**96.7**	**109.9**	**140**	**2.88**	**75.3**	**97.4**	**3.21**	**1.20**	**149.8**	**19.1**	**21.9**	**32.9**	**3.6**

Appendix A-5

Sewage Batch Averages for the MBR UCT System

	COD					TKN			FSA		TSS				VSS	
SB #	Influent	Aerobic	Eff 0.1	Eff 0.45	Eff unfilt.	Influent	Aerobic	Effluent	Influent	Effluent	AN	AX	AE	RE	AN	AX
	(mgCOD/l)					(mgN/l)			(mgN/l)		(mgTSS/l)				(mgVSS/l)	
2	958.4	18873.2	34.2			101.4	1089.6	3.3	81.1	1.2	7711	13275	16311		6452	10681
3	1147.7	19226.1	38.1			139.4	1201.9	3.9	107.3	2.4	7826	13173	15845		6649	10851
4	1021.6	18414.3	31.7			97.0	1094.1	3.0	70.1	1.3	6177	10217	14051		5188	8916
5	992.2	18417.9	39.1			112.6	1267.2	2.23	88.6	1.2	6010	11033	16567		4910	9048
6	912.4	19590.6	42.7		89.4	133.6	1261.6	1.6	104.1	1.0	7235	13026	17495		5977	10563
7	834.6	19912.6	30.5		115.0	93.1	1218.6	1.5	77.5	0.4	7434	14479	18058		6219	11543
8	785.4	18991.1	39.7		93.6	127.3	1207.7	1.0	76.0	0.5	8290	14770	17767		6733	11740
9	980.2	18537.0	41.5		98.9	117.8	1142.1	1.4	78.7	0.7	7286	13420	18128		5917	10571
10	1006.3	19004.9	28.6		92.7	91.5	1196.3	1.5	67.6	0.4	7443	14332	17636		6315	11838
11	975.9	18999.4	40.0		126.2	93.3	1165.3	0.9	76.4	0.3	7178	13854	17150		6026	11300
12	887.8	17487.4	47.6		118.0	131.7	1090.3	1.1	99.6	0.6	7504	13318	16130		6221	10705
13	855.6	16936.7	39.0	56.9	99.0	101.3	1056.9	1.4	79.2	0.4	7329	13534	16880		6030	10766
14	869.9	16877.8	38.9	52.9	118.1	112.4	1054.2	1.3	94.7	0.4	7838	12735	16062		6325	10001
15	933.9	19298.4	39.7	53.4	110.7	108.6	1222.2	1.3	82.5	1.3	8049	13554	17512	12308	6546	10747
16	947.5	18482.4	50.3	84.7	116.6	108.9	1189.5	1.8	79.0	0.4	7157	12949	17115	13008	5971	10250
17	926.2	19815.2	27.9	57.8	87.7	93.4	1310.4	2.3	78.0	1.3	7545	13655	18184	13433	6192	10842
18	914.2	21603.6	46.9	47.2	96.4	100.1	1342.3	1.8	80.8	1.0	8021	13788	18266	14014	6926	11114
19	1070.7	21775.5	55.1	58.6	139.3	110.2	1272.4	1.6	80.6	0.5	7234	14545	18938	14277	5936	11428
20																
21																
[redacted]	1008.8	17413.4	58.3	71.9	134.1	112.0	933.8	1.2	88.0	0.5	7019	12442	15414	12254	5656	9758
23	940.6	15898.4	47.3	60.9	101.0	104.9	967.4	1.9	72.5	0.3	6133	11806	15538	11704	5044	9332
24	787.4	19453.4	50.2	67.3	122.9	76.6	1015.5	1.1	63.7	0.0	7486	13937	17789	13655	6244	11077
25	908.9	18519.0	42.0	86.4	119.4	102.8	1018.5	1.0	83.9	0.4	7379	13095	16741	13108	5858	10267
26	989.1	19356.4	48.8	90.5	138.7	102.2	1140.7	1.1	85.2	0.5	7400	13414	17963	13680	5927	10510
27	969.3	18905.2	32.6	67.3	134.1	101.2	1229.2	1.3	79.7	0.3	7358	13292	17454	13285	5946	10367
28	1115.6	19400.4	51.4	107.1	132.6	101.4	1133.2	1.5	78.3	0.8	7284	13076	16975	12931	6019	10476
29	983.3	20113.2	49.5	95.0	143.5	95.0	1235.4	1.5	71.7	0.6	7057	13037	17820	13489	5953	10888
Ave	950.9	18896.3	42.0	70.5	114.9	106.5	1156.0	1.7	81.7	0.7	7322	13221	17069	13165	6045	10599

	OUR	NO_3				NO_2				Ortho-P						Rs	TKN/ COD	COD/ VSS	TKN/ VSS	VSS/TSS			
AE		AN	AX	AE	E	AN	AX	AE	E	Infl.	AN	AX	AE	Effl.	P-rem	Rs	fi	fcv		AN	AX	AE	ave
	(mgO/L/h)	(mgN/l)				(mgN/l)				(mgP/l)						(d)	-	-	-	-	-	-	-
13277		0.0	0.0	19.3	24.9	0.0	0.0	0.0	0.0	28.6	54.6	51.9	24.3	34.6	16.2	20.8	0.11	1.42	0.08	0.84	0.80	0.81	0.82
13014		0.4	0.4	17.8	23.8	0.0	0.0	0.0	0.0	36.2	91.2	47.3	14.0	13.4	22.8	21.3	0.12	1.48	0.09	0.85	0.82	0.82	0.83
11260		0.0	0.3	9.6	10.7	0.0	0.0	0.0	0.0	28.4	79.9	33.1	11.5	11.2	17.3	20.2	0.09	1.64	0.10	0.84	0.87	0.80	0.83
13705		0.0	0.0	11.0	15.1	0.1	1.1	0.0	0.0	24.0	73.7	34.2	8.5	6.7	18.2	19.3	0.11	1.34	0.09	0.82	0.82	0.83	0.82
14073		0.0	0.4	14.6	18.7	0.0	0.3	0.0	0.0	25.1	65.2	30.2	2.1	2.8	22.3	19.2	0.15	1.39	0.09	0.83	0.81	0.80	0.81
14336		0.0	0.1	10.4	13.7	0.1	0.0	0.0	0.0	29.1	85.7	44.7	10.8	10.5	18.5	21.3	0.11	1.39	0.09	0.84	0.80	0.79	0.81
13618	140.9	0.0	0.2	12.6	17.3	0.0	0.0	0.0	0.0	28.5	79.4	38.6	10.1	10.0	18.5	21.0	0.16	1.39	0.09	0.81	0.79	0.77	0.79
13995	131.5	0.1	0.5	11.8	17.1	0.0	0.0	0.0	0.0	29.3	84.5	39.8	9.5	9.0	21.2	19.6	0.12	1.32	0.08	0.81	0.79	0.77	0.79
14205	121.2	0.0	0.0	12.0	14.1	0.0	0.0	0.0	0.0	29.3	79.8	36.3	8.0	8.9	20.5	20.7	0.09	1.34	0.08	0.85	0.83	0.81	0.82
13795	116.5	0.0	0.0	14.5	15.3	0.0	0.0	0.0	0.0	24.0	69.2	35.4	8.7	8.9	16.0	20.7	0.10	1.38	0.08	0.84	0.82	0.80	0.82
13137	131.3	0.0	2.5	21.6	23.0	0.0	0.0	0.0	0.0	28.3	74.6	29.4	6.5	6.5	22.0	21.0	0.15	1.33	0.08	0.83	0.80	0.81	0.82
13296	138.3	0.0	0.4	12.5	13.2	0.0	0.0	0.0	0.0	29.6	95.9	41.7	6.0	5.8	23.3	21.0	0.12	1.27	0.08	0.82	0.80	0.79	0.80
12539	135.7	0.0	2.4	20.9	21.9	0.0	0.0	0.0	0.0	31.2	80.6	33.3	7.8	7.5	22.9	21.4	0.13	1.35	0.08	0.81	0.79	0.78	0.79
13790	124.8	0.0	0.4	16.7	18.5	0.0	0.0	0.0	0.0	29.8	88.9	40.1	11.8	10.3	19.5	21.0	0.12	1.40	0.09	0.81	0.79	0.79	0.80
13425	130.9	0.0	1.3	18.4	19.9	0.0	0.0	0.0	0.0	31.4	94.9	38.7	7.6	6.3	25.1	20.4	0.11	1.38	0.09	0.83	0.79	0.78	0.80
14458	106.9	0.0	0.3	11.9	11.9	0.0	0.0	0.0	0.0	39.1	100.5	47.0	12.2	12.7	26.2	20.8	0.10	1.37	0.09	0.82	0.79	0.80	0.80
14350	114.6	0.0	1.3	15.9	15.4	0.0	0.1	0.0	0.0	36.6	87.5	39.8	9.8	9.9	27.0	20.7	0.11	1.51	0.09	0.86	0.81	0.79	0.81
14804	123.9	0.0	0.1	12.7	12.9	0.0	0.0	0.0	0.0	36.5	83.6	33.5	7.0	6.0	30.5	20.2	0.10	1.47	0.09	0.82	0.79	0.78	0.79
12182	123.9	0.0	0.0	20.3	19.8	0.0	0.0	0.0	0.0	32.0	72.9	33.7	6.4	5.4	26.8	21.2	0.11	1.43	0.08	0.81	0.78	0.79	0.79
12164	112.9	0.0	0.3	13.4	16.5	0.0	0.1	0.0	0.4	34.7	98.9	43.3	10.9	11.2	23.3	20.7	0.11	1.31	0.08	0.82	0.79	0.78	0.80
13980	98.6	0.0	0.0	14.2	16.0	0.0	0.2	0.0	0.0	30.2	97.8	41.0	8.1	7.3	24.1	25.6	0.10	1.39	0.07	0.83	0.79	0.79	0.80
13055	139.8	0.0	1.0	29.0	31.0	0.0	1.0	0.0	0.0	35.2	88.2	36.0	7.9	7.4	27.8	21.6	0.11	1.42	0.08	0.79	0.78	0.78	0.78
13984	110.9	0.0	0.0	13.9	17.0	0.0	0.2	0.0	0.0	28.9	95.8	39.2	8.2	7.5	21.5	21.4	0.10	1.38	0.08	0.80	0.78	0.78	0.79
13520	108.1	0.0	0.4	15.1	19.8	0.1	0.3	0.2	0.1	29.2	93.8	39.5	13.5	7.9	20.5	20.9	0.10	1.40	0.09	0.81	0.78	0.77	0.78
13556	93.2	0.0	0.2	17.2	20.7	0.1	0.2	0.2	0.1	20.7	95.5	36.5	4.5	0.8	20.1	20.9	0.09	1.43	0.08	0.83	0.80	0.80	0.81
14640	97.4	0.0	0.0	10.1	13.3	0.0	0.2	0.3	0.0	31.0	84.1	33.9	4.0	4.7	26.3	20.5	0.10	1.37	0.08	0.84	0.84	0.82	0.83
13545	120.1	0.0	0.5	15.3	17.7	0.0	0.1	0.0	0.0	30.3	84.5	38.4	9.2	9.0	22.2	20.9	0.11	1.40	0.09	0.83	0.80	0.79	0.80

APPENDIX B

CONVENTIONAL UCT DAILY MEASUREMENTS

TABLE OF CONTENTS

Appendix B-1

Measured COD, TSS and VSS values for the conventional UCT system

			COD				TSS			VSS		
Day	Date	SB#	Influent	Aerobic	Eff unfilt	Eff 0.45	Anaerobic	Anoxic	Aerate	Anaerobic	Anoxic	Aerate
-	-	-	(mgCOD/l)				(mgTSS/l)			(mgVSS/l)		
19	1-Mar-05											
20	2-Mar-05											
21	3-Mar-05	Batch 2										
22	4-Mar-05											
23	5-Mar-05											
24	6-Mar-05											
25	7-Mar-05		1083.7	3550.0	87.2	64.4	3128	2470		2602	2150	
26	8-Mar-05		1075.4	3778.3	99.6	78.9	2832	2850	3706	2380	2352	2894
27	9-Mar-05		1054.6	4089.7	49.8	39.4	2214	3284	3512	1924	2752	2896
28	10-Mar-05		1046.3	4027.4	68.5	45.7	2710	3194	3418	2298	2618	2738
29	11-Mar-05		871.9	4069.0	45.7	27.0	2704	3238	3502	2314	2688	2866
30	12-Mar-05											
31	13-Mar-05											
32	14-Mar-05		988.2	3321.6	60.2	49.8	1994	3784	3152	1724	3160	2550
33	15-Mar-05		772.3	3861.4	41.5	27.0	1972	3432	3500	1706	2824	2828
34	16-Mar-05		950.8	3819.8	58.1	54.0	2056	3134	3134	1766	2576	2506
35	17-Mar-05		860.5	3366.5	59.8	45.8	1854	2950	3234	1652	2458	2662
36	18-Mar-05		880.5	3705.1	63.7	43.8	2076	3044	3094	1760	2522	2522
Batch Average		2	958.4	3758.9	59.4	47.6	2354	3212	3361	2013	2549	2718
37	19-Mar-05	Batch 3										
38	20-Mar-05											
39	21-Mar-05											
40	22-Mar-05		792.8	3764.9	61.8	71.7	2092	2998	3148	1856	2614	2680
41	23-Mar-05		996.0	3984.0	81.7	63.7	1504	1956	3014	1312	1652	2440
42	24-Mar-05											
43	25-Mar-05		981.9									
44	26-Mar-05											
45	27-Mar-05		1038.0									
46	28-Mar-05											
47	29-Mar-05		1156.0									
48	30-Mar-05		1212.7	3853.2	58.8	40.6	2526	3370	3418	2122	2744	2816
49	31-Mar-05		1249.2	4157.4	64.9	58.8	2060	3312	3380	1746	2722	2768
50	1-Apr-05		1249.2	4502.2	93.3	87.2	2136	3400	3440	1846	2796	2802
51	2-Apr-05		1131.6									
52	3-Apr-05											
53	4-Apr-05		1314.1	4157.4	81.1	71.0	2270	3632	3766	1948	2988	3060
Batch Average		3	1147.7	4069.8	73.6	65.5	2098	3111	3361	1805	2773	2761
54	5-Apr-05	Batch 4	1326.3	4664.4	105.5	75.0	2440	3564	3794	2134	2980	3126
55	6-Apr-05											
56	7-Apr-05											
57	8-Apr-05		880.0									
58	9-Apr-05											
59	10-Apr-05		1155.9									
60	11-Apr-05		1302.0	4705.0	58.8	54.8	2582	3978	4042	2186	3214	3212
61	12-Apr-05		1018.1	5151.1	50.7	50.7	4568	6150	5146	3944	5056	4142
62	13-Apr-05		904.5	5130.8	66.9	58.8	5034	7178	5372	4158	5858	4292
63	14-Apr-05		1257.4	4583.3	50.7	44.6	5678	8548	5632	4796	7042	4558
64	15-Apr-05		1164.1	4867.2	50.7	32.4	4296	6742	7466	3634	5500	5938
65	16-Apr-05		949.1									
66	17-Apr-05											
67	18-Apr-05		851.8	4765.8	42.6	38.5	2952	7996	6432	2496	7152	5196
68	19-Apr-05		872.0	4826.6	36.5	32.4	4794	6064	4960	4138	4992	4022
69	20-Apr-05		1105.7	5018.4	36.7	34.7	7148	7500	6780	5900	6104	5386
70	21-Apr-05		1326.0	4324.8	46.9	38.8	4924	5738	5400	4230	4678	4302
71	22-Apr-05		726.2	4120.8	53.0	38.8	5060	5864	5328	4301	4766	3360
72	23-Apr-05		790.9									
73	24-Apr-05											
74	25-Apr-05		681.4	6834.0	38.8	26.5	5090	7494	3710	4388	6152	3030
75	26-Apr-05		1056.7	4324.8	53.0	32.6	4580	6552	8624	3934	5452	6914
Batch Average		4	1021.6	4706.9	48.8	40.3	4333	6650	5339	3865	5304	4214

76	27-Apr-05	Batch 5										
77	28-Apr-05											
78	29-Apr-05											
79	30-Apr-05											
80	1-May-05											
81	2-May-05		763.0									
82	3-May-05											
83	4-May-05		1130.2	4834.8	151.0	134.6	5392	7322	6514	4504	6094	5290
84	5-May-05		991.4	3651.6	61.2	49.0	4770	6708	4130	4118	5690	3490
85	6-May-05		1224.0	3774.0	53.0	38.8	4392	5122	7576	3788	4316	6136
86	7-May-05		962.8									
87	8-May-05		652.8									
88	9-May-05		895.5	4141.2	63.2	61.2	3916	6466	7920	3296	5390	6414
89	10-May-05		934.5	5201.9	48.8	48.8	3434	5326	5284	2966	4512	4356
90	11-May-05		942.7	5262.9	44.7	40.6	3834	6808	7108	3306	5682	5790
91	12-May-05		1207.2	4490.7	42.7	40.6	4740	3818	8142	4152	3170	4190
92	13-May-05		981.3	4572.0	58.9	40.6	5688	6146	6056	4760	5112	4874
93	14-May-05		881.3									
94	15-May-05											
Batch Average		5	992.2	4491.1	53.2	45.7	4521	5965	6591	3861	4996	5068
95	16-May-05	Batch 6	947.0									
96	17-May-05											
97	18-May-05											
98	19-May-05		681.4									
99	20-May-05		734.6									
100	21-May-05		759.0									
101	22-May-05		853.0									
102	23-May-05		907.2	3180.6	51.3	34.9	2930	3024	4310	2444	2508	3650
103	24-May-05		1153.9	3057.5	61.6	49.2	2308	4430	4354	1984	3688	3706
104	25-May-05		1002.1	3098.5	69.8	59.5	2426	2354	1698	2066	2024	1512
105	26-May-05		969.2	3775.7	55.4	51.3	3524	6200	6952	3032	5304	5752
106	27-May-05		1133.5	3180.6	51.3	28.7	5252	6918	5106	4536	5834	4214
107	28-May-05		1072.6									
108	29-May-05											
109	30-May-05		741.3	3406.3	51.3	45.1	1944	2376	2554	1672	2020	2156
110	31-May-05		907.0	3016.4	78.0	51.3	4378	7640	5466	3798	6600	4474
Batch Average		6	912.4	3156.7	59.8	45.7	3252	4706	4349	2790	3997	3638
111	1-Jun-05	Batch 7										
112	2-Jun-05		904.1									
113	3-Jun-05		830.2	3764.9	73.7	59.8	4524	6920	4808	3890	5866	4000
114	4-Jun-05											
115	5-Jun-05		678.1									
116	6-Jun-05		905.8	3067.7	65.7	45.8	2894	7098	6858	2472	5978	5624
117	7-Jun-05		888.4	3824.6	67.7	67.7	3160	4370	5874	2704	3896	4666
118	8-Jun-05		846.6	3565.7	89.6	55.8	2871.6	3016	2622	2477.6	2542	2184
119	9-Jun-05		788.8	3207.1	61.8	59.8	2624	3040	3020	2298	2510	2530
120	10-Jun-05		996.2	3365.3	73.9	57.5	2288	3014	2778	2154	2730	2546
121	11-Jun-05		813.7				2680	2650	1842	2430	2370	1734
122	12-Jun-05		669.8				2718	2608	1868	2534	2462	1784
123	13-Jun-05		742.0	3652.6	121.1	90.3	2442	2794	2922	2194	2500	2596
124	14-Jun-05		952.0	3693.6	133.4	110.8	1800	2562	2704			
Batch Average		7	834.6	3517.7	85.9	62.4	2609	3807	3530	2408	3428	3074
125	15-Jun-05	Batch 8										
126	16-Jun-05		660.0									
127	17-Jun-05		764.0									
128	18-Jun-05		652.0									
129	19-Jun-05											
130	20-Jun-05		684.0	4320.0	72.0	72.0	4114	4028	5102	3644	3426	4278
131	21-Jun-05		966.5	4400.0	88.0	64.0	3646	3218	3596	2658	2726	3002
132	22-Jun-05		986.0	5080.0	70.0	62.0	2322	3698	6022	1952	3142	5012
Batch Average		8	785.4	4600.0	76.7	66.0	3361	3648	4907	2751	3098	4097
133	23-Jun-05	9										
134	24-Jun-05		995.0	3700.0	76.0	66.0	1824	3100	3058	1580	2664	2580
135	25-Jun-05		1052.0									
136	26-Jun-05		580.0									
137	27-Jun-05		648.0	3420.0	74.0	54.0	1822	2968	3064	1588	2534	2560
138	28-Jun-05		902.0	3960.0	64.0	58.0	2100	4060	3004	1834	3444	2492

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139	29-Jun-05	Batch	1004.0	3880.0	62.0	50.0	2318	3366	4156	2022	2828	3384
140	30-Jun-05		1010.0	3380.0	76.0	64.0	2486	3490	4160	2124	2922	3366
141	1-Jul-05		960.0	4320.0	64.0	60.0	4124	4288	4658	3434	3560	3734
142	2-Jul-05		840.0									
143	3-Jul-05		1016.0									
144	4-Jul-05		1144.0	3900.0	62.0	52.0	2396	3470	3216	2098	2916	2700
145	5-Jul-05		980.0	4260.0	56.0	44.0	2602	4150	5032	2256	3472	4084
146	6-Jul-05		1136.0	3960.0	60.0	56.0	3474	4358	5084	2994	3660	4176
147	7-Jul-05		1056.0									
Batch Average		9	980.2	3864.4	66.0	56.0	2378	3694	3937	2062	3111	3231
148	8-Jul-05	Batch 10	1072.0									
149	9-Jul-05											
150	10-Jul-05											
151	11-Jul-05		891.4	5974.1	42.7	38.6	4280	4822	5334	3772	4090	4392
152	12-Jul-05		901.9	4409.4	46.7	28.4	3248	5316	4676	2852	4508	3868
153	13-Jul-05		965.1	4368.8	32.5	20.3	2450	3470	4560	2166	2938	3766
154	14-Jul-05		1079.8	3962.4	42.7	42.7	2108	4462	3774	1848	3790	3134
155	15-Jul-05		1142.0	3860.8	42.7	32.5	2248	4580	3362	2010	3902	2830
156	16-Jul-05											
157	17-Jul-05											
158	18-Jul-05		1123.7	4470.4	36.6	32.5	4618	4548	5688	4068	3914	4668
159	19-Jul-05		953.0	3982.7	44.7	24.4	2884	4790	5342	2564	4120	4376
160	20-Jul-05		1093.2	4795.5	50.8	50.8	2952	4890	5392	2626	4184	4474
161	21-Jul-05		1060.8	4794.0	55.1	55.1	3656	3856	5436	3198	3310	4482
162	22-Jul-05		991.6	4773.6	46.9	42.8	3728	5230	5274	3444	4612	4536
163	23-Jul-05											
164	24-Jul-05											
165	25-Jul-05		832.3	4386.0	61.2	40.8	2602	3536	4020	2324	3040	3484
166	26-Jul-05		1079.2	4284.0	46.9	40.8	3542	5354	5784	3054	4556	4734
167	27-Jul-05		901.7	5140.8	85.7	75.5	3068	6332	5488	2728	5408	4558
Batch Average		10	1006.3	4435.7	45.8	37.5	3183	4571	5064	2820	3914	4206
168	28-Jul-05	Batch 11	824.2									
169	29-Jul-05		1191.4									
170	30-Jul-05											
171	31-Jul-05											
172	1-Aug-05		838.9	4447.2	65.3	32.6	4500	5398	6496	3920	4538	5270
173	2-Aug-05		1087.3	4386.0	63.2	46.9	4394	3984	4654	3794	3308	3808
174	3-Aug-05		1122.0	5324.4	79.6	46.9	2870	5286	5922	2478	4452	4812
175	4-Aug-05		1014.0	4048.0	91.1	60.7	2544	4934	5486	2254	4196	4506
176	5-Aug-05		1129.4	4857.6	64.8	40.5	2962	4238	6718	2626	3494	5408
177	6-Aug-05											
178	7-Aug-05											
179	8-Aug-05		935.1	4351.6	87.0	60.7	3620	3948	7674	3188	3320	6188
180	9-Aug-05		939.1	4432.6	83.0	58.7	4422	7130	6326	3878	6064	5154
181	10-Aug-05		799.5	4290.9	83.0	52.6	2924	4906	7330	2604	4192	6018
182	11-Aug-05											
183	12-Aug-05											
184	13-Aug-05											
185	14-Aug-05											
186	15-Aug-05		918.9	3784.9	99.2	52.6	4010	6028	6762	3540	5092	5338
187	16-Aug-05		900.7	4493.3	78.9	48.6	5034	8642	3532	4416	7250	2898
188	17-Aug-05		985.7	5181.4	103.2	58.7						
Batch Average		11	975.9	4508.9	81.7	52.7	3728	5449	6374	3270	4295	5167
189	18-Aug-05	Batch 12	802.4	4132.8	78.6	40.3	3564	3544	3628	3084	2898	2958
190	19-Aug-05		906.8									
191	20-Aug-05											
192	21-Aug-05											
193	22-Aug-05		894.6									
194	23-Aug-05		1135.2	3427.2	110.9	58.5	4402	4150	5312	3562	3170	3440
195	24-Aug-05		959.6	4233.6	90.7	48.4	2012	3500	3622	1658	2708	2716
196	25-Aug-05		888.7	3749.8	102.8	52.4	2042	3804	3322	1706	2898	2476
197	26-Aug-05		830.2	4092.5	72.6	54.4	1800	3274	3356	1530	2560	2596
198	27-Aug-05		866.3									
199	28-Aug-05											
200	29-Aug-05		896.9	3790.1	76.6	50.4	1834	3224	3554	1512	2428	2566
201	30-Aug-05		870.6	3870.7	70.6	50.4	1866	3328	3570	1476	2462	2484
202	31-Aug-05		862.2									

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203	1-Sep-05		987.5	3689.3	90.7	48.4	1974	3228	3534	1700	2554	2730
204	2-Sep-05											
Batch Average		12	887.8	3873.2	86.7	50.4	2156	3415	3512	2029	2710	2647
205	3-Sep-05	Batch 13										
206	4-Sep-05											
207	5-Sep-05		829.5	3738.9	52.8	36.6	1854	3288	3308	1586	2606	2552
208	6-Sep-05		865.9	3413.8	52.8	42.7	1852	3404	3494	1562	2626	2622
209	7-Sep-05		926.4	3820.2	164.6	54.9	1756	2988	3222	1456	2290	2354
210	8-Sep-05		707.1	3718.6	111.8	65.0	2168	3348	3540	1804	2680	2796
211	9-Sep-05		934.7	3434.1	87.4	44.7	1970	2540	3126	1684	2058	2464
212	10-Sep-05		918.5									
213	11-Sep-05											
214	12-Sep-05		910.3	2783.8	93.5	65.0	2260	2492	2652	1840	2008	2118
215	13-Sep-05		827.9	2743.2	89.4	54.9	2408	2402	2544	1908	1896	2016
216	14-Sep-05		735.6				2384	2192	2654	1872	1762	2070
217	15-Sep-05		837.2									
218	16-Sep-05		918.5									
Batch Average		13	855.6	3378.9	93.2	52.0	2082	2832	3068	1714	2241	2374
219	17-Sep-05	Batch 14	995.7									
220	18-Sep-05											
221	19-Sep-05		866.9	3185.3	84.7	38.3	1842	3122	3322	1546	2496	2608
222	20-Sep-05		728.9									
223	21-Sep-05		920.4	3306.2	139.1	62.5	2116	2608	3132	1728	2072	2436
224	22-Sep-05		926.3	3407.0	98.8	84.7	1618	3134	3270	1358	2440	2516
225	23-Sep-05		939.2	3386.9	98.8	54.4	1720	3000	3030	1424	2360	2344
226	24-Sep-05		833.1									
227	25-Sep-05											
228	26-Sep-05		913.9	3508.8	271.3	61.2	1654	3054	3012	1420	2388	2338
229	27-Sep-05		924.7	2570.4	89.8	40.8	1498	2762	2956	1242	2156	2290
230	28-Sep-05		839.2	3325.2	93.8	59.2	1908	2620	3074	1650	2082	2380
231	29-Sep-05		728.9	3141.6	124.4	44.9	1726	2586	3034	1480	2108	2438
232	30-Sep-05		1175.0	3264.0	106.1	55.1	1728	3100	3236	1510	2482	2552
233	1-Oct-05											
234	2-Oct-05		793.8									
235	3-Oct-05		897.6	3570.0	93.8	49.0	2368	3618	3366	1964	2882	2632
Batch Average		14	869.9	3343.9	103.3	55.0	1757	2887	3143	1484	2287	2453
236	4-Oct-05	Batch 15										
237	5-Oct-05											
238	6-Oct-05		1224.0									
239	7-Oct-05		1241.7	3621.0			2508	3688	3260	2120	2942	2574
240	8-Oct-05		767.2	3774.0	80.8	40.8						
241	9-Oct-05											
242	10-Oct-05		860.9	3468.0	91.0	51.0	2046	3310	3624	1654	2628	2838
243	11-Oct-05		701.8				1873	3044	3347	1568	2407	2603
244	12-Oct-05		807.8				2286	3210	2918	1884	2964	2260
Batch Average		15	933.9	3621.0	85.9	45.9	2178	3313	3287	1807	2735	2569
245	13-Oct-05	Batch 16					1734	3078	3000	1462	2450	2364
246	14-Oct-05		979.2	3682.2	151.0	63.2	2180	3104	3202	1874	2488	2514
247	15-Oct-05		942.5									
248	16-Oct-05											
249	17-Oct-05		950.6	3529.2	100.0	55.1	1894	3186	2946	1658	2646	2408
250	18-Oct-05		995.5				2050	3070	3132	1788	2632	2612
251	19-Oct-05		983.3	3672.0	120.4	81.6	1714	2742	3222	1458	2156	2502
252	20-Oct-05						1816	3306	2738	1574	2740	2208
253	21-Oct-05		1183.2	4080.0	44.9	85.7	1984	3346	3102	1720	2708	2474
254	22-Oct-05											
255	23-Oct-05		938.4									
256	24-Oct-05		930.2	3631.2	100.0	61.2	2330	3240	2946	1928	2602	2296
257	25-Oct-05		967.0				2134	3196	3230	1774	2534	2546
258	26-Oct-05		840.5	3447.6	112.2	63.2	1914	3190	3030	1600	2542	2382
259	27-Oct-05						2900	2898	2948	2304	2288	2332
Batch Average		16	947.5	3673.7	104.7	68.3	2059	3123	3076	1684	2563	2422
260	28-Oct-05	7	599.8	3672.0	79.6	26.5	2534	3270	2928	2128	2608	2338
261	29-Oct-05											
262	30-Oct-05		1011.8									
263	31-Oct-05		869.0	2488.8	104.0	26.5	1910	3034	3070	1604	2416	2424
264	1-Nov-05		1289.3				1750	3178	3338	1468	2568	2626

265	2-Nov-05	Batch 1	995.5	4161.6	79.6	38.8	1814	3494	3392	1542	2792	2690
266	3-Nov-05		950.6									
267	4-Nov-05		869.0	3610.8	61.2	20.4	1912	3302	3472	1620	2668	2756
268	5-Nov-05		954.7									
269	6-Nov-05											
270	7-Nov-05		865.0	3468.0	51.0	26.5	2010	3102	3168	1674	2492	2518
271	8-Nov-05		983.3				1898	3168	3254	1646	2570	2612
272	9-Nov-05		901.7	3814.8	77.5	46.9	1440	2948	2940	1248	2342	2304
273	10-Nov-05		860.9				2048	3040	3114	1694	2428	2448
Batch Average		17	926.2	3536.0	75.5	30.9	1848	3171	3186	1562	2543	2524
274	11-Nov-05	Batch 18	897.6	3794.4	83.6	63.2		3114	3198		2468	2494
275	12-Nov-05		869.0									
276	13-Nov-05											
277	14-Nov-05						2032	3070	3028	1756	2460	2404
278	15-Nov-05		852.7	3896.4	71.4	44.9	2054	3304	3430	1778	2650	2710
279	16-Nov-05		954.7	3447.6	77.5	44.9	1550	2882	2988	1312	2288	2348
280	17-Nov-05						3058	2932	2052	2468	2356	1768
281	18-Nov-05		1003.7	3406.8	89.8	61.2	1782	2756	2584	1438	2148	2008
282	19-Nov-05		889.4									
283	20-Nov-05											
284	21-Nov-05		848.6				2562	3124	2902	2138	2382	2168
285	22-Nov-05		909.8	4202.4	73.4	51.0	1692	3276	3266	1444	2562	2616
286	23-Nov-05		918.0	3202.8	87.7	46.9						
287	24-Nov-05		999.6									
288	25-Nov-05		958.8	3672.0	85.7	46.9						
289	26-Nov-05		877.2									
290	27-Nov-05											
291	28-Nov-05		905.8									
Batch Average		18	914.2	3660.3	81.3	51.3	2104	3057	3057	1762	2414	2314
292	29-Nov-05	Batch 19	1122.0									
293	30-Nov-05		885.4	4161.6	67.3	22.4	2132	3436	3668	1760	2680	2822
294	1-Dec-05		1020.0				2370	3538	3684	2012	2862	2936
295	2-Dec-05		1085.3	4202.4	91.8	77.5	2148	3488	3740	1788	2826	2982
296	3-Dec-05											
297	4-Dec-05		975.1									
298	5-Dec-05		1020.0	3957.6	81.6	44.9	2120	3450	3596	1810	2832	2868
299	6-Dec-05						1582	2716	2798	1350	2214	2250
300	7-Dec-05		767.0				1898	3084	3262	1630	2478	2568
301	8-Dec-05		1060.8	3447.6	165.2	40.8	2038	3008	3086	1674	2356	2378
302	9-Dec-05		962.9	3998.4	75.5	34.7	1652	3194	3004	1444	2600	2390
303	10-Dec-05											
304	11-Dec-05											
305	12-Dec-05		1244.4				1954	2986	3386	1688	2448	2758
306	13-Dec-05		1211.8	6630.0	97.9	75.5	2530	3072	3556	2130	2542	2930
307	14-Dec-05		1077.1									
308	15-Dec-05		1183.2	3284.4	91.8	57.1						
309	16-Dec-05											
310	17-Dec-05											
311	18-Dec-05											
312	19-Dec-05											
Batch Average		19	1070.7	3842.0	84.3	50.4	2042	3197	3378	1729	2584	2688
313	20-Dec-05	Batch 20										
314	21-Dec-05											
315	22-Dec-05											
316	23-Dec-05											
317	24-Dec-05											
318	25-Dec-05											
319	26-Dec-05											
320	27-Dec-05											
321	28-Dec-05											
322	29-Dec-05											
323	30-Dec-05											
324	31-Dec-05											
325	1-Jan-06											
326	2-Jan-06											
		20										
327	3-Jan-06											

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328	4-Jan-06	Batch 21										
329	5-Jan-06											
330	6-Jan-06											
331	7-Jan-06											
332	8-Jan-06											
333	9-Jan-06											
334	10-Jan-06											
335	11-Jan-06											
336	12-Jan-06											
337	13-Jan-06											
338	14-Jan-06											
339	15-Jan-06											
340	16-Jan-06											
341	17-Jan-06											
		21										
342	18-Jan-06	Batch 22					2998	2848	2164	2360	2278	1814
343	19-Jan-06											
344	20-Jan-06		1044.5	3651.6	104.0		2316	2768	2982	1860	2156	2296
345	21-Jan-06											
346	22-Jan-06		1048.6									
347	23-Jan-06		1064.9	2917.2	81.6	75.5	1736	2892	2946	1510	2360	2370
348	24-Jan-06		1044.5				1588	2736	2914	1434	2246	2360
349	25-Jan-06			3610.8	81.6	65.3	2270	2738	2924	1812	2146	2276
350	26-Jan-06		869.0				2114	2614	2974	1732	2060	2324
351	27-Jan-06		942.5	3549.6	75.5	46.9	1750	2752	2914	1476	2184	2278
352	28-Jan-06											
353	29-Jan-06		1113.8									
354	30-Jan-06		942.5	2407.2	112.2	63.2	1338	1744	1336	1140	1432	1066
Batch Average		22	1008.8	3227.3	91.0	62.7	2014	2764	2831	1666	2204	2245
355	31-Jan-06	Batch 23	987.4									
356	1-Feb-06		1048.6	2856.0	89.8	57.1	1834	1808	1804	1618	1582	1510
357	2-Feb-06		913.9				1492	2044	2258	1204	1666	1810
358	3-Feb-06		820.1	2590.8	61.2	12.2	1838	2242	2360	1500	1784	1854
359	4-Feb-06		652.8									
360	5-Feb-06											
361	6-Feb-06		901.7	2917.2	93.8	57.1	1342	2220	2280	1124	1772	1798
362	7-Feb-06		938.4				1292	2344	2410	1118	1922	1916
363	8-Feb-06		954.7	2733.6	71.4	30.6	1326	2668	2470	1128	2180	1972
364	9-Feb-06		946.6				1408	2490	2612	1218	2026	2058
365	10-Feb-06		913.9	3060.0	69.4	46.9	2068	2712	2822	1770	2158	2204
366	11-Feb-06		922.1									
367	12-Feb-06		950.6									
368	13-Feb-06		950.6	3202.8	73.4	53.0	1852	2644	2734	1570	2134	2168
369	14-Feb-06		979.2	3855.6	67.3	46.9	1506	2570	2788	1264	2042	2152
Batch Average		23	940.6	2893.4	75.2	43.4	1596	2374	2526	1351	1927	1992
370	15-Feb-06	Batch 24	918.0				1958	2642	2790	1618	2114	2200
371	16-Feb-06		811.9				1600	3362	2812	1386	2748	2246
372	17-Feb-06		803.8	3468.0	69.4	36.7	2312	2996	2968	1824	2302	2274
373	18-Feb-06											
374	19-Feb-06											
375	20-Feb-06		758.9									
376	21-Feb-06		787.4	3508.8	71.4	30.6	1318	2346	3244	1104	1878	2524
377	22-Feb-06		783.4				1360	2610	2820	1168	2128	2220
378	23-Feb-06		624.2	2631.6		32.6	1142	2074	2446	1040	1716	1964
379	24-Feb-06		632.4	3202.8	59.2	42.8	1580	2254	2212	1302	1784	1722
380	25-Feb-06		799.7				2868	2764	2980	2330	2220	2362
381	26-Feb-06		885.4				2186	2752	3030	1844	2216	2422
382	27-Feb-06		856.8	3488.4	102.0	65.3	2182	2980	2964	1774	2380	2336
383	28-Feb-06						1672	3036	3262	1444	2456	2608
Batch Average		24	787.4	3259.9	75.5	41.6	1731	2711	2932	1450	2177	2316
384	1-Mar-06	Batch 25	1028.19	3556.00	60.96	36.58	2030	3054	3144	1696	2470	2510
385	2-Mar-06		735.58				2204	3012	3316	1840	2452	2642
386	3-Mar-06		881.28									
387	4-Mar-06		860.88				2660	2622	2904	2244	2174	2382
388	5-Mar-06		901.68									
389	6-Mar-06		926.16									
390	7-Mar-06		879.09	2986.39	94.64	48.37	1708	2722	2340	1396	2172	1800

391	8-Mar-06		1030.52	2776.08	73.61	54.68	1936	2524	2462	1722	2068	2010
Batch Average		25	905.4	3106.2	76.4	46.5	2108	2787	2833	1780	2267	2269
392	9-Mar-06	Batch 26	1179.1	3080.4	61.2	57.1	2488	1986	2306	2014	1616	1862
393	10-Mar-06											
394	11-Mar-06		1195.4									
395	12-Mar-06		897.6				2526	2738	2944	2016	2170	2302
396	13-Mar-06		958.8	3590.4	83.6	53.0		2752	2920		2312	2424
397	14-Mar-06		1007.8				1550	2682	3162	1352	2190	2542
398	15-Mar-06		913.9		53.0	22.4	2290	2774	2732	1886	2258	2168
399	16-Mar-06		1011.9				1776	2708	2868	1550	2258	2342
400	17-Mar-06		869.7	3576.3	63.0	54.9	1772	2874	2864	1438	2330	2330
401	18-Mar-06		910.3									
402	19-Mar-06		1081.0									
403	20-Mar-06		1016.0	3312.2	81.3	79.2	1626	2948	2760	1402	2420	2256
404	21-Mar-06											
405	22-Mar-06		886.0									
406	23-Mar-06		934.7	3332.5	79.2	61.0	1612	2754	2830	1430	2298	2362
Batch Average		26	989.4	3378.4	70.2	54.6	1955	2779	2885	1636	2280	2341
407	24-Mar-06	Batch 27	1097.3	3840.5	81.3	61.0	1414	2828	2596	1252	2346	2148
408	25-Mar-06		938.8									
409	26-Mar-06		930.7									
410	27-Mar-06		1068.8	3413.8	91.4	48.8	1488	2448	2536	1196	2006	
411	28-Mar-06		860.9				2292	3264	2540	1952	2714	2114
412	29-Mar-06		913.9	3570.0	61.2	8.2	1644	2804	2922	1438	2340	2448
413	30-Mar-06		811.9									
414	31-Mar-06		746.6	2794.8	36.7	16.3	1834	2572	2780	1590	2164	2352
415	1-Apr-06		799.7									
416	2-Apr-06		950.6									
417	3-Apr-06		1028.2	3712.8	81.6	55.1		2946	2694		2470	2240
418	4-Apr-06		1293.4				1590	2856	2758	1536	2416	2322
419	5-Apr-06		1040.4	3692.4	73.4	51.0	1702	2964	3036	1506	2522	2570
420	6-Apr-06		1428.0									
421	7-Apr-06		1089.4									
Batch Average		27	969.3	3504.0	70.9	40.0	1612	2835	2733	1496	2372	2313
422	8-Apr-06	Batch 28	926.2									
423	9-Apr-06		999.6				1968	2854	2538	1702	2400	2102
424	10-Apr-06		909.8	3406.8	118.3	67.3	1712	2088	2114	1496	1790	1808
425	11-Apr-06						1408	2158	2204	1220	1812	1878
426	12-Apr-06		1069.0				1582	2498	2444	1416	2174	2114
427	13-Apr-06			3141.6	61.2	4.1	1340	2228	2362	1234	1974	2054
428	14-Apr-06		1024.1				2008	2508	2046	1784	2132	1742
429	15-Apr-06		1028.2	3712.8	49.0	34.7	1352	2252	2392	1180	1910	2014
430	16-Apr-06		999.6									
431	17-Apr-06		1166.9									
432	18-Apr-06		1069.0	4202.4	75.5	51.0	1778	3028	2954	1534	2584	2502
433	19-Apr-06		1317.8				1436	2626	2632	1272	2266	2240
434	20-Apr-06		1350.5				1828	2410	2722	1634	2058	2306
435	21-Apr-06		1383.1	3794.4	67.3	61.2	1592	2844	2862	1434	2464	2448
436	22-Apr-06		1258.9									
Batch Average		28	1115.6	3651.6	74.3	43.7	1637	2499	2479	1446	2142	2110
437	23-Apr-06	Batch 29	922.9									
438	24-Apr-06		1226.5	3562.2	68.8	58.7						
439	25-Apr-06		1028.2				2564	3324	3204	2292	2892	2738
440	26-Apr-06		910.8	4149.2	97.2	38.5	1500	2350	2620		2018	2232
441	27-Apr-06		632.4				2198	3218	3158			
442	28-Apr-06		999.6	4243.2	89.8	83.6	1932	2482	2854			
443	29-Apr-06		820.1									
444	30-Apr-06		926.2				1940	2978	3220	1638	2464	2636
445	1-May-06		1040.4	3447.6	116.3	59.2	1890	2322	2560	1606	1942	2106
446	2-May-06		962.9									
447	3-May-06		1105.7	4549.2	102.0	55.1	2450	3458	3344	2152	2956	2814
448	4-May-06		967.0									
449	5-May-06		889.4	4018.8	89.8	57.1						
Batch Average		29	983.3	3995.0	94.0	58.7	2068	2876	2994	1922	2454	2505

Appendix B-2

Measured TKN and FSA in the conventional UCT system

			TKN				FSA	
Day	Date	SB#	Influent	Aerobic	Effluent Unfilt.	Effluent 0.45 Filt.	Influent	Effluent 0.45 Filt.
-	-	-	(mgN/l)				(mgN/l)	
19	1-Mar-05							
20	2-Mar-05							
21	3-Mar-05	Batch 2						
22	4-Mar-05							
23	5-Mar-05							
24	6-Mar-05							
25	7-Mar-05		104.4	245.7	12.6	8.0	84.1	6.6
26	8-Mar-05		101.9	235.9	15.4	12.2	88.2	9.0
27	9-Mar-05		99.1		9.0	8.8	72.7	6.2
28	10-Mar-05		112.0	265.3	8.3	8.1	86.0	6.2
29	11-Mar-05		89.3	270.2	12.6	7.1	69.1	3.6
30	12-Mar-05							
31	13-Mar-05							
32	14-Mar-05		94.5	228.9	26.5	25.6	75.7	16.4
33	15-Mar-05		91.2	240.8	9.7	9.1	69.7	7.3
34	16-Mar-05		96.3	253.4	7.3	6.2	80.7	5.7
35	17-Mar-05		115.0	228.2	7.8	7.8	94.6	5.9
36	18-Mar-05		110.6	259.7	10.6	9.5	89.9	6.7
Batch Average		2	101.4	247.6	10.4	8.5	81.1	6.3
37	19-Mar-05	Batch 3						
38	20-Mar-05							
39	21-Mar-05		140.0				102.5	
40	22-Mar-05		89.0	272.3			65.7	
41	23-Mar-05		123.1	259.0			101.7	
42	24-Mar-05							
43	25-Mar-05		141.4				105.0	
44	26-Mar-05							
45	27-Mar-05		114.8				93.0	
46	28-Mar-05							
47	29-Mar-05		111.2				101.6	
48	30-Mar-05		151.8	276.5	8.1	7.4	134.7	6.6
49	31-Mar-05		134.7	278.6	8.3	7.8	102.4	6.4
50	1-Apr-05		150.1	279.3	8.0	7.6	109.9	6.9
51	2-Apr-05		160.4				116.2	
52	3-Apr-05							
53	4-Apr-05		166.8	260.4	9.0	8.4	148.1	6.2
Batch Average		3	139.4	271.0	8.3	7.8	107.3	6.5
54	5-Apr-05	Batch4	113.1	287.0	12.0	11.1	83.9	7.0
55	6-Apr-05							
56	7-Apr-05							
57	8-Apr-05		97.4				64.7	
58	9-Apr-05							
59	10-Apr-05		99.4				68.6	
60	11-Apr-05		105.3	313.6	8.8	8.8	83.7	8.4
61	12-Apr-05		98.0	289.8	9.5	10.5	75.4	7.3
62	13-Apr-05		67.1	302.4	10.8	11.5	51.0	8.8
63	14-Apr-05		108.7	296.1	9.8	7.1	80.0	7.3
64	15-Apr-05		75.9	308.0	13.7	9.9	51.5	8.3
65	16-Apr-05		91.8				60.5	
66	17-Apr-05							
67	18-Apr-05		89.9	301.0	9.5	9.7	77.8	8.5
68	19-Apr-05		96.3	293.3	8.7	8.4	62.7	5.9
69	20-Apr-05		105.1	285.6	11.1	9.0	81.2	7.0

70	21-Apr-05		105.4	266.0	8.7	8.1	78.1	7.0
71	22-Apr-05		90.4	277.2	10.2	7.3	69.6	7.6
72	23-Apr-05		86.5				59.9	
73	24-Apr-05							
74	25-Apr-05		95.3		9.0	6.6	71.8	4.3
75	26-Apr-05		94.2	277.2	11.3	10.4	71.8	8.5
Batch Average		4	97.0	291.4	10.0	9.1	70.1	7.6
76	27-Apr-05	Batch 5						
77	28-Apr-05							
78	29-Apr-05		105.3				81.5	
79	30-Apr-05							
80	1-May-05							
81	2-May-05		12.0				12.6	
82	3-May-05							
83	4-May-05		116.2	244.3	10.4	7.7	88.3	6.6
84	5-May-05		115.2	243.6	10.1	9.9	89.9	9.4
85	6-May-05		93.1	244.3	7.8	7.8	78.9	8.0
86	7-May-05		136.1					
87	8-May-05		95.8					
88	9-May-05		119.4	283.5	21.1	19.6	87.8	16.7
89	10-May-05		99.1	277.9	10.6	11.5	84.3	9.1
90	11-May-05		108.2	335.3	11.6	9.9	79.9	8.0
91	12-May-05		123.8	308.0	13.7	11.8	103.5	7.4
92	13-May-05		113.1	300.3	9.1	7.4	95.6	7.1
93	14-May-05		125.7				96.0	
94	15-May-05							
Batch Average		5	112.6	279.7	10.5	9.4	88.6	7.9
95	16-May-05	Batch 6	119.6				93.8	
96	17-May-05							
97	18-May-05							
98	19-May-05							
99	20-May-05		113.0				88.5	
100	21-May-05							
101	22-May-05							
102	23-May-05		148.1	264.6	9.5	8.0	112.6	8.0
103	24-May-05		146.6	262.5	12.6	10.6	117.0	8.5
104	25-May-05		138.1	216.3	14.3	11.3	109.2	7.0
105	26-May-05		130.1	226.8			101.5	
106	27-May-05		143.2	223.3			100.3	
107	28-May-05							
108	29-May-05							
109	30-May-05		132.9	235.2	12.5	10.9	103.8	9.4
110	31-May-05		130.8	217.0	13.4	10.8	109.9	9.4
Batch Average		6	133.6	235.1	12.5	10.3	104.1	8.5
111	1-Jun-05	Batch 7						
112	2-Jun-05							
113	3-Jun-05		99.5	252.0	10.4	9.5	79.8	8.5
114	4-Jun-05							
115	5-Jun-05							
116	6-Jun-05		83.4	215.6	11.9	11.2	83.8	9.9
117	7-Jun-05		92.0	260.4	21.8	21.0	74.3	20.7
118	8-Jun-05		88.6	229.6	27.7	24.2	71.8	18.8
119	9-Jun-05		86.9	205.1	8.0	6.6	74.8	3.8
120	10-Jun-05		97.3					
121	11-Jun-05							
122	12-Jun-05							
123	13-Jun-05		95.5	219.8	39.3	35.3	79.5	26.2
124	14-Jun-05		101.8	212.1	16.0	10.5	78.5	7.0
Batch Average		7	93.1	227.8	19.3	16.9	77.5	13.6
125	15-Jun-05							
126	16-Jun-05							

127	17-Jun-05	Batch 8						
128	18-Jun-05		129.1				90.4	
129	19-Jun-05		101.8					
130	20-Jun-05		123.1	313.6	10.5	9.5	77.0	7.8
131	21-Jun-05		137.3	261.8	11.2	8.5	52.6	5.7
132	22-Jun-05		145.4	291.9	10.8	9.7	84.0	4.9
Batch Average		8	127.3	289.1	10.8	9.2	76.0	6.2
133	23-Jun-05	Batch 9						
134	24-Jun-05		133.3	249.9	6.4	5.0	73.3	2.9
135	25-Jun-05							
136	26-Jun-05							
137	27-Jun-05		103.7	236.6	9.9	10.5	67.2	7.8
138	28-Jun-05		115.5	259.0	9.1	8.4	68.3	6.9
139	29-Jun-05		121.5	244.3	9.9	10.2	75.9	6.2
140	30-Jun-05		117.6	228.9	8.8	8.4	69.1	6.7
141	1-Jul-05		112.4	250.6	10.1	9.2	94.4	7.4
142	2-Jul-05							
143	3-Jul-05							
144	4-Jul-05		121.9	265.3	11.5	11.3	102.2	8.4
145	5-Jul-05		124.1	291.2	10.1	9.5	75.1	8.0
146	6-Jul-05		119.4	277.2	8.7	8.7	93.5	6.2
147	7-Jul-05		108.4				67.8	
Batch Average		9	117.8	255.9	9.8	9.5	78.7	7.2
148	8-Jul-05	Batch 10	91.3				71.4	
149	9-Jul-05							
150	10-Jul-05							
151	11-Jul-05		91.7	371.7	10.1	9.8	58.8	8.7
152	12-Jul-05		91.6	256.9	10.4	10.4	56.8	6.9
153	13-Jul-05		93.3	299.6	6.6	7.0	73.6	5.6
154	14-Jul-05		100.1	313.6	9.4	8.1	73.2	5.2
155	15-Jul-05		90.9	264.6	9.5	8.4	73.9	7.0
156	16-Jul-05							
157	17-Jul-05							
158	18-Jul-05		99.7	290.5	12.0	9.7	69.2	7.6
159	19-Jul-05		92.0	250.6	10.6	9.8	62.1	8.8
160	20-Jul-05		87.5	261.8	8.3	8.1	62.9	7.0
161	21-Jul-05		95.1	277.9	9.4	2.1	67.0	5.7
162	22-Jul-05		87.9	291.9	10.2	9.8	70.1	6.9
163	23-Jul-05							
164	24-Jul-05							
165	25-Jul-05		90.9	267.4	7.3	6.0	72.9	5.0
166	26-Jul-05		87.5	280.0	8.7	7.7	69.6	7.8
167	27-Jul-05		89.5	353.5	12.5	7.1	64.6	6.6
Batch Average		10	91.5	284.0	9.6	8.5	67.6	6.8
168	28-Jul-05	Batch 11						
169	29-Jul-05		90.7				59.1	
170	30-Jul-05							
171	31-Jul-05							
172	1-Aug-05		88.8	268.8	12.2	8.4	75.4	6.6
173	2-Aug-05		95.3	289.8	9.7	9.8	73.2	7.3
174	3-Aug-05		102.5	323.4	9.4	9.1	80.9	7.8
175	4-Aug-05		93.7	242.2	9.7	8.1	70.4	5.9
176	5-Aug-05		108.8	298.9	10.8	9.7	82.2	6.6
177	6-Aug-05							
178	7-Aug-05							
179	8-Aug-05		95.3	230.3	10.5	6.4	75.7	2.4
180	9-Aug-05		94.9	277.2	7.4	5.0	82.0	3.6
181	10-Aug-05		97.1	252.7	6.3	7.3	73.9	5.7
182	11-Aug-05							
183	12-Aug-05							
184	13-Aug-05							

185	14-Aug-05							
186	15-Aug-05		89.2	224.0	7.8	7.7	74.9	5.7
187	16-Aug-05		89.6	269.5	7.7	7.3	78.0	5.5
188	17-Aug-05		89.5	282.1	7.3	6.0	73.7	5.6
Batch Average		11	93.3	269.0	9.0	7.7	76.4	6.0
189	18-Aug-05	Batch 12	69.2	261.1	7.3	7.1	54.9	5.3
190	19-Aug-05							
191	20-Aug-05							
192	21-Aug-05							
193	22-Aug-05							
194	23-Aug-05		138.5	231.7	15.1	14.4	111.2	11.3
195	24-Aug-05		144.3	293.3	11.1	9.8	107.4	9.9
196	25-Aug-05		110.3	262.5	8.3		86.8	7.4
197	26-Aug-05		110.0	281.4	7.6	7.3	87.4	6.2
198	27-Aug-05							
199	28-Aug-05							
200	29-Aug-05		142.1	275.8	8.8	7.7	107.1	5.2
201	30-Aug-05		128.1	266.0	7.7	7.4	98.3	6.2
202	31-Aug-05		137.5				97.4	
203	1-Sep-05		142.9	249.2	9.8	8.3	101.4	6.6
204	2-Sep-05							
Batch Average		12	131.7	265.1	8.6	7.9	99.6	7.3
205	3-Sep-05	Batch 13						
206	4-Sep-05							
207	5-Sep-05		87.4	246.4	8.5	7.8	75.1	6.2
208	6-Sep-05		99.5	236.6	8.7	7.7	69.4	6.0
209	7-Sep-05		103.5	237.3	7.3	6.9	68.2	5.5
210	8-Sep-05		111.6	254.8	7.6	7.1	112.3	5.2
211	9-Sep-05		101.5	224.0	7.7	6.4	82.1	4.8
212	10-Sep-05							
213	11-Sep-05							
214	12-Sep-05		101.9	223.3	7.3	6.7	86.4	5.7
215	13-Sep-05		101.5	180.6	9.0	8.4	78.0	
216	14-Sep-05		99.3	196.7	9.2	5.6	91.1	
217	15-Sep-05							
218	16-Sep-05		105.7				83.1	
Batch Average		13	103.1	225.0	8.2	7.1	79.2	5.6
219	17-Sep-05	Batch 14						
220	18-Sep-05							
221	19-Sep-05		113.1	232.4	13.9	11.1	94.0	6.7
222	20-Sep-05							
223	21-Sep-05		114.8	229.6	13.0	9.8	92.3	7.6
224	22-Sep-05		102.3	247.8	9.1	7.8	85.1	6.4
225	23-Sep-05		106.3	231.7	7.8	7.0	84.1	5.2
226	24-Sep-05							
227	25-Sep-05							
228	26-Sep-05		106.3	224.7	12.2	9.0	89.3	7.8
229	27-Sep-05		122.9	222.6	9.4	6.7	104.9	6.2
230	28-Sep-05		109.6	221.9	13.2	8.8	94.2	5.6
231	29-Sep-05		117.6	223.3	12.7	9.1	97.3	6.9
232	30-Sep-05		135.2	236.6	4.8	7.8	109.2	4.3
233	1-Oct-05							
234	2-Oct-05							
235	3-Oct-05		118.7	230.3	9.5	8.3	96.6	5.7
Batch Average		14	112.4	228.1	10.6	8.5	94.7	6.2
236	4-Oct-05	atch 15					76.2	
237	5-Oct-05		106.1					
238	6-Oct-05						83.2	
239	7-Oct-05		109.5					
240	8-Oct-05							0.0
241	9-Oct-05						90.2	

242	10-Oct-05	Ba	120.4	330.4	5.2			0.3
243	11-Oct-05						80.4	
244	12-Oct-05		98.3	212.8	2.8	1.8		
Batch Average		15	108.6	271.6	4.0	1.8	82.5	0.2
245	13-Oct-05	Batch 16						
246	14-Oct-05		94.4	242.9	2.2	1.8	77.0	1.4
247	15-Oct-05							
248	16-Oct-05							
249	17-Oct-05		105.3	252.0	4.3	2.7	83.4	2.2
250	18-Oct-05							
251	19-Oct-05		105.8	280.0	16.0	10.3	84.0	13.5
252	20-Oct-05							
253	21-Oct-05		137.8	345.1	4.4	1.9	79.2	1.5
254	22-Oct-05							
255	23-Oct-05							
256	24-Oct-05		108.9	116.2	2.835	2.9	73.9	2.3
257	25-Oct-05							
258	26-Oct-05		101.1	217.7	3.15	3.6	76.4	0.0
259	27-Oct-05							
Batch Average		16	108.9	242.3	3.4	2.6	79.0	1.5
260	28-Oct-05	Batch 17	96.6	138.6	3.8	2.1	83.4	1.5
261	29-Oct-05							
262	30-Oct-05							
263	31-Oct-05		92.4	218.4	2.2	2.0	64.7	1.7
264	1-Nov-05							
265	2-Nov-05		97.4	282.8	2.8	1.9	100.5	1.5
266	3-Nov-05							
267	4-Nov-05		84.8	272.3	2.9	2.7	75.9	1.2
268	5-Nov-05							
269	6-Nov-05							
270	7-Nov-05		98.8	280.0	6.4	2.2	76.2	2.0
271	8-Nov-05							
272	9-Nov-05		90.4	105.7	1.8	3.0	67.5	1.2
273	10-Nov-05							
Batch Average		17	93.4	216.3	3.3	2.3	78.0	1.5
274	11-Nov-05	Batch 18	101.9	246.4	3.5	2.3	72.2	0.8
275	12-Nov-05							
276	13-Nov-05							
277	14-Nov-05							
278	15-Nov-05		97.4	292.6	3.2	2.6	81.8	1.3
279	16-Nov-05		94.9	305.2	5.7	2.7	97.2	2.1
280	17-Nov-05							
281	18-Nov-05		88.2	219.8	9.5	9.6	79.0	3.9
282	19-Nov-05							
283	20-Nov-05							
284	21-Nov-05							
285	22-Nov-05		101.1	307.3	4.3	2.7	81.5	1.8
286	23-Nov-05		105.6	263.2	11.4	11.6	84.0	9.3
287	24-Nov-05							
288	25-Nov-05		107.2	240.8	3.0	5.3	80.6	3.0
289	26-Nov-05							
290	27-Nov-05							
291	28-Nov-05		104.2				86.8	
Batch Average		18	100.1	267.9	5.8	5.2	80.8	2.2
292	29-Nov-05							
293	30-Nov-05		96.9	295.4	5.6	2.0	73.6	1.6
294	1-Dec-05							
295	2-Dec-05		139.7	293.3	4.5	1.6	103.0	2.8
296	3-Dec-05							
297	4-Dec-05							
298	5-Dec-05		90.7	259.0	2.2	1.2	70.6	0.0

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299	6-Dec-05	Batch 19						
300	7-Dec-05							
301	8-Dec-05		73.6	221.9	3.7	1.3	70.8	0.4
302	9-Dec-05		114.8	235.9	2.2	1.6	82.9	0.0
303	10-Dec-05							
304	11-Dec-05							
305	12-Dec-05							
306	13-Dec-05		104.2	249.2	0.0	0.0	85.7	0.0
307	14-Dec-05							
308	15-Dec-05		151.8	179.2	4.9	1.8	77.3	0.3
309	16-Dec-05							
310	17-Dec-05							
311	18-Dec-05							
312	19-Dec-05							
Batch Average		19	110.2	247.7	3.3	1.4	80.6	0.7
313	20-Dec-05	Batch 20						
314	21-Dec-05							
315	22-Dec-05							
316	23-Dec-05							
317	24-Dec-05							
318	25-Dec-05							
319	26-Dec-05							
320	27-Dec-05							
321	28-Dec-05							
322	29-Dec-05							
323	30-Dec-05							
324	31-Dec-05							
325	1-Jan-06							
326	2-Jan-06							
		20						
327	3-Jan-06	Batch 21						
328	4-Jan-06							
329	5-Jan-06							
330	6-Jan-06							
331	7-Jan-06							
332	8-Jan-06							
333	9-Jan-06							
334	10-Jan-06							
335	11-Jan-06							
336	12-Jan-06							
337	13-Jan-06							
338	14-Jan-06							
339	15-Jan-06							
340	16-Jan-06							
341	17-Jan-06							
		21						
342	18-Jan-06	Batch 22						
343	19-Jan-06							
344	20-Jan-06		100.2				70.3	
345	21-Jan-06							
346	22-Jan-06							
347	23-Jan-06		125.2	216.3	3.8		103.0	1.6
348	24-Jan-06							
349	25-Jan-06		103.3	206.5	1.9	0.9	82.9	0.5
350	26-Jan-06							
351	27-Jan-06		117.0	191.8	2.9	2.2	91.3	
352	28-Jan-06							
353	29-Jan-06							
354	30-Jan-06		114.2	152.6			92.7	1.8
Batch Average		22	112.0	191.8	2.9	1.6	88.0	1.3
355	31-Jan-06							

356	1-Feb-06	Batch 23						
357	2-Feb-06							
358	3-Feb-06						70.3	0.2
359	4-Feb-06							
360	5-Feb-06							
361	6-Feb-06						41.2	0.5
362	7-Feb-06							
363	8-Feb-06		102.8	177.8	3.5	1.5	85.7	0.2
364	9-Feb-06							
365	10-Feb-06			156.8	4.0	1.7	78.4	0.6
366	11-Feb-06							
367	12-Feb-06							
368	13-Feb-06		109.2	169.4	3.3	2.8	80.4	1.1
369	14-Feb-06		102.8	213.5	4.3	1.2	79.2	0.7
Batch Average		23	104.9	179.4	3.8	1.8	72.5	0.5
370	15-Feb-06	Batch 24						
371	16-Feb-06							
372	17-Feb-06		65.0	210.0	3.0	1.8	93.5	0.4
373	18-Feb-06							
374	19-Feb-06							
375	20-Feb-06							
376	21-Feb-06		85.7	217.0	2.3	1.0	59.1	1.5
377	22-Feb-06							
378	23-Feb-06							
379	24-Feb-06		71.4		1.3		47.9	
380	25-Feb-06							
381	26-Feb-06							
382	27-Feb-06		86.0	249.2			54.3	
383	28-Feb-06		74.8	210.0	1.2	0.6		
Batch Average		24	76.6	221.6	1.9	1.1	63.7	0.9
384	1-Mar-06	Batch 25	92.1	200.2	1.5		72.5	0.2
385	2-Mar-06							
386	3-Mar-06							
387	4-Mar-06							
388	5-Mar-06							
389	6-Mar-06		98.0				82.3	
390	7-Mar-06		118.2	147.7			82.9	
391	8-Mar-06			139.3	1.8	0.7	98.0	0.0
Batch Average		25	102.8	162.4	1.7	0.7	83.9	0.1
392	9-Mar-06	Batch 26					96.9	0.4
393	10-Mar-06							
394	11-Mar-06							
395	12-Mar-06							
396	13-Mar-06		91.3	275.8		0.4	74.8	
397	14-Mar-06							
398	15-Mar-06		132.7	209.3		1.5	102.8	0.4
399	16-Mar-06							
400	17-Mar-06		90.7	214.2	4.0	1.8	70.0	0.7
401	18-Mar-06							
402	19-Mar-06							
403	20-Mar-06		98.3	205.8	5.6	1.5	84.6	1.0
404	21-Mar-06							
405	22-Mar-06							
406	23-Mar-06		98.0	224.0	3.4	2.1	82.0	0.6
Batch Average		26	102.2	225.8	4.3	1.5	85.2	0.6
407	24-Mar-06	27	107.0		3.6		76.7	0.7
408	25-Mar-06					1.7		
409	26-Mar-06							
410	27-Mar-06		101.9	201.6			93.2	0.0
411	28-Mar-06							
412	29-Mar-06		98.6	224.7	3.2		72.5	0.6

413	30-Mar-06	Batch				1.3		
414	31-Mar-06		84.6	199.5	2.9		75.0	0.2
415	1-Apr-06					0.3		
416	2-Apr-06							
417	3-Apr-06		108.6	205.8	3.1		82.3	0.8
418	4-Apr-06					2.5		
419	5-Apr-06		106.4	253.4	3.6		78.1	0.4
420	6-Apr-06					1.2		
421	7-Apr-06							
Batch Average		27	101.2	217.0	3.3	1.4	79.7	0.5
422	8-Apr-06	Batch 28						
423	9-Apr-06							
424	10-Apr-06		80.6	186.2		3.4	58.8	2.2
425	11-Apr-06							
426	12-Apr-06							
427	13-Apr-06		100.2	189.7	4.3	2.2	83.7	0.9
428	14-Apr-06		94.9					
429	15-Apr-06		100.0	204.4	1.4	1.4	81.8	1.2
430	16-Apr-06		98.0					
431	17-Apr-06		101.9					
432	18-Apr-06		117.0	250.6	2.4	1.8	80.4	0.4
433	19-Apr-06							
434	20-Apr-06							
435	21-Apr-06		118.2	238.7	2.5	2.3	86.8	0.9
436	22-Apr-06							
Batch Average		28	101.4	213.9	2.7	2.2	78.3	1.1
437	23-Apr-06	Batch 29						
438	24-Apr-06		105.8	238.0	2.6	1.3	77.0	0.5
439	25-Apr-06							
440	26-Apr-06		94.4	222.6		2.6	76.7	0.0
441	27-Apr-06							
442	28-Apr-06		88.2	236.6	2.4	1.8	69.7	0.4
443	29-Apr-06							
444	30-Apr-06							
445	1-May-06						79.5	1.2
446	2-May-06							
447	3-May-06		96.9	252.0		2.2	64.1	1.1
448	4-May-06							
449	5-May-06		89.6	242.2	2.3	2.7	63.0	1.4
Batch Average		29	95.0	238.3	2.4	2.1	71.7	0.8

Appendix B-3

Measured NO3, NO2 and soluble P in the conventional UCT system

			NO3				NO2				Ortho-P				
Day	Date	SB#	AN	AX	AE	E	AN	AX	AE	E	I	AN	AX	AE	E
-	-	-	(mgN/l)				(mgN/l)				(mgP/l)				
19	1-Mar-05														
20	2-Mar-05														
21	3-Mar-05	Batch 2													
22	4-Mar-05														
23	5-Mar-05														
24	6-Mar-05														
25	7-Mar-05		0.0	0.0	23.5	35.2	0.0	0.0	0.0	0.0		37.0	29.1	16.3	19.7
26	8-Mar-05		0.0	0.0	14.7	27.5	0.0	0.0	0.0	0.0		74.3	47.6	27.2	19.1
27	9-Mar-05		0.0	1.8	26.8	28.9	0.0	0.0	0.0	0.0		66.7	50.4	32.3	29.1
28	10-Mar-05		0.0	0.0	33.9	36.4	0.0	0.0	0.0	0.0		74.3	51.1	34.5	34.1
29	11-Mar-05		0.0	0.7	30.6	31.9	0.0	0.0	0.0	0.0		73.9	59.5	32.9	42.9
30	12-Mar-05														
31	13-Mar-05														
32	14-Mar-05		0.0	0.1	36.2	30.8	0.0	0.0	0.0	0.0	49.3	73.3	51.4	32.3	29.4
33	15-Mar-05		0.0	0.9	37.3	39.4	0.0	0.0	0.0	0.0	17.8	61.4	45.7	29.7	31.3
34	16-Mar-05		0.0	1.1	39.6	40.6	0.0	0.0	0.0			52.0	37.0	31.3	28.8
35	17-Mar-05		0.0	0.9	37.5	44.8	0.0	0.0	0.0	0.0	18.7	47.6	32.9	22.9	23.2
36	18-Mar-05		0.0	2.6	35.0	46.3	0.0	0.0	0.0	0.0		47.6	52.6	47.3	21.9
Batch Average		2	0.0	0.6	33.4	36.2	0.0	0.0	0.0	0.0	28.6	60.8	45.7	28.8	28.0
37	19-Mar-05	Batch 3													
38	20-Mar-05														
39	21-Mar-05										18.0				
40	22-Mar-05										18.0	49.8	48.6	15.6	9.4
41	23-Mar-05		0.1	4.2	27.2	33.3	0.0	1.2	0.0	0.0	25.8	34.6	28.1	15.3	18.7
42	24-Mar-05														
43	25-Mar-05										18.3				
44	26-Mar-05														
45	27-Mar-05										39.3				
46	28-Mar-05														
47	29-Mar-05										34.8				
48	30-Mar-05		0.1	4.1	30.9	32.2	0.0	0.6	0.0	0.0	37.1	36.8	17.8	11.5	10.9
49	31-Mar-05		0.2	5.6	29.2	32.8	0.0	0.9	0.0	0.0	34.5	44.3	24.9	17.1	15.0
50	1-Apr-05		0.1	5.9	28.7	28.1	0.0	0.5	0.0	0.0	41.8	56.8	30.9	19.9	19.3
51	2-Apr-05										36.7				
52	3-Apr-05														
53	4-Apr-05		0.2	5.5	24.7	27.9	0.0	0.8	0.0	0.0	35.9	64.3	28.7	15.6	15.9
Batch Average		3	0.1	5.1	28.1	30.9	0.0	0.8	0.0	0.0	30.9	47.8	29.8	15.8	14.9
54	5-Apr-05	Batch4			42.1	38.7					34.6	62.7	29.9	16.2	14.6
55	6-Apr-05														
56	7-Apr-05														
57	8-Apr-05										27.5				
58	9-Apr-05														
59	10-Apr-05										27.8				
60	11-Apr-05		0.2	0.1	8.3	6.8	0.2	0.1	0.0	0.0		54.8	20.3	3.0	3.0
61	12-Apr-05		0.5	0.4	10.0	10.0	0.4	0.3	0.0	0.0	26.9	66.1	21.9	3.6	2.0
62	13-Apr-05		0.4	0.6	8.8	10.7	0.3	0.2	0.0	0.0		20.3	6.8		
63	14-Apr-05		0.4	1.7	10.4	9.9	0.3	0.9	0.0	0.0	29.0	52.6	18.1	3.6	
64	15-Apr-05		0.4	2.8	12.7	12.0	0.4	1.6	0.0	0.0	26.0	53.8	18.8	3.6	2.6
65	16-Apr-05										34.6				
66	17-Apr-05														
67	18-Apr-05		0.5	4.6	10.1	11.1	0.7	1.6	0.0	0.0	21.3	45.0	18.1	5.8	4.5
68	19-Apr-05		1.5	4.0	12.3	11.3	0.7	1.5	0.0	0.0	24.9	55.4	25.7	11.5	7.7
69	20-Apr-05		1.0	4.2	13.0	13.6	0.3	1.2	0.0	0.0	21.3	51.9	22.9	9.9	9.6

70	21-Apr-05		0.3	3.8	12.4	14.2	0.0	1.3	0.0	0.0	28.5	50.0	22.9	9.9	11.2
71	22-Apr-05		0.0	5.2	18.5	25.8	0.1	0.1	0.0	0.0	22.6	45.3	28.7	17.3	15.3
72	23-Apr-05										26.3	38.1	25.1	15.3	17.0
73	24-Apr-05										25.9	42.0	25.9	16.7	14.8
74	25-Apr-05		0.0	1.1	15.2	15.6	0.1	0.1	0.0	0.0	22.7				
75	26-Apr-05		0.1	0.5	18.1	17.9	0.2	0.0	0.0	0.0					
Batch Average		4	0.4	2.4	12.5	13.2	0.3	0.7	0.0	0.0	26.7	51.5	23.2	9.7	9.3
76	27-Apr-05	Batch 5													
77	28-Apr-05														
78	29-Apr-05										28.8				
79	30-Apr-05														
80	1-May-05														
81	2-May-05										31.5				
82	3-May-05														
83	4-May-05		1.0	7.0	38.7	40.9	0.9	3.0	0.0	0.0	29.0	33.4	26.4	21.7	22.3
84	5-May-05		0.7	4.7	32.8	34.2	0.7	1.5	0.0	0.0	29.3	32.0	25.3	20.6	21.4
85	6-May-05		0.0	0.4	24.4	31.3	0.0	0.4	0.0	0.0	25.5	33.4	28.4	16.4	19.5
86	7-May-05														
87	8-May-05														
88	9-May-05		0.3	5.2	22.4	13.8	0.3	1.3	0.0	0.0	19.0	15.6	6.4		5.9
89	10-May-05		0.0	0.8	17.3	10.3	0.1	0.4	0.0	0.0	19.2	30.3	16.4	6.2	7.0
90	11-May-05		0.3	1.6	24.0	18.5	0.3		0.0	0.0	19.6	27.0	13.1	4.8	4.5
91	12-May-05		0.0	0.3	25.8	19.5	0.0	0.6	0.0	0.0	17.3	17.0	9.2	5.6	3.9
92	13-May-05		0.3	6.2	36.2	31.1	0.3	1.1	0.0	0.0	20.5	25.1	16.4	11.7	8.7
93	14-May-05														
94	15-May-05														
Batch Average		5	0.3	3.3	27.7	25.0	0.3	0.9	0.0	0.0	24.0	26.7	17.7	12.4	11.7
95	16-May-05	Batch 6									21.7				
96	17-May-05														
97	18-May-05														
98	19-May-05														
99	20-May-05										18.9				
100	21-May-05														
101	22-May-05														
102	23-May-05		0.0	8.5	27.6	26.8	0.0	1.3	0.0	0.0	22.2	14.5	7.8	11.4	10.0
103	24-May-05		0.0	8.6	31.9	30.1	0.0	1.6	0.0	0.0	23.3	17.7	15.4	13.1	9.7
104	25-May-05		0.0	4.7	28.7	30.7	0.0	0.6	0.0	0.0	22.1	27.6	19.6	15.1	14.5
105	26-May-05		0.0	7.7	27.8	30.1	0.0	1.6	0.0	0.0	25.3	18.2	15.4	11.4	13.7
106	27-May-05		0.0	8.0	29.7	31.5	0.0	0.8	0.0	0.0	31.6	32.1	19.6	14.3	12.3
107	28-May-05														
108	29-May-05														
109	30-May-05		0.0	9.0	23.7	27.8	0.0	2.4	0.0	0.0	31.4	23.6	21.6	19.9	20.2
110	31-May-05		0.0	9.9	29.5	29.1		1.5			30.1	28.1	21.6	20.2	20.8
Batch Average		6	0.0	8.6	28.4	29.5	0.0	1.4	0.0	0.0	25.2	23.1	17.3	15.1	14.5
111	1-Jun-05	Batch 7									28.8				
112	2-Jun-05										26.5				
113	3-Jun-05		0.0	0.0	7.9	4.7	0.0	0.0	0.0	0.0	26.3	37.9	26.7	18.1	17.5
114	4-Jun-05														
115	5-Jun-05														
116	6-Jun-05		0.0	0.0	11.9	14.2	0.0	0.0	0.0	0.0	28.4	37.3	26.7	18.4	19.8
117	7-Jun-05		0.0	0.4		4.9	0.0	0.0	0.0	0.0	30.4	41.2	48.2	53.5	30.1
118	8-Jun-05		0.0	0.0	18.5	12.7	0.0	0.0	0.0	0.0	30.9	37.3	20.3	17.0	24.2
119	9-Jun-05		0.0	2.2	10.6	11.7	0.0	0.0	0.0	0.0	30.3	35.3	20.9	11.7	12.2
120	10-Jun-05						0.0	0.0	0.0	0.0	34.3	40.6	46.8	49.8	26.4
121	11-Jun-05														
122	12-Jun-05														
123	13-Jun-05		0.0	11.7	26.3	20.6	0.0	7.5	19.0	15.7	29.2	26.4	15.6	11.1	13.9
124	14-Jun-05		0.0	0.0	15.5	16.1	0.0	1.0	11.6	11.4	38.4	31.4	16.7	10.0	10.0
Batch Average		7	0.0	0.4	15.1	12.1	0.0	0.1	1.7	3.4	29.5	35.9	27.7	23.7	19.3
125	15-Jun-05														

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126	16-Jun-05	Batch 8													
127	17-Jun-05														
128	18-Jun-05										25.8				
129	19-Jun-05														
130	20-Jun-05		0.0	4.6	14.0	11.9	0.0	3.5	8.8	7.3	28.3	36.0	22.6	15.6	14.5
131	21-Jun-05		0.0	2.1	16.4	14.8	0.0	0.0	4.6	3.6	29.7	38.8	21.0	15.6	15.9
132	22-Jun-05		0.0	5.6	23.7	19.3	0.0	0.0	4.0	2.2	30.9	40.5	24.0	17.3	15.9
Batch Average		8	0.0	4.1	18.0	15.3	0.0	1.2	5.8	4.4	28.7	38.5	22.5	16.2	15.5
133	23-Jun-05	Batch 9									33.6				
134	24-Jun-05		0.0	7.9		25.1					31.3	36.3	23.7	20.4	18.7
135	25-Jun-05														
136	26-Jun-05														
137	27-Jun-05		0.0	4.9		20.7	0.0	0.0	0.0	0.0	27.5	37.7	25.4	20.7	20.1
138	28-Jun-05		0.0	4.4		20.4	0.0	0.0	0.0	0.0	28.2	38.8	25.4	20.4	19.0
139	29-Jun-05		0.0	1.2		19.6	0.0	0.0	0.0	0.0	31.2	43.9	25.1	19.6	20.1
140	30-Jun-05		0.0	6.7	22.5	21.4	0.0	0.0	0.0	0.0	30.1	37.7	26.8	20.7	21.2
141	1-Jul-05		0.0	7.3	22.9	22.2	0.0	0.0	0.0	0.0	30.5	38.0	26.8	20.1	21.0
142	2-Jul-05														
143	3-Jul-05														
144	4-Jul-05		0.1	5.5	21.6	18.7					33.8	38.5	26.8	19.8	19.6
145	5-Jul-05		0.0	3.7	18.6	18.3					31.7	44.1	27.1	19.8	19.3
146	6-Jul-05		0.0	6.5	16.8	16.2					17.3	30.7	16.8	12.0	16.2
147	7-Jul-05										12.5				
Batch Average		9	0.0	5.9	20.5	20.3	0.0	0.0	0.0	0.0	29.5	38.4	25.9	19.3	19.5
148	8-Jul-05	Batch 10									10.9				
149	9-Jul-05														
150	10-Jul-05														
151	11-Jul-05				11.1	10.1	0.0	0.0	0.0	0.0	9.6	29.2	16.0	5.0	4.4
152	12-Jul-05		0.3	1.4	10.1	6.3	0.0	0.0	0.0	0.0	10.1	27.8	14.8	5.5	4.1
153	13-Jul-05						0.1	0.1	0.0	0.0	13.2	30.9	14.6	4.1	3.9
154	14-Jul-05				11.6						12.7	29.5	14.0	3.9	3.9
155	15-Jul-05				11.3	11.2	0.0	0.0	0.0	0.0	15.2	35.1	12.9	4.4	4.1
156	16-Jul-05														
157	17-Jul-05														
158	18-Jul-05				10.8	9.7	0.0	0.0	0.0	0.0	11.2	33.7	15.1	4.4	3.9
159	19-Jul-05		0.0	1.8	11.4	6.3	0.1	0.0	0.0	0.5	12.2	29.5	14.0	3.9	5.3
160	20-Jul-05											30.3	10.9	4.4	3.9
161	21-Jul-05				10.4	6.7			0.0	1.9	11.7	23.3	8.4	3.9	4.1
162	22-Jul-05				11.6	8.3			0.0	0.1	12.5	28.1	9.5	5.3	3.9
163	23-Jul-05										9.6				
164	24-Jul-05														
165	25-Jul-05				14.7	16.0	0.0	0.0	0.6	1.2	28.7	38.2	22.2	13.2	12.0
166	26-Jul-05		0.0	5.1	14.1	13.3	0.0	1.1	0.0	0.5	30.2	27.8	18.5	14.3	14.0
167	27-Jul-05				12.1	6.7	0.0	0.0	0.0	0.1	29.2	45.0	23.0	14.0	13.4
Batch Average		10	0.1	2.8	11.7	9.5	0.0	0.1	0.1	0.2	29.3	37.0	21.2	13.8	13.2
168	28-Jul-05	Batch 11													
169	29-Jul-05														
170	30-Jul-05										27.8				
171	31-Jul-05														
172	1-Aug-05				12.6	10.1			0.0	0.0	23.3	34.4	21.7	14.0	10.9
173	2-Aug-05		0.3	3.8	10.6	8.9	0.0	0.2	0.0	0.0	22.0	44.9	23.9	14.3	10.9
174	3-Aug-05				17.7	11.5			0.0	0.0	27.0	58.8	28.8	15.7	13.8
175	4-Aug-05				13.7	9.9			0.0	0.0	25.5	38.9	23.7	14.6	14.9
176	5-Aug-05				14.5	11.8			0.0	0.0	25.3	34.4	19.4	10.9	10.4
177	6-Aug-05														
178	7-Aug-05														
179	8-Aug-05				12.5	8.8			0.0	0.7	24.8	42.3	22.5	12.1	9.5
180	9-Aug-05		0.3	2.3	13.6	3.8	0.0	0.3	0.0	0.5	24.6	35.3	18.3	15.7	15.2
181	10-Aug-05				14.3	7.4			0.0	0.5	24.5	39.8	20.0	10.4	13.8
182	11-Aug-05										20.6				

183	12-Aug-05		0.0	0.0	14.2	8.4									
184	13-Aug-05														
185	14-Aug-05														
186	15-Aug-05		0.0	0.0	15.1	15.4					31.0	43.5	21.7	11.2	10.9
187	16-Aug-05		0.0	1.9	14.9	15.1					22.7	40.9	19.7	10.6	6.7
188	17-Aug-05		0.0	0.0	17.7	14.5					24.4	28.5	16.0	9.8	9.5
Batch Average		11	0.1	1.3	14.3	10.5	0.0	0.3	0.0	0.2	24.4	38.3	20.7	12.7	11.5
189	18-Aug-05	Batch 12	0.0	0.0	20.0	18.8	0.0	0.0	0.0	0.0		25.9	14.6	9.5	9.8
190	19-Aug-05														
191	20-Aug-05														
192	21-Aug-05														
193	22-Aug-05		0.0	0.0	0.0		0.0	0.0	0.0	0.0	27.4				
194	23-Aug-05		0.0	0.0	34.5	20.4	0.0	0.0	0.0	0.0	28.7	42.2	26.2	15.1	13.1
195	24-Aug-05		0.0	0.0	34.6	31.4	0.0	0.0	0.0	0.0	30.9	39.4	22.5	10.8	10.5
196	25-Aug-05		0.5	8.0	28.2	34.3	0.0	0.0	0.0	0.0	27.4	55.1	25.7	11.9	9.7
197	26-Aug-05		0.0	0.0	27.3	29.6	0.0	0.0	0.0	0.0	27.7	52.8	25.4	21.1	10.8
198	27-Aug-05														
199	28-Aug-05														
200	29-Aug-05		0.0	0.0	37.7	35.4	0.0	0.0	0.0	0.0	26.6	51.4	25.1	11.9	11.1
201	30-Aug-05		0.0	12.2	26.6	27.1	0.0	0.0	0.0	0.0		49.7	25.7	12.2	11.1
202	31-Aug-05											67.7	37.4	19.9	15.9
203	1-Sep-05		0.0	0.0	22.2	19.7					28.3				
204	2-Sep-05										29.4				
Batch Average		12	0.0	1.0	28.9	27.1	0.0	0.0	0.0	0.0	28.3	48.0	25.3	14.1	10.9
205	3-Sep-05	Batch 13													
206	4-Sep-05														
207	5-Sep-05		0.0	0.6	10.0	11.7	0.0	0.0	0.0	0.0	28.8	80.5	46.0	17.2	11.3
208	6-Sep-05		0.0	0.0	9.1	10.1	0.0	0.0	0.0	0.0	28.3	58.6	26.9	12.2	9.7
209	7-Sep-05		0.0	1.8	11.3	10.8	0.0	0.0	0.0	0.0	32.3	60.5	28.2	14.1	10.6
210	8-Sep-05			0.0	13.3	14.0	0.0	0.0	0.0	0.0	30.5	62.3	28.2	13.8	11.6
211	9-Sep-05		0.0	1.9	11.4	11.7	0.0	0.0	0.0	0.0	30.6	57.0	24.4	10.3	10.9
212	10-Sep-05										31.2				
213	11-Sep-05														
214	12-Sep-05		0.0	9.3	16.7	18.1	0.0	0.0	0.0	0.0	32.2	26.6	15.0	9.7	10.0
215	13-Sep-05		0.0	0.0	11.1	13.8	0.0	0.0	0.0	0.0	31.7	16.0	10.3	8.7	9.1
216	14-Sep-05		0.0	5.2	12.1	11.1	0.0	0.0	0.0	0.0	30.7	32.6	16.0	9.4	10.6
217	15-Sep-05										29.3				
218	16-Sep-05										30.2				
Batch Average		13	0.0	1.3	11.2	11.9	0.0	0.0	0.0	0.0	30.5	49.3	24.4	11.9	10.5
219	17-Sep-05	Batch 14													
220	18-Sep-05														
221	19-Sep-05		0.0	8.7	24.6	24.6	0.0	0.0	0.0	0.0	29.5	42.3	19.9	7.1	8.7
222	20-Sep-05										45.9				
223	21-Sep-05		0.0	3.9	19.7	19.0	0.0	0.0	0.0	0.0	29.9	41.0	24.0	13.1	11.2
224	22-Sep-05		0.0		16.2	16.5					29.0	54.8	25.0	8.7	6.1
225	23-Sep-05			7.0	26.0	23.3					30.9	53.8	26.9	9.6	8.0
226	24-Sep-05														
227	25-Sep-05														
228	26-Sep-05			8.8	29.0	30.1					31.8	59.6	27.9	11.5	9.9
229	27-Sep-05			11.6	31.7	31.5					30.0	53.2	28.2	14.7	12.5
230	28-Sep-05										32.1	71.8	30.4	12.8	11.9
231	29-Sep-05											60.9	28.8	13.1	16.4
232	30-Sep-05			1.0	20.3	23.8					33.3	71.8	29.5	8.7	8.0
233	1-Oct-05														
234	2-Oct-05														
235	3-Oct-05			14.0	26.5	30.1					32.3	38.5	19.6	8.0	9.9
Batch Average		14	0.0	7.9	24.2	24.9	0.0	0.0	0.0	0.0	31.0	54.8	26.0	10.7	9.6
236	4-Oct-05	15									29.1				
237	5-Oct-05										23.5				
238	6-Oct-05														

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239	7-Oct-05	Batch	0.0	1.3	13.2	12.3	0.0	0.0	0.0	0.0	26.9				
240	8-Oct-05														
241	9-Oct-05						0.0	0.0	0.0	0.0					
242	10-Oct-05		0.0	11.7	24.9	24.9	0.0	0.0	0.0	0.0	30.1	17.6	12.8	14.1	18.3
243	11-Oct-05		0.0	9.7	25.9	25.1					26.9	49.7	23.4	11.9	11.5
244	12-Oct-05		0.0	11.4	21.5	28.2					42.0	33.4	14.4	11.6	12.8
Batch Average		15	0.0	8.5	21.4	22.6	0.0	0.0	0.0	0.0	29.8	33.6	16.9	12.5	14.2
245	13-Oct-05	Batch 16	0.0	9.7	27.0	26.9					33.4	54.8	28.8	17.7	19.3
246	14-Oct-05		0.0	4.6	22.1	25.6					33.4	63.1	30.6	17.4	14.4
247	15-Oct-05														
248	16-Oct-05						0.0	0.0	0.0	0.2					
249	17-Oct-05		0.0	0.0	15.5	12.1	0.0	0.0	0.2	0.2	30.3	59.6	29.4	13.0	13.0
250	18-Oct-05						0.0	0.0	0.0	0.0	29.7	66.9	79.5	61.2	42.9
251	19-Oct-05		0.0	1.2	10.2	10.0					33.5	56.5	30.9	24.6	9.2
252	20-Oct-05		0.0	0.4	16.5	14.1					29.3	58.0	29.3	11.7	9.8
253	21-Oct-05		0.0	0.2	15.8	15.7	0.0	0.0	0.0	0.2		59.6	25.1	9.5	7.9
254	22-Oct-05						0.0	0.0	0.0	0.0					
255	23-Oct-05						0.0	0.0	0.2	0.2					
256	24-Oct-05		0.0	0.0	15.2	15.9	0.0	0.0	0.0	0.1	26.9	58.1	30.0	13.8	13.5
257	25-Oct-05		0.0	1.9	16.4	15.3					35.8	59.6	28.8	13.2	10.1
258	26-Oct-05		0.0	2.5	19.2	19.4					30.0	55.7	26.3	14.1	12.6
259	27-Oct-05		0.0	5.7	15.9	19.1					31.4	17.2	10.8	10.5	11.1
Batch Average		16	0.0	1.8	16.3	17.4	0.0	0.0	0.0	0.1	31.4	59.2	27.0	18.8	12.1
260	28-Oct-05	Batch 17	0.0	1.8	6.8	4.7	0.0	0.0	0.0	0.0	38.0	51.3	19.3	13.9	14.8
261	29-Oct-05														
262	30-Oct-05														
263	31-Oct-05		0.0	0.4	6.9	5.0	0.0	0.0	0.0	0.0	38.9	54.6	29.2	19.3	14.7
264	1-Nov-05		0.0	0.3	11.6	10.9	0.0	0.0	0.0	0.0	41.3	63.0	45.8	16.2	16.2
265	2-Nov-05		0.0	0.0	12.0	10.8	0.0	0.0	0.0	0.0	39.2	59.7	28.9	16.2	16.5
266	3-Nov-05														
267	4-Nov-05		0.0	0.5	11.4	9.7	0.0	0.0	0.0	0.0	39.6	66.0	40.2	22.8	20.4
268	5-Nov-05														
269	6-Nov-05														
270	7-Nov-05		0.0	2.3	12.5	8.9	0.0	0.0	0.0	0.0	31.4	17.2	10.8	10.5	11.1
271	8-Nov-05		0.0	0.3	6.8		0.0	0.0	0.0	0.0	38.0	51.3	19.3	13.9	14.8
272	9-Nov-05		0.0	0.8	11.3	8.9	0.0	0.0	0.0	0.0					
273	10-Nov-05		0.0	0.0	11.2	10.4	0.0	0.0	0.0	0.0	38.4	62.8	32.8	18.4	17.8
Batch Average		17	0.0	0.7	10.1	8.7	0.0	0.0	0.0	0.0	39.1	58.4	28.3	16.4	15.8
274	11-Nov-05	Batch 18		0.3	12.7	12.6	0.0	0.0	0.0	0.0	34.6	72.5	34.9	15.7	15.7
275	12-Nov-05														
276	13-Nov-05														
277	14-Nov-05		0.0	5.4	15.4		0.0	0.0	0.0	0.0	36.3	60.8	24.3	14.8	
278	15-Nov-05		0.0	7.5	20.3	17.8	0.0	0.0	0.0	0.0		57.8	24.6	19.0	18.4
279	16-Nov-05		0.0	3.7	18.5	18.2	0.0	0.0	0.4	0.0		56.1	34.0	22.2	16.9
280	17-Nov-05		0.0	0.0	15.9	17.3	0.0	0.0	1.9	0.5	36.1	55.9	32.2	20.6	17.3
281	18-Nov-05		0.0	4.7	13.6	10.8	0.0	0.5	0.3	0.2	37.1	44.3		16.7	22.2
282	19-Nov-05														
283	20-Nov-05														
284	21-Nov-05		0.0	0.6	14.3	13.1	0.0	0.0	0.0	0.0	41.6	70.5	35.5	21.9	18.5
285	22-Nov-05		0.0	0.3	14.7	13.4	0.0	0.0	0.0	0.0	32.2	57.1	29.8	14.6	17.6
286	23-Nov-05		0.0	0.5	12.2	9.3	0.0	0.3	0.6	0.0	38.6	56.2	34.6	22.2	29.5
287	24-Nov-05		0.0	9.7	16.0	12.4	0.0	0.3	0.0	0.0	56.3	25.9	33.1	21.2	17.8
288	25-Nov-05					12.7	0.0	0.0	0.0	0.2	55.7				
289	26-Nov-05														
290	27-Nov-05														
291	28-Nov-05										56.0				
Batch Average		18	0.0	3.3	14.8	13.8	0.0	0.1	0.1	0.0	39.1	59.0	31.4	18.9	18.0
292	29-Nov-05										57.9				
293	30-Nov-05		0.0	0.3	10.6	10.0	0.0	0.0	0.0	0.0	51.9	60.1	35.6	22.8	30.3
294	1-Dec-05		0.0	1.8	12.0	11.2	0.0	0.0	0.0	0.0	29.3	50.2	21.0	7.4	5.6

295	2-Dec-05	Batch 19	0.0	2.5	14.5	12.7	0.0	0.2	0.0	0.0	35.7	52.6	21.6	8.3	6.2
296	3-Dec-05														
297	4-Dec-05														
298	5-Dec-05		0.0	6.4	18.9	18.6	0.0	0.4	0.0	0.0	35.4	45.0	24.0	14.2	10.8
299	6-Dec-05		0.0	5.6	16.9	18.9	0.0	0.0	0.0	0.0	41.9	50.5	28.6	17.0	14.8
300	7-Dec-05										44.4	51.0	19.0	6.4	2.7
301	8-Dec-05			1.4			0.0	0.0	0.2	0.0	36.9	39.1	12.7	5.8	5.8
302	9-Dec-05		0.0	0.3	11.8	10.2	0.0	0.0	0.0	0.0	33.7	55.7	25.3	7.0	6.7
303	10-Dec-05														
304	11-Dec-05														
305	12-Dec-05														
306	13-Dec-05		0.0	3.8	16.1	10.7	0.0	0.0	0.5	0.0	33.4	41.3	21.8	4.2	10.8
307	14-Dec-05		0.0	6.1	5.8	11.0	0.0	0.0	0.0	0.0	39.1	43.8	11.4	9.9	5.2
308	15-Dec-05		0.0	0.3	12.4	11.2	0.0	0.0	0.0	0.0	41.0	90.3	23.7	13.3	5.2
309	16-Dec-05														
310	17-Dec-05														
311	18-Dec-05														
312	19-Dec-05														
Batch Average		19	0.0	2.8	13.2	12.7	0.0	0.0	0.0	0.0	38.4	48.9	20.9	9.4	7.4
313	20-Dec-05	Batch 20													
314	21-Dec-05														
315	22-Dec-05														
316	23-Dec-05														
317	24-Dec-05														
318	25-Dec-05														
319	26-Dec-05														
320	27-Dec-05														
321	28-Dec-05														
322	29-Dec-05														
323	30-Dec-05														
324	31-Dec-05														
325	1-Jan-06														
326	2-Jan-06														
		20													
327	3-Jan-06	Batch 21													
328	4-Jan-06														
329	5-Jan-06														
330	6-Jan-06														
331	7-Jan-06														
332	8-Jan-06														
333	9-Jan-06														
334	10-Jan-06														
335	11-Jan-06														
336	12-Jan-06														
337	13-Jan-06														
338	14-Jan-06														
339	15-Jan-06														
340	16-Jan-06														
341	17-Jan-06														
		21													
342	18-Jan-06	Batch 22													
343	19-Jan-06														
344	20-Jan-06		0.0	1.7	18.0	15.7	0.0	0.7	0.0	0.0	36.2	47.0	31.1	12.6	12.0
345	21-Jan-06														
346	22-Jan-06														
347	23-Jan-06		0.0	0.8	21.4	19.7	0.0	0.0	0.0	0.0	32.4	41.0	17.4	12.5	8.6
348	24-Jan-06		0.0	0.0	23.9	25.1	0.0	0.0	0.0	0.0	32.0	42.5	30.4	14.2	9.8
349	25-Jan-06		0.0	1.6	22.0	21.9	0.0	0.7	0.0	2.6	32.4	65.8	30.1	10.7	11.0
350	26-Jan-06		0.0	1.0	18.4	20.5	0.0	0.7	0.0	0.0	30.1	36.2	16.8	5.6	7.8
351	27-Jan-06		0.0	0.5			0.0	0.0	0.0	0.0		49.5	19.3	7.2	7.5

352	28-Jan-06														
353	29-Jan-06														
354	30-Jan-06		0.0	0.1	15.3		0.0	0.7	0.0	3.7	29.2	54.6	25.7	12.9	8.8
Batch Average		22	0.0	0.8	19.8	20.6	0.0	0.4	0.0	0.9	32.0	48.1	24.4	10.8	9.4
355	31-Jan-06	Batch 23													
356	1-Feb-06		0.0	0.0	13.3	12.5	0.0	0.0	0.0	0.0	32.4	58.8	49.1	33.9	14.7
357	2-Feb-06		0.0	0.0	14.7	15.4	0.0	0.0	0.0	0.0	33.9	33.3	18.1	4.6	5.2
358	3-Feb-06		0.0	0.0	14.0	15.2	0.0	0.0	0.0	0.0	33.6	33.9	14.7	7.7	5.8
359	4-Feb-06														
360	5-Feb-06														
361	6-Feb-06		0.0	0.8	15.9	16.6	0.0	1.0	0.0	0.0	33.0	42.1	24.8	13.7	12.5
362	7-Feb-06		0.0	0.3	16.3	18.9	0.0	0.0	0.0	0.0	34.2	56.5	28.6	13.8	11.0
363	8-Feb-06		0.0	0.4	16.3	20.1	0.0	0.0	0.0	0.0	35.1	43.5	27.4	17.5	15.3
364	9-Feb-06		0.0	0.2	14.5		0.0	0.0	0.0	0.0	36.1	57.4	30.2	16.3	14.4
365	10-Feb-06		0.0	0.4	15.5	17.9	0.0	0.0	0.0	0.0	37.6	57.7	29.6	14.7	11.6
366	11-Feb-06														
367	12-Feb-06														
368	13-Feb-06		0.0	1.2	20.5	19.5	0.0	0.8	0.0	0.0	36.4	51.9	26.2	14.1	12.5
369	14-Feb-06		0.0	0.5	17.0	20.8	0.2	0.8	0.0	0.0	34.8	50.0	27.4	16.7	15.5
Batch Average		23	0.0	0.3	15.3	17.4	0.0	0.3	0.0	0.0	34.7	48.5	25.2	13.2	11.8
370	15-Feb-06	Batch 24													
371	16-Feb-06		0.0	0.0	16.8	21.0	0.2	0.1	0.0	0.0	30.1	46.5	46.2	21.1	15.8
372	17-Feb-06		0.0	0.3	14.4	18.1	0.2	0.3	0.0	0.0	32.5	52.4	21.7	13.4	13.1
373	18-Feb-06														
374	19-Feb-06														
375	20-Feb-06														
376	21-Feb-06		0.0	0.2	15.5	14.2	0.1	0.6	0.0	0.0	27.2	41.6	25.4	11.8	11.2
377	22-Feb-06		0.0	0.0	19.0	19.7	0.1	0.6	0.0	0.0	40.1	59.7	35.0	18.1	16.3
378	23-Feb-06		0.0	0.4	15.1	16.4	0.1	0.8	0.0	0.0	30.2	55.5	38.3	19.6	19.6
379	24-Feb-06		0.0	1.5	19.9	19.9	0.1	0.8	0.0	0.0	27.8	41.0	29.6	21.1	19.0
380	25-Feb-06														
381	26-Feb-06														
382	27-Feb-06		0.0	2.6	15.2	10.2	0.1	1.6	0.0	0.0	31.0	33.7	19.0	8.2	26.2
383	28-Feb-06		0.0	0.0	12.9	12.1	0.1	0.5	0.0	0.0	32.5	57.6	28.0	11.2	12.7
Batch Average		24	0.0	0.3	16.1	16.4	0.1	0.5	0.0	0.0	30.2	48.5	30.4	15.6	16.7
384	1-Mar-06	Batch 25	0.0	2.0	17.9	17.9	0.1	1.6	0.0	0.0	34.6	36.1	17.8	9.4	11.8
385	2-Mar-06														
386	3-Mar-06														
387	4-Mar-06														
388	5-Mar-06														
389	6-Mar-06										40.0				
390	7-Mar-06		0.0	5.7	28.9	37.5	3.0	1.9	3.7	0.0	37.0	31.6	21.7	20.8	19.9
391	8-Mar-06		5.5	9.1	22.8	33.9	3.3	1.6	0.0	1.8	29.3	49.8	34.5	25.1	25.1
Batch Average		25	1.8	5.6	23.2	29.8	2.1	1.7	1.2	0.6	35.2	39.2	24.7	18.4	18.9
392	9-Mar-06	Batch 26									32.0	14.5	10.3	8.2	26.3
393	10-Mar-06														
394	11-Mar-06														
395	12-Mar-06														
396	13-Mar-06		0.0	1.2	17.1	13.1	0.1	1.8	0.0	5.1	27.8	45.0	23.6	12.4	13.9
397	14-Mar-06		0.0	0.0	14.0	18.4	0.1	0.2	0.0	0.0	26.0	52.9	25.7	14.2	13.3
398	15-Mar-06		0.0		14.8	14.4	0.1		0.0	0.0	25.4	51.0	26.3	16.8	15.6
399	16-Mar-06		0.0		15.4	14.1	0.1		0.0	0.0	32.4	48.6	26.3	16.8	13.8
400	17-Mar-06		0.0		19.9	19.7	0.2		0.0	0.0	25.4	44.6	26.9	22.0	18.0
401	18-Mar-06														
402	19-Mar-06														
403	20-Mar-06										34.5	30.9	21.4	17.1	17.4
404	21-Mar-06		0.0	0.0	20.6	17.4	0.1		0.0	0.0	29.5				
405	22-Mar-06														
406	23-Mar-06		0.0	0.6	13.7	16.7	0.1	0.0	0.0	0.0	27.0	47.4	29.0	20.4	18.7
Batch Average		26	0.0	0.4	16.5	16.2	0.1	0.7	0.0	0.0	28.9	45.8	25.6	16.0	15.8

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407	24-Mar-06	Batch 27	0.0	2.0	17.7	15.7	0.1	1.8	0.0	0.0	29.3	45.4	28.7	22.4	20.4
408	25-Mar-06														
409	26-Mar-06														
410	27-Mar-06		0.0	2.6	21.2	18.7	0.1	2.7	0.0	0.0	33.9	29.9	24.7	23.3	22.4
411	28-Mar-06		0.0	5.1	18.3	11.4	0.1	2.7	1.5	3.1	29.6	35.1	25.3	21.8	28.4
412	29-Mar-06														
413	30-Mar-06		0.0	0.4	14.7	18.5	0.1	0.2	0.8	0.8	25.4	44.3	27.0	18.4	19.7
414	31-Mar-06		0.0	1.6	18.2	19.8	0.1	1.4	0.8	0.7	27.7	43.3	27.3	20.0	19.0
415	1-Apr-06		0.0	3.3	18.5	22.1	0.1	2.2	1.0	1.5	27.7	46.9	32.1	27.0	22.9
416	2-Apr-06		0.0	4.4	20.5	24.7	0.1	2.9	1.0	1.0	30.5	46.2	32.8	27.3	23.2
417	3-Apr-06		0.0	6.5	25.4	25.6	0.1	3.6	1.0	3.6	27.7	42.4	27.3	22.9	22.2
418	4-Apr-06		0.1	4.2	23.2	23.2	0.2	2.9	1.0	1.5	31.8	40.8	29.6	22.9	21.3
419	5-Apr-06										24.5	41.6	27.8		21.1
420	6-Apr-06														
421	7-Apr-06										32.4	31.5	44.0	23.3	22.0
Batch Average		27	0.0	3.3	19.7	20.0	0.1	2.5	0.8	1.4	29.1	40.7	28.3	22.9	21.4
422	8-Apr-06	Batch 28													
423	9-Apr-06														
424	10-Apr-06		0.0	1.9	33.0	28.6	0.2	1.1	5.8	6.7	28.2	28.2	15.9	8.0	11.7
425	11-Apr-06		0.0	0.7	24.7	32.5	0.1	0.6	0.7	3.3	14.4	22.7	10.4	5.9	7.4
426	12-Apr-06		0.0	0.0	15.7	18.8	0.1	0.1	0.0	0.0	17.7	20.8	7.0	2.0	1.3
427	13-Apr-06		0.0	0.0	16.0	17.8	0.1	0.3	0.0	0.0		20.1	6.3	1.3	0.3
428	14-Apr-06										18.4				
429	15-Apr-06		0.0	0.0	16.9	17.4	0.1	0.3	0.0	0.0	18.1	22.4	10.0	2.0	0.3
430	16-Apr-06														
431	17-Apr-06														
432	18-Apr-06		0.0	0.0	17.7	20.7	0.3	0.1	0.0	0.0	25.6	20.7	8.5	1.6	2.1
433	19-Apr-06		0.0	0.0	18.5	15.2	0.1	0.1	0.0	0.0	19.5	23.9	16.1	5.3	2.4
434	20-Apr-06		0.0	0.0	15.8	16.4	0.1	0.6	0.0	0.0	20.1	27.4	7.1	1.6	1.9
435	21-Apr-06		0.0	0.0	17.9	16.8	0.0	0.1	0.0	0.0	23.9	25.6	13.2	1.9	1.0
436	22-Apr-06														
Batch Average		28	0.0	0.1	17.9	19.0	0.1	0.3	0.1	1.1	20.7	23.5	10.5	3.3	2.1
437	23-Apr-06	Batch 29													
438	24-Apr-06					10.9					9.1				2.3
439	25-Apr-06		0.0	0.0	4.8	4.7	0.1	0.1		0.9	10.3	38.3	16.5	2.9	1.7
440	26-Apr-06		0.0	0.0	7.9	7.4	0.0	0.1		0.0	27.8	35.2	17.1	5.4	2.3
441	27-Apr-06					12.2				0.7	18.7				3.2
442	28-Apr-06		0.0	0.2	12.7	14.3	0.1	1.0	1.2	0.1	34.9	49.0	25.1	13.7	7.8
443	29-Apr-06										45.8				
444	30-Apr-06		0.0	0.5	10.8	14.8	0.1	1.6	0.8	0.4	36.3	33.0	25.1	22.0	22.6
445	1-May-06		0.0	0.0	11.5	7.0	0.1	0.9	0.5	2.1	35.1	51.2	38.1	28.1	26.0
446	2-May-06														
447	3-May-06		0.0	0.0	8.1	8.7	0.0	0.2	0.6	0.8	36.0	53.1	29.6	21.7	20.5
448	4-May-06														
449	5-May-06		0.0	1.1	13.2	12.7	0.1	2.5	0.7	1.1	37.8	34.8	25.4	22.0	23.2
Batch Average		29	0.0	0.1	9.9	10.3	0.1	0.9	0.7	0.6	29.2	42.1	25.2	16.5	12.2

Appendix B-4

Miscellaneous measurements on the conventional UCT system

			DSVI		Vol Flow		OUR	Recycles			Reactor Vol		
Day	Date	SB#	msrd.	adj.	Qi	Qw	mgO/l/hr	a	r	s	AN	AX	AE
-	-	-	(mm/gTSS/L)		(l)		(mgO/L-h)	-			(l)		
21	3-Mar-05	Batch 2									6.2	5.6	13.2
22	4-Mar-05										6.2	5.6	13.2
23	5-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
24	6-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
25	7-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
26	8-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
27	9-Mar-05				15	1.1	40.1	2.0	1.0	1.0	6.2	5.6	13.2
28	10-Mar-05				15	1.1	30.8	2.0	1.0	1.0	6.2	5.6	13.2
29	11-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
30	12-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
31	13-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
32	14-Mar-05				15	1.1	30.5	2.0	1.0	1.0	6.2	5.6	13.2
33	15-Mar-05				15	1.1	21.6	2.0	1.0	1.0	6.2	5.6	13.2
34	16-Mar-05				15	1.1	21.0	2.0	1.0	1.0	6.2	5.6	13.2
35	17-Mar-05				15	1.1	20.6	2.0	1.0	1.0	6.2	5.6	13.2
36	18-Mar-05				15	1.1	21.7	2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		2			15.0	1.1	26.6	2.0	1.0	1.0	6.20	5.60	13.20
37	19-Mar-05	Batch 3			15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
38	20-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
39	21-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
40	22-Mar-05				15	1.1	55.4	2.0	1.0	1.0	6.2	5.6	13.2
41	23-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
42	24-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
43	25-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
44	26-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
45	27-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
46	28-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
47	29-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
48	30-Mar-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
49	31-Mar-05				15	1.1	33.7	2.0	1.0	1.0	6.2	5.6	13.2
50	1-Apr-05				15	1.1	32.6	2.0	1.0	1.0	6.2	5.6	13.2
51	2-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
52	3-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
53	4-Apr-05				15	1.1	41.5	2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		3			15.0	1.1	40.8	2.0	1.0	1.0	6.20	5.60	13.20
54	5-Apr-05	Batch4	160.0	140.6	15	1.1	41.2	2.0	1.0	1.0	6.2	5.6	13.2
55	6-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
56	7-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
57	8-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
58	9-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
59	10-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
60	11-Apr-05		150.0	123.7	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
61	12-Apr-05		180.0	116.6	15	1.1	41.6	2.0	1.0	1.0	6.2	5.6	13.2
62	13-Apr-05		170.0	105.5	15	1.1	39.4	2.0	1.0	1.0	6.2	5.6	13.2
63	14-Apr-05		165.0	97.7	15	1.1	39.4	2.0	1.0	1.0	6.2	5.6	13.2
64	15-Apr-05		160.0	71.4	15	1.1	48.0	2.0	1.0	1.0	6.2	5.6	13.2
65	16-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
66	17-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
67	18-Apr-05		170.0	88.1	15	1.1	57.1	2.0	1.0	1.0	6.2	5.6	13.2
68	19-Apr-05		150.0	100.8	15	1.1	43.5	2.0	1.0	1.0	6.2	5.6	13.2
69	20-Apr-05		150.0	73.7	15	1.1	45.2	2.0	1.0	1.0	6.2	5.6	13.2
70	21-Apr-05		145.0	89.5	15	1.1	36.7	2.0	1.0	1.0	6.2	5.6	13.2
71	22-Apr-05		140.0	87.6	15	1.1	32.6	2.0	1.0	1.0	6.2	5.6	13.2
72	23-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
73	24-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
74	25-Apr-05		130.0	116.8	15	1.1	30.7	2.0	1.0	1.0	6.2	5.6	13.2
75	26-Apr-05		150.0	58.0	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		4			15.0	1.1	39.8	2.0	1.0	1.0	6.20	5.60	13.20
76	27-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
77	28-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2

78	29-Apr-05	Batch 5			15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
79	30-Apr-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
80	1-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
81	2-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
82	3-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
83	4-May-05		140.0	71.6	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
84	5-May-05		140.0	113.0	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
85	6-May-05		135.0	59.4	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
86	7-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
87	8-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
88	9-May-05		130.0	54.7	15	1.1	18.8	2.0	1.0	1.0	6.2	5.6	13.2
89	10-May-05		130.0	82.0	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
90	11-May-05		130.0	61.0	15	1.1	24.3	2.0	1.0	1.0	6.2	5.6	13.2
91	12-May-05		130.0	53.2	15	1.1	20.5	2.0	1.0	1.0	6.2	5.6	13.2
92	13-May-05		135.0	74.3	15	1.1	20.4	2.0	1.0	1.0	6.2	5.6	13.2
93	14-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
94	15-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		5			15.0	1.1	21.0	2.0	1.0	1.0	6.20	5.60	13.20
95	16-May-05	Batch 6			15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
96	17-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
97	18-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
98	19-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
99	20-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
100	21-May-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
101	22-May-05				15	2.8		2.0	1.0	1.0	6.2	5.6	13.2
102	23-May-05		110.0	85.1	15			2.0	1.0	1.0	6.2	5.6	13.2
103	24-May-05		100.0	76.6	15		15.1	2.0	1.0	1.0	6.2	5.6	13.2
104	25-May-05		105.0	206.1	15		15.3	2.0	1.0	1.0	6.2	5.6	13.2
105	26-May-05		110.0	52.7	15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
106	27-May-05		110.0	71.8	15	1.1	18.9	2.0	1.0	1.0	6.2	5.6	13.2
107	28-May-05				15			2.0	1.0	1.0	6.2	5.6	13.2
108	29-May-05				15	2.8		2.0	1.0	1.0	6.2	5.6	13.2
109	30-May-05		100.0	130.5	15	0.5	25.0	2.0	1.0	1.0	6.2	5.6	13.2
110	31-May-05		90.0	54.9		0.6					6.2	5.6	13.2
Batch Average		6			15.0	1.3	18.6	2.0	1.0	1.0	6.20	5.60	13.20
111	1-Jun-05	Batch 7			15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
112	2-Jun-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
113	3-Jun-05		140.0	97.1	15	3.0	15.4	2.0	1.0	1.0	6.2	5.6	13.2
114	4-Jun-05				15			2.0	1.0	1.0	6.2	5.6	13.2
115	5-Jun-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
116	6-Jun-05		100.0	48.6	15	1.1	21.1	2.0	1.0	1.0	6.2	5.6	13.2
117	7-Jun-05		100.0	56.7	15	1.1	40.4	2.0	1.0	1.0	6.2	5.6	13.2
118	8-Jun-05		130.0	165.3	15	1.1	28.7	2.0	1.0	1.0	6.2	5.6	13.2
119	9-Jun-05		220.0	145.7	15	1.1	21.9	2.0	1.0	1.0	6.2	5.6	13.2
120	10-Jun-05		240.0	172.8	15	1.1	54.9	2.0	1.0	1.0	6.2	5.6	13.2
121	11-Jun-05				15			2.0	1.0	1.0	6.2	5.6	13.2
122	12-Jun-05				15			2.0	1.0	1.0	6.2	5.6	13.2
123	13-Jun-05		220.0	150.6	15	2.8	53.3	2.0	1.0	1.0	6.2	5.6	13.2
124	14-Jun-05				15	1.1	24.5	2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		7			15.0	1.4	32.5	2.0	1.0	1.0	6.20	5.60	13.20
125	15-Jun-05	Batch 8			15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
126	16-Jun-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
127	17-Jun-05				15	2.8		2.0	1.0	1.0	6.2	5.6	13.2
128	18-Jun-05				15	0.7		2.0	1.0	1.0	6.2	5.6	13.2
129	19-Jun-05				15	1.1		2.0	1.0	1.0	6.2	5.6	13.2
130	20-Jun-05		120.0	78.4	15	1.1	25.1	2.0	1.0	1.0	6.2	5.6	13.2
131	21-Jun-05		125.0	115.9	15	1.1	23.5	2.0	1.0	1.0	6.2	5.6	13.2
132	22-Jun-05		130.0	72.0	15		28.3	2.0	1.0	1.0	6.2	5.6	13.2
Batch Average		8			15.0	1.3	25.6	2.0	1.0	1.0	6.20	5.60	13.20
133	23-Jun-05	tch 9			15	2.8		2.0	1.0	1.0	6.2	5.6	13.2
134	24-Jun-05		135.0	147.2	15	0.5	30.0	2.0	1.0	1.0	5.6	6.2	13.2
135	25-Jun-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
136	26-Jun-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
137	27-Jun-05		130.0	141.4	15	1.1	28.5	2.0	1.0	1.0	5.6	6.2	13.2
138	28-Jun-05		130.0	144.3	15	1.1	24.7	2.0	1.0	1.0	5.6	6.2	13.2
139	29-Jun-05		150.0	120.3	15	3.3	22.9	2.0	1.0	1.0	5.6	6.2	13.2
140	30-Jun-05		160.0	128.2	15		31.9	2.0	1.0	1.0	5.6	6.2	13.2

141	1-Jul-05	Ba	150.0	107.3	15	1.1	30.3	2.0	1.0	1.0	5.6	6.2	13.2
142	2-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
143	3-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
144	4-Jul-05		150.0	155.5	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
145	5-Jul-05		175.0	115.9	15	0.5	30.6	2.0	1.0	1.0	5.6	6.2	13.2
146	6-Jul-05		180.0	118.0	15	3.3	28.2	2.0	1.0	1.0	5.6	6.2	13.2
147	7-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		9			15.0	1.4	28.4	2.0	1.0	1.0	5.64	6.16	13.20
148	8-Jul-05	Batch 10			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
149	9-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
150	10-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
151	11-Jul-05		180.0	112.5	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
152	12-Jul-05		175.0	124.8	15	1.1	27.8	2.0	1.0	1.0	5.6	6.2	13.2
153	13-Jul-05		175.0	127.9	15	1.1	28.6	2.0	1.0	1.0	5.6	6.2	13.2
154	14-Jul-05		180.0	159.0	15	1.1	26.0	2.0	1.0	1.0	5.6	6.2	13.2
155	15-Jul-05		180.0	178.5	15	1.1	22.5	2.0	1.0	1.0	5.6	6.2	13.2
156	16-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
157	17-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
158	18-Jul-05		190.0	111.3	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
159	19-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
160	20-Jul-05		185.0	114.4	15	1.1	20.7	2.0	1.0	1.0	5.6	6.2	13.2
161	21-Jul-05		150.0	92.0	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
162	22-Jul-05		190.0	120.1	15	1.1	21.5	2.0	1.0	1.0	5.6	6.2	13.2
163	23-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
164	24-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
165	25-Jul-05		160.0	132.7	15	1.1	28.1	2.0	1.0	1.0	5.6	6.2	13.2
166	26-Jul-05		165.0	95.1	15	1.1	29.7	2.0	1.0	1.0	5.6	6.2	13.2
167	27-Jul-05		175.0	106.3	15	1.1	21.3	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		10			15.0	1.1	25.1	2.0	1.0	1.0	5.60	6.20	13.20
168	28-Jul-05	Batch 11			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
169	29-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
170	30-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
171	31-Jul-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
172	1-Aug-05		165.0	84.7	15	1.1	22.6	2.0	1.0	1.0	5.6	6.2	13.2
173	2-Aug-05		170.0	121.8	15	1.1	22.3	2.0	1.0	1.0	5.6	6.2	13.2
174	3-Aug-05		190.0	106.9	15	1.1	20.7	2.0	1.0	1.0	5.6	6.2	13.2
175	4-Aug-05		170.0	103.3	15	1.1	20.9	2.0	1.0	1.0	5.6	6.2	13.2
176	5-Aug-05				15	1.1	25.9	2.0	1.0	1.0	5.6	6.2	13.2
177	6-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
178	7-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
179	8-Aug-05		160.0	69.5	15	1.1	26.0	2.0	1.0	1.0	5.6	6.2	13.2
180	9-Aug-05		175.0	92.2	15	1.1	21.2	2.0	1.0	1.0	5.6	6.2	13.2
181	10-Aug-05		155.0	70.5	15	1.1	22.1	2.0	1.0	1.0	5.6	6.2	13.2
182	11-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
183	12-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
184	13-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
185	14-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
186	15-Aug-05		145.0	71.5	15	1.1	22.3	2.0	1.0	1.0	5.6	6.2	13.2
187	16-Aug-05		170.0	160.4	15	1.1	20.5	2.0	1.0	1.0	5.6	6.2	13.2
188	17-Aug-05				15	1.1	22.8	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		11			15.0	1.1	22.5	2.0	1.0	1.0	5.60	6.20	13.20
189	18-Aug-05	Batch 12	180.0	165.4	15	1.1	19.2	2.0	1.0	1.0	5.6	6.2	13.2
190	19-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
191	20-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
192	21-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
193	22-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
194	23-Aug-05		120.0	75.3	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
195	24-Aug-05		160.0	147.2	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
196	25-Aug-05		140.0	140.5	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
197	26-Aug-05		170.0	168.9	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
198	27-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
199	28-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
200	29-Aug-05				15	1.1	29.9	2.0	1.0	1.0	5.6	6.2	13.2
201	30-Aug-05		160.0	149.4	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
202	31-Aug-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
203	1-Sep-05		135.0	127.3	15	1.1	27.9	2.0	1.0	1.0	5.6	6.2	13.2
204	2-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2

Batch Average		12			15.0	1.1	25.7	2.0	1.0	1.0	5.60	6.20	13.20
205	3-Sep-05	Batch 13			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
206	4-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
207	5-Sep-05		150.0	151.1	15	1.1	22.7	2.0	1.0	1.0	5.6	6.2	13.2
208	6-Sep-05		135.0	128.8	15	1.1	18.3	2.0	1.0	1.0	5.6	6.2	13.2
209	7-Sep-05		135.0	139.7	15	1.1	18.0	2.0	1.0	1.0	5.6	6.2	13.2
210	8-Sep-05		140.0	131.8	15	1.1	25.3	2.0	1.0	1.0	5.6	6.2	13.2
211	9-Sep-05				15	1.1	30.8	2.0	1.0	1.0	5.6	6.2	13.2
212	10-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
213	11-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
214	12-Sep-05		120.0	150.8	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
215	13-Sep-05		100.0	131.0	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
216	14-Sep-05		120.0	150.7	15	1.1	26.8	2.0	1.0	1.0	5.6	6.2	13.2
217	15-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
218	16-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		13			15.0	1.1	23.6	2.0	1.0	1.0	5.60	6.20	13.20
219	17-Sep-05	Batch 14			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
220	18-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
221	19-Sep-05		115.0	115.4	15	1.1	24.2	2.0	1.0	1.0	5.6	6.2	13.2
222	20-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
223	21-Sep-05		110.0	117.1	15	1.1	45.3	2.0	1.0	1.0	5.6	6.2	13.2
224	22-Sep-05		140.0	142.7	15	1.1	23.8	2.0	1.0	1.0	5.6	6.2	13.2
225	23-Sep-05		140.0	154.0	15	1.1	23.9	2.0	1.0	1.0	5.6	6.2	13.2
226	24-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
227	25-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
228	26-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
229	27-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
230	28-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
231	29-Sep-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
232	30-Sep-05				15	1.1	21.2	2.0	1.0	1.0	5.6	6.2	13.2
233	1-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
234	2-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
235	3-Oct-05				15	1.1	22.2	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		14			15.0	1.1	23.1	2.0	1.0	1.0	5.60	6.20	13.20
236	4-Oct-05	Batch 15			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
237	5-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
238	6-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
239	7-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
240	8-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
241	9-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
242	10-Oct-05		100.0	92.0	15	1.1	24.9	2.0	1.0	1.0	5.6	6.2	13.2
243	11-Oct-05				15	1.1	24.4	2.0	1.0	1.0	5.6	6.2	13.2
244	12-Oct-05		80.0	91.4	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		15	90.0	91.7	15.0	1.1	24.6	2.0	1.0	1.0	5.60	6.20	13.20
245	13-Oct-05	Batch 16			15	1.1	24.0	2.0	1.0	1.0	5.6	6.2	13.2
246	14-Oct-05		95.0	98.9	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
247	15-Oct-05				15	1.1	17.0	2.0	1.0	1.0	5.6	6.2	13.2
248	16-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
249	17-Oct-05		90.0	101.8	15	1.1	27.0	2.0	1.0	1.0	5.6	6.2	13.2
250	18-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
251	19-Oct-05		110.0	113.8	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
252	20-Oct-05				15	1.1	23.0	2.0	1.0	1.0	5.6	6.2	13.2
253	21-Oct-05		100.0	107.5	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
254	22-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
255	23-Oct-05				15	1.1	23.0	2.0	1.0	1.0	5.6	6.2	13.2
256	24-Oct-05		100.0	113.1	15	1.1	23.0	2.0	1.0	1.0	5.6	6.2	13.2
257	25-Oct-05				15	1.1	21.0	2.0	1.0	1.0	5.6	6.2	13.2
258	26-Oct-05		110.0	121.0	15	1.1	39.5	2.0	1.0	1.0	5.6	6.2	13.2
259	27-Oct-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		16	100.8	109.4	15.0	1.1	22.6	2.0	1.0	1.0	5.60	6.20	13.20
260	28-Oct-05	h 17	100.0	113.8	15	1.1	39.7	2.0	1.0	1.0	5.6	6.2	13.2
261	29-Oct-05				15	1.1	33.8	2.0	1.0	1.0	5.6	6.2	13.2
262	30-Oct-05				15	1.1	37.5	2.0	1.0	1.0	5.6	6.2	13.2
263	31-Oct-05		100.0	108.6	15	1.1	33.6	2.0	1.0	1.0	5.6	6.2	13.2
264	1-Nov-05				15	1.1	38.0	2.0	1.0	1.0	5.6	6.2	13.2
265	2-Nov-05		140.0	137.6	15	1.1	20.0	2.0	1.0	1.0	5.6	6.2	13.2
266	3-Nov-05				15	1.1	16.0	2.0	1.0	1.0	5.6	6.2	13.2

267	4-Nov-05	Batc	140.0	134.4	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
268	5-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
269	6-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
270	7-Nov-05		130.0	136.8	15	1.1	14.0	2.0	1.0	1.0	5.6	6.2	13.2
271	8-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
272	9-Nov-05		130.0	147.4	15	1.1	23.0	2.0	1.0	1.0	5.6	6.2	13.2
273	10-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		17	123.3	129.8	15.0	1.1	28.4	2.0	1.0	1.0	5.60	6.20	13.20
274	11-Nov-05	Batch 18	145.0	151.1	15	1.1	24.0	2.0	1.0	1.0	5.6	6.2	13.2
275	12-Nov-05										5.6	6.2	13.2
276	13-Nov-05										5.6	6.2	13.2
277	14-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
278	15-Nov-05		120.0	116.6	15	1.1	20.0	2.0	1.0	1.0	5.6	6.2	13.2
279	16-Nov-05		130.0	145.0	15	1.1	25.0	2.0	1.0	1.0	5.6	6.2	13.2
280	17-Nov-05				15	1.1	38.0	2.0	1.0	1.0	5.6	6.2	13.2
281	18-Nov-05		110.0	141.9	15	1.1	24.0	2.0	1.0	1.0	5.6	6.2	13.2
282	19-Nov-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
283	20-Nov-05										5.6	6.2	13.2
284	21-Nov-05		110.0	126.3	15	1.1	16.0	2.0	1.0	1.0	5.6	6.2	13.2
285	22-Nov-05		135.0	137.8	15	1.1	21.0	2.0	1.0	1.0	5.6	6.2	13.2
286	23-Nov-05		110.0		15	1.1	18.4	2.0	1.0	1.0	5.6	6.2	13.2
287	24-Nov-05		130.0				19.3				5.6	6.2	13.2
288	25-Nov-05		130.0				24.1				5.6	6.2	13.2
289	26-Nov-05										5.6	6.2	13.2
290	27-Nov-05										5.6	6.2	13.2
291	28-Nov-05										5.6	6.2	13.2
Batch Average		18	124.4	136.5	15.0	1.1	21.3	2.0	1.0	1.0	5.60	6.20	13.20
292	29-Nov-05	Batch 19			15	1.1	20.4	2.0	1.0	1.0	5.6	6.2	13.2
293	30-Nov-05		140.0	127.2	15	1.1	20.2	2.0	1.0	1.0	5.6	6.2	13.2
294	1-Dec-05				15	1.1	21.2	2.0	1.0	1.0	5.6	6.2	13.2
295	2-Dec-05		115.0	102.5	15	1.1	22.3	2.0	1.0	1.0	5.6	6.2	13.2
296	3-Dec-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
297	4-Dec-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
298	5-Dec-05		115.0	106.6	15	1.1	25.4	2.0	1.0	1.0	5.6	6.2	13.2
299	6-Dec-05				15	1.1	28.7	2.0	1.0	1.0	5.6	6.2	13.2
300	7-Dec-05				15	1.1	35.8	2.0	1.0	1.0	5.6	6.2	13.2
301	8-Dec-05		100.0	108.0	15	1.1	22.9	2.0	1.0	1.0	5.6	6.2	13.2
302	9-Dec-05				15	1.1	20.1	2.0	1.0	1.0	5.6	6.2	13.2
303	10-Dec-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
304	11-Dec-05				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
305	12-Dec-05				15	1.1	24.4	2.0	1.0	1.0	5.6	6.2	13.2
306	13-Dec-05		100.0	93.7	15	1.1	34.0	2.0	1.0	1.0	5.6	6.2	13.2
307	14-Dec-05				15	1.1	32.2	2.0	1.0	1.0	5.6	6.2	13.2
308	15-Dec-05				15	1.1	28.2	2.0	1.0	1.0	5.6	6.2	13.2
309	16-Dec-05										5.6	6.2	13.2
310	17-Dec-05										5.6	6.2	13.2
311	18-Dec-05										5.6	6.2	13.2
312	19-Dec-05										5.6	6.2	13.2
Batch Average		19	114.0	107.6	15.0	1.1	25.8	2.0	1.0	1.0	5.60	6.20	13.20
313	20-Dec-05	Batch 20											
314	21-Dec-05												
315	22-Dec-05												
316	23-Dec-05												
317	24-Dec-05												
318	25-Dec-05												
319	26-Dec-05												
320	27-Dec-05												
321	28-Dec-05												
322	29-Dec-05												
323	30-Dec-05												
324	31-Dec-05												
325	1-Jan-06												
326	2-Jan-06												
		20											
327	3-Jan-06												
328	4-Jan-06												
329	5-Jan-06												

330	6-Jan-06	Batch 21											
331	7-Jan-06												
332	8-Jan-06												
333	9-Jan-06												
334	10-Jan-06												
335	11-Jan-06												
336	12-Jan-06												
337	13-Jan-06												
338	14-Jan-06												
339	15-Jan-06												
340	16-Jan-06												
341	17-Jan-06												
		21											
342	18-Jan-06	Batch 22			15	1.1		2.0	1.0	1.0			
343	19-Jan-06				15	1.1		2.0	1.0	1.0			
344	20-Jan-06				15	1.1		2.0	1.0	1.0			
345	21-Jan-06				15	1.1		2.0	1.0	1.0			
346	22-Jan-06				15	1.1		2.0	1.0	1.0			
347	23-Jan-06		90.0	101.8	15	1.1	27.8	2.0	1.0	1.0	5.6	6.2	13.2
348	24-Jan-06				15	1.1	24.8	2.0	1.0	1.0	5.6	6.2	13.2
349	25-Jan-06		90.0	102.6	15	1.1	28.3	2.0	1.0	1.0	5.6	6.2	13.2
350	26-Jan-06				15	1.1	24.3	2.0	1.0	1.0	5.6	6.2	13.2
351	27-Jan-06		90.0	103.0	15	1.1	21.9	2.0	1.0	1.0	5.6	6.2	13.2
352	28-Jan-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
353	29-Jan-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
354	30-Jan-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		22	90.0	102.5	15.0	1.1	25.4	2.0	1.0	1.0	5.60	6.20	13.20
355	31-Jan-06	Batch 23			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
356	1-Feb-06		70.0	129.3	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
357	2-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
358	3-Feb-06		80.0	113.0	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
359	4-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
360	5-Feb-06				15	1.1	26.7	2.0	1.0	1.0	5.6	6.2	13.2
361	6-Feb-06		70.0	102.3	15	1.1	27.5	2.0	1.0	1.0	5.6	6.2	13.2
362	7-Feb-06				15	1.1	24.9	2.0	1.0	1.0	5.6	6.2	13.2
363	8-Feb-06		90.0	121.5	15	1.1	30.8	2.0	1.0	1.0	5.6	6.2	13.2
364	9-Feb-06				15	1.1	27.2	2.0	1.0	1.0	5.6	6.2	13.2
365	10-Feb-06		100.0	118.1	15	1.1	26.5	2.0	1.0	1.0	5.6	6.2	13.2
366	11-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
367	12-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
368	13-Feb-06		110.0	134.1	15	1.1	26.2	2.0	1.0	1.0	5.6	6.2	13.2
369	14-Feb-06		120.0	143.5	15	1.1	35.0	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		23	91.4	123.1	15.0	1.1	27.1	2.0	1.0	1.0	5.60	6.20	13.20
370	15-Feb-06	Batch 24			15	1.1	36.2	2.0	1.0	1.0	5.6	6.2	13.2
371	16-Feb-06				15	1.1	30.3	2.0	1.0	1.0	5.6	6.2	13.2
372	17-Feb-06		100.0	112.3	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
373	18-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
374	19-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
375	20-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
376	21-Feb-06		140.0	143.9	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
377	22-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
378	23-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
379	24-Feb-06		110.0	165.8	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
380	25-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
381	26-Feb-06				15	1.1	26.7	2.0	1.0	1.0	5.6	6.2	13.2
382	27-Feb-06		120.0	135.0	15	1.1	23.9	2.0	1.0	1.0	5.6	6.2	13.2
383	28-Feb-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		24	117.5	139.2	15.0	1.1	29.3	2.0	1.0	1.0	5.60	6.20	13.20
384	1-Mar-06	Batch 25	120.0	127.2	15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
385	2-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
386	3-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
387	4-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
388	5-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
389	6-Mar-06				15	1.1	36.7	2.0	1.0	0.9	5.6	6.2	13.2
390	7-Mar-06		90.0	128.2	15	1.1	26.7	2.0	1.0	0.9	5.6	6.2	13.2
391	8-Mar-06		85.0	115.1	15	1.1	23.7	2.0	1.0	0.9	5.6	6.2	13.2
Batch Average		25	98.3	123.5	15.0	1.1	29.0	2.0	1.0	0.9	5.60	6.20	13.20

392	9-Mar-06	Batch 26			15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
393	10-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
394	11-Mar-06				15	1.1		2.0	1.0	0.9	5.6	6.2	13.2
395	12-Mar-06				15	1.1	22.2	2.0	1.0	0.9	5.6	6.2	13.2
396	13-Mar-06		120.0	137.0	15	1.1	23.4	2.0	1.0	0.9	5.6	6.2	13.2
397	14-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
398	15-Mar-06		100.0	122.0	15	1.1	22.1	2.0	1.0	1.0	5.6	6.2	13.2
399	16-Mar-06				15	1.1	23.4	2.0	1.0	1.0	5.6	6.2	13.2
400	17-Mar-06		170.0	197.9	15	1.1	24.7	2.0	1.0	1.0	5.6	6.2	13.2
401	18-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
402	19-Mar-06				15	1.1	22.4	2.0	1.0	1.0	5.6	6.2	13.2
403	20-Mar-06		95.0	114.7	15	1.1	25.7	2.0	1.0	1.0	5.6	6.2	13.2
404	21-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
405	22-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
406	23-Mar-06		100.0	117.8	15	1.1	22.3	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		26	117.0	137.9	15.0	1.1	23.3	2.0	1.0	1.0	5.60	6.20	13.20
407	24-Mar-06	Batch 27	110.0	141.2	15	1.1	21.7	2.0	1.0	1.0	5.6	6.2	13.2
408	25-Mar-06				15	1.1	21.3	2.0	1.0	1.0	5.6	6.2	13.2
409	26-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
410	27-Mar-06		125.0	164.3	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
411	28-Mar-06				15	1.1	28.5	2.0	1.0	1.0	5.6	6.2	13.2
412	29-Mar-06		140.0	159.7	15	1.1	24.0	2.0	1.0	1.0	5.6	6.2	13.2
413	30-Mar-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
414	31-Mar-06		135.0	161.9	15	1.1	24.8	2.0	1.0	1.0	5.6	6.2	13.2
415	1-Apr-06				15	1.1	24.1	2.0	1.0	1.0	5.6	6.2	13.2
416	2-Apr-06				15	1.1	28.1	2.0	1.0	1.0	5.6	6.2	13.2
417	3-Apr-06		110.0	136.1	15	1.1	36.6	2.0	1.0	1.0	5.6	6.2	13.2
418	4-Apr-06				15	1.1	34.0	2.0	1.0	1.0	5.6	6.2	13.2
419	5-Apr-06		130.0	142.7							5.6	6.2	13.2
420	6-Apr-06										5.6	6.2	13.2
421	7-Apr-06										5.6	6.2	13.2
Batch Average		27	125.0	151.0	15.0	1.1	27.0	2.0	1.0	1.0	5.60	6.20	13.20
422	8-Apr-06	Batch 28				1.1					5.6	6.2	13.2
423	9-Apr-06					1.1					5.6	6.2	13.2
424	10-Apr-06		140.0	220.8	15	0.0	24.1	2.0	1.0	1.0	5.6	6.2	13.2
425	11-Apr-06				15	0.0	18.0	2.0	1.0	1.0	5.6	6.2	13.2
426	12-Apr-06				15	0.0	18.3	2.0	1.0	1.0	5.6	6.2	13.2
427	13-Apr-06		150.0	211.7	15	0.0	26.9	2.0	1.0	1.0	5.6	6.2	13.2
428	14-Apr-06				15	1.0		2.0	1.0	1.0	5.6	6.2	13.2
429	15-Apr-06		130.0	181.2	15	1.1	23.1	2.0	1.0	1.0	5.6	6.2	13.2
430	16-Apr-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
431	17-Apr-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
432	18-Apr-06		145.0	163.6	15	1.1	23.6	2.0	1.0	1.0	5.6	6.2	13.2
433	19-Apr-06				15	1.1	24.6	2.0	1.0	1.0	5.6	6.2	13.2
434	20-Apr-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
435	21-Apr-06		130.0	151.4	15	1.1	23.6	2.0	1.0	1.0	5.6	6.2	13.2
436	22-Apr-06						22.1				5.6	6.2	13.2
Batch Average		28	139.0	185.7	15.0	0.8	22.7	2.0	1.0	1.0	5.60	6.20	13.20
437	23-Apr-06	Batch 29			15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
438	24-Apr-06		135.0		15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
439	25-Apr-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
440	26-Apr-06		105.0	133.6	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
441	27-Apr-06				15	1.1	17.0	2.0	1.0	1.0	5.6	6.2	13.2
442	28-Apr-06		120.0	140.2	15	1.1	14.7	2.0	1.0	1.0	5.6	6.2	13.2
443	29-Apr-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
444	30-Apr-06				15	1.1	18.6	2.0	1.0	1.0	5.6	6.2	13.2
445	1-May-06		100.0	130.2	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
446	2-May-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
447	3-May-06		110.0	109.6	15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
448	4-May-06				15	1.1		2.0	1.0	1.0	5.6	6.2	13.2
449	5-May-06		135.0		15	1.1	19.3	2.0	1.0	1.0	5.6	6.2	13.2
Batch Average		29	117.5	128.4	15.0	1.1	17.4	2.0	1.0	1.0	5.6	6.2	13.2

Appendix B-5

Sewage Batch Averages for the Conventional UCT System

	COD				TKN				FSA		TSS			VSS		
SB #	Influent	Aerobic	Eff unfilt	Eff 0.45	Influent	Aerobic	Eff unfilt.	Eff 0.45	Influent	Eff 0.45	AN	AX	AE	AN	AX	AE
	(mgCOD/l)				(mgN/l)				(mgN/l)		(mgTSS/l)			(mgVSS/l)		
2	958.4	3758.9	59.4	47.6	101.4	247.6	10.4	8.5	81.1	6.3	2354	3212	3361	2013	2549	2718
3	1147.7	4069.8	73.6	65.5	139.4	271.0	8.3	7.8	107.3	6.5	2098	3111	3361	1805	2773	2761
4	1021.6	4706.9	48.8	40.3	97.0	291.4	10.0	9.1	70.1	7.6	4333	6650	5339	3865	5304	4214
5	992.2	4491.1	53.2	45.7	112.6	279.7	10.5	9.4	88.6	7.9	4521	5965	6591	3861	4996	5068
6	912.4	3156.7	59.8	45.7	133.6	235.1	12.5	10.3	104.1	8.5	3252	4706	4349	2790	3997	3638
7	834.6	3517.7	85.9	62.4	93.1	227.8	19.3	16.9	77.5	13.6	2609	3807	3530	2408	3428	3074
8	785.4	4600.0	76.7	66.0	127.3	289.1	10.8	9.2	76.0	6.2	3361	3648	4907	2751	3098	4097
9	980.2	3864.4	66.0	56.0	117.8	255.9	9.8	9.5	78.7	7.2	2378	3694	3937	2062	3111	3231
10	1006.3	4435.7	45.8	37.5	91.5	284.0	9.6	8.5	67.6	6.8	3183	4571	5064	2820	3914	4206
11	975.9	4508.9	81.7	52.7	93.3	269.0	9.0	7.7	76.4	6.0	3728	5449	6374	3270	4295	5167
12	887.8	3873.2	86.7	50.4	131.7	265.1	8.6	7.9	99.6	7.3	2156	3415	3512	2029	2710	2647
13	855.6	3378.9	93.2	52.0	103.1	225.0	8.2	7.1	79.2	5.6	2082	2832	3068	1714	2241	2374
14	869.9	3343.9	103.3	55.0	112.4	228.1	10.6	8.5	94.7	6.2	1757	2887	3143	1484	2287	2453
15	933.9	3621.0	85.9	45.9	108.6	271.6	4.0	1.8	82.5	0.2	2178	3313	3287	1807	2735	2569
16	947.5	3673.7	104.7	68.3	108.9	242.3	3.4	2.6	79.0	1.5	2059	3123	3076	1684	2563	2422
17	926.2	3536.0	75.5	30.9	93.4	216.3	3.3	2.3	78.0	1.5	1848	3171	3186	1562	2543	2524
18	914.2	3660.3	81.3	51.3	100.1	267.9	5.8	5.2	80.8	2.2	2104	3057	3057	1762	2414	2314
19	1070.7	3842.0	84.3	50.4	110.2	247.7	3.3	1.4	80.6	0.7	2042	3197	3378	1729	2584	2688
20																
21																
[redacted]	1008.8	3227.3	91.0	62.7	112.0	191.8	2.9	1.6	88.0	1.3	2014	2764	2831	1666	2204	2245
23	940.6	2893.4	75.2	43.4	104.9	179.4	3.8	1.8	72.5	0.5	1596	2374	2526	1351	1927	1992
24	787.4	3259.9	75.5	41.6	76.6	221.6	1.9	1.1	63.7	0.9	1731	2711	2932	1450	2177	2316
25	905.4	3106.2	76.4	46.5	102.8	162.4	1.7	0.7	83.9	0.1	2108	2787	2833	1780	2267	2269
26	989.4	3378.4	70.2	54.6	102.2	225.8	4.3	1.5	85.2	0.6	1955	2779	2885	1636	2280	2341
27	969.3	3504.0	70.9	40.0	101.2	217.0	3.3	1.4	79.7	0.5	1612	2835	2733	1496	2372	2313
28	1115.6	3651.6	74.3	43.7	101.4	213.9	2.7	2.2	78.3	1.1	1637	2499	2479	1446	2142	2110
29	983.3	3995.0	94.0	58.7	95.0	238.3	2.4	2.1	71.7	0.8	2068	2876	2994	1922	2454	2505
Ave	951.2	3732.9	76.7	50.6	106.6	241.0	6.9	5.6	81.7	4.1	2414	3517	3644	2083	2899	2933

UR	NO$_3$				NO$_2$				Ortho-P					Rs	TKN/ COD	COD/ VSS	TKN/ VSS	VSS/TSS			
	AN	AX	AE	E	AN	AX	AE	E	Infl.	AN	AX	AE	Effl.	Rs	Inf	fcv		AN	AX	AE	ave
mgO/L-h)	(mgN/l)				(mgN/l)				(mgP/l)					d	-	-	-	-	-	-	-
26.6	0.0	0.6	33.4	36.2	0.0	0.0	0.0	0.0	28.6	60.8	45.7	28.8	28.0	20.68	0.11	1.39	0.09	0.86	0.83	0.81	0.78
40.8	0.1	5.1	28.1	30.9	0.0	0.8	0.0	0.0	30.9	47.8	29.8	15.8	14.9	20.19	0.12	1.48	0.10	0.86	0.83	0.82	0.83
39.8	0.4	2.4	12.5	13.2	0.3	0.7	0.0	0.0	26.7	51.5	23.2	9.7	9.3	22.77	0.09	1.16	0.07	0.85	0.83	0.79	0.81
21.0	0.3	3.3	27.7	25.0	0.3	0.9	0.0	0.0	24.0	26.7	17.7	12.4	11.7	20.13	0.11	0.92	0.06	0.86	0.84	0.78	0.81
18.6	0.0	8.6	28.4	29.5	0.0	1.4	0.0	0.0	25.2	23.1	17.3	15.1	14.5	18.50	0.14	1.06	0.08	0.86	0.85	0.84	0.85
32.5	0.0	0.4	15.1	12.1	0.0	0.1	1.7	3.4	29.5	35.9	27.7	23.7	19.3	18.11	0.11	1.13	0.07	0.89	0.88	0.87	0.88
25.6	0.0	4.1	18.0	15.3	0.0	1.2	5.8	4.4	28.7	38.5	22.5	16.2	15.5	21.42	0.17	1.21	0.07	0.82	0.85	0.84	0.83
28.4	0.0	5.9	20.5	20.3	0.0	0.0	0.0	0.0	29.5	38.4	25.9	19.3	19.5	24.16	0.12	1.23	0.08	0.86	0.84	0.82	0.84
25.1	0.1	2.8	11.7	9.5	0.0	0.1	0.1	0.2	29.3	37.0	21.2	13.8	13.2	20.74	0.09	1.13	0.07	0.89	0.86	0.83	0.85
22.5	0.1	1.3	14.3	10.5	0.0	0.3	0.0	0.2	24.4	38.3	20.7	12.7	11.5	20.87	0.10	0.94	0.06	0.88	0.84	0.81	0.83
25.7	0.0	1.0	28.9	27.1	0.0	0.0	0.0	0.0	28.3	48.0	25.3	14.1	10.9	20.61	0.14	1.43	0.10	0.83	0.77	0.74	0.77
23.6	0.0	1.3	11.2	11.9	0.0	0.0	0.0	0.0	30.5	49.3	24.4	11.9	10.5	20.42	0.12	1.40	0.10	0.84	0.79	0.77	0.79
23.1	0.0	7.9	24.2	24.9	0.0	0.0	0.0	0.0	31.0	54.8	26.0	10.7	9.6	20.24	0.13	1.33	0.09	0.84	0.79	0.78	0.80
24.6	0.0	8.5	21.4	22.6	0.0	0.0	0.0	0.0	29.8	33.6	16.9	12.5	14.2	21.12	0.12	1.31	0.07	0.83	0.83	0.78	0.80
22.6	0.0	1.8	16.3	17.4	0.0	0.0	0.0	0.1	31.4	59.2	27.0	18.8	12.1	21.25	0.11	1.51	0.10	0.85	0.81	0.80	0.81
28.4	0.0	0.7	10.1	8.7	0.0	0.0	0.0	0.0	39.1	58.4	28.3	16.4	15.8	20.71	0.11	1.41	0.09	0.85	0.80	0.79	0.81
21.3	0.0	3.3	14.8	13.8	0.0	0.1	0.1	0.0	39.1	59.0	31.4	18.9	18.0	21.40	0.11	1.55	0.11	0.84	0.79	0.79	0.78
25.8	0.0	2.8	13.2	12.7	0.0	0.0	0.0	0.0	38.4	48.9	20.9	9.4	7.4	20.42	0.10	1.48	0.10	0.85	0.81	0.80	0.81
25.4	0.0	0.8	19.8	20.6	0.0	0.4	0.0	0.9	32.0	48.1	24.4	10.8	9.4	21.21	0.11	1.64	0.10	0.83	0.80	0.80	0.81
27.1	0.0	0.3	15.3	17.4	0.0	0.3	0.0	0.0	34.7	48.5	25.2	13.2	11.8	20.82	0.11	1.56	0.08	0.85	0.81	0.79	0.81
29.3	0.0	0.3	16.1	16.4	0.1	0.5	0.0	0.0	30.2	48.5	30.4	15.6	16.7	20.61	0.10	1.52	0.09	0.84	0.80	0.79	0.80
29.0	1.8	5.6	23.2	29.8	2.1	1.7	1.2	0.6	35.2	39.2	24.7	18.4	18.9	21.41	0.11	1.49	0.08	0.84	0.81	0.80	0.81
23.3	0.0	0.4	16.5	16.2	0.1	0.7	0.0	0.0	28.9	45.8	25.6	16.0	15.8	20.58	0.11	1.51	0.10	0.84	0.82	0.81	0.80
27.0	0.0	3.3	19.7	20.0	0.1	2.5	0.8	1.4	29.1	40.7	28.3	22.9	21.4	20.71	0.10	1.51	0.09	0.88	0.84	0.84	0.77
22.7	0.0	0.1	17.9	19.0	0.1	0.3	0.1	1.1	20.7	23.5	10.5	3.3	2.1	21.43	0.09	1.70	0.10	0.88	0.86	0.85	0.86
17.4	0.0	0.1	9.9	10.3	0.1	0.9	0.7	0.6	29.2	42.1	25.2	16.5	12.2	20.89	0.09	1.70	0.09	0.87	0.85	0.84	0.81
26	0.1	2.8	18.8	18.9	0.1	0.5	0.4	0.5	30.2	44.1	24.9	15.3	14.0	20.8	0.1	1.4	0.09	0.85	0.82	0.81	0.81

APPENDIX C

NITROGEN AND COD MASS BALANCES

(After Musvoto 1992). In order to test the accuracy of the measured system response data, nitrogen and COD mass balances were performed on the system. These are discussed in detail below.

C.1 NITROGEN MASS BALANCE

The daily mass of nitrogen that enters the laboratory system in the form of influent TKN and dosed nitrate or nitrite should be accounted for as follows:

i) Nitrogen that is denitrified.
ii) Nitrogen in the waste sludge.
iii) Nitrogen in the effluent i.e. TKN plus nitrite and nitrate.

i) Mass of nitrogen denitrified

For the UCT configuration in the MBR and conventional systems (Figs. C.1 and C.2) this mass is obtained by a nitrate and nitrite mass balance around the anaerobic and anoxic sections of the system. Where significant amounts of nitrite are generated it is necessary to split the nitrite and nitrate in order to produce an accurate calculation particularly for the COD mass balance.

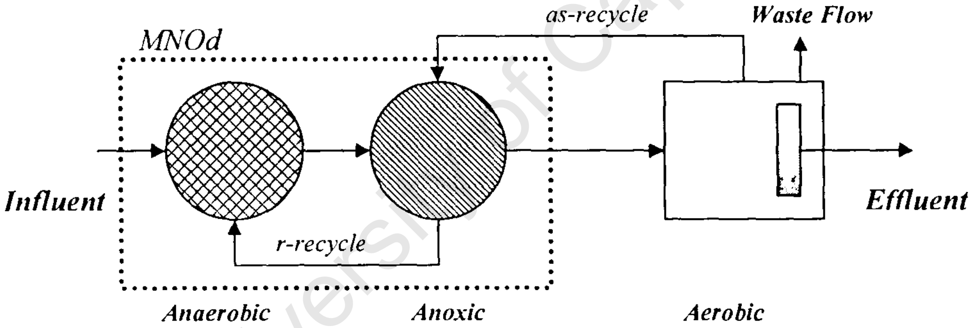

Figure C.1: *Schematic layout of the MBR UCT system, the dotted line indicates the mass balance around the unaerated zones.*

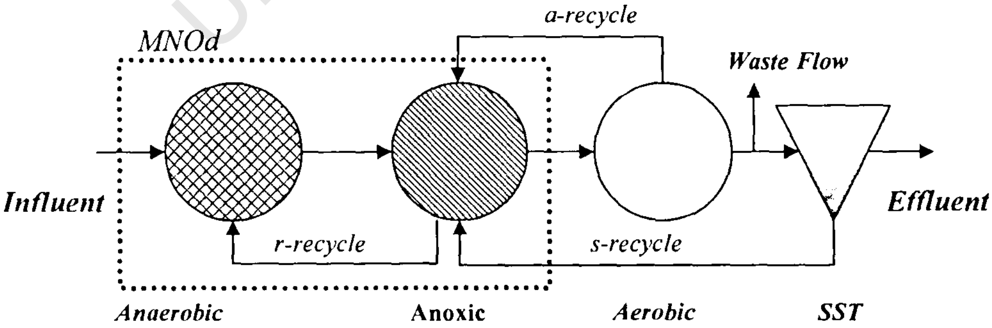

Figure C.2: *Schematic layout of the conventional UCT system, the dotted line indicates the mass balance around the unaerated zones.*

Mass of nitrite and nitrate denitrified considering a UCT system is calculated using Equations (C.1) and (C.2) respectively.

$$\begin{aligned} MNO_{2d} &= MNO_{2in} - MNO_{2out} \\ &= (a+s)QNO_{2aer.} + MNO_{2added} - (1+a+s)QNO_{2anox.} \quad \text{(mgN-NO}_2\text{/d)} \end{aligned} \qquad \text{(C.1)}$$

$$\begin{aligned} MNO_{3d} &= MNO_{3in} - MNO_{3out} \\ &= (a+s)QNO_{3aer.} + MNO_{3added} - (1+a+s)QNO_{3anox.} \quad \text{(mgN-NO}_3\text{/d)} \end{aligned} \qquad \text{(C.2)}$$

Where:
MNO2d = mass of nitrite denitrified per day (mgN-NO_2/d)
MNO3d = mass of nitrate denitrified per day (mgN-NO_3/d)
NO2aer. = effluent nitrite concentration from the aerobic reactor (mgN-NO_2/ℓ)
NO3aer. = effluent nitrite concentration from the aerobic reactor (mgN-NO_3/ℓ)
NO2anox. = effluent nitrite concentration from the anoxic reactor (mgN-NO_2/ℓ)
NO3anox. = effluent nitrite concentration from the anoxic reactor (mgN-NO_3/ℓ)
Q = daily influent flow rate (ℓ/d)
a, s, r = recycle ratios (*a* + *s* is represented by *as* in the MBR system)

ii) Mass of Nitrogen in the waste sludge

The mass of N in the waste sludge is given by the product of the TKN/VSS (f_n) ratio and the mass of VSS wasted per day.

$$MX_N = f_n.MX_{Vwasted} \qquad \text{(mgN/d)} \qquad \text{(C.3)}$$

iii) Mass of Nitrogen in the effluent

This is the product of the daily flow rate and the sum of the effluent TKN, nitrate and nitrite concentrations.

$$MN_e = (N_{te} + NO_{2e} + NO_{3e}).Q \qquad \text{(mgN/d)} \qquad \text{(C.4)}$$

iv) Nitrogen mass balance

The % N mass balance is given by Equation (C.5)

$$\%N\_balance = {}^{100(MNO + MNO_{3d} + MX_N + MN_e)}\!\big/_{MN_i} \qquad \text{(C.5)}$$

Where MN_i is the sum of the mass of TKN in the influent (given by the product of the influent TKN concentration and the daily flow rate) and the mass of nitrate and nitrite dosed, i.e.

$$MN_i = Nti.Q + MNO_{x\_dosed} \qquad \text{(mgN/d)} \qquad \text{(C.6)}$$

C.2 COD MASS BALANCE

The daily mass of COD (MS_{ti}) that enters the system should be accounted by:

- i) The mass of oxygen demand required per day for degradation of carbonaceous material in the aerobic reactor.
- ii) The equivalent mass of oxygen demand per day by denitrification of nitrate and nitrite.
- iii) COD mass in the waste sludge.
- iv) COD mass in the effluent.

i) Carbonaceous oxygen demand

The total amount of oxygen utilized in the aerobic zone is made up of the nitrification demand and the carbonaceous oxygen demand. Since nitrification does not consume any of the influent COD, the oxygen demand due to nitrification must not be subtracted from the total measured oxygen demand. Stoichiometrically the oxygen requirements for nitrification of ammonia to nitrite and to nitrate is different, being slightly less in the former reaction (ie. 3.43 mgO/mgN and 4.57 mgO/mgN generated from ammonia). The oxygen demand for the nitrification of nitrite to nitrate is far less than these two being 1.14 mgO/mgN. The calculation for the carbonaceous oxygen demand is as follows:

1) The mass of nitrate and nitrite generated by nitrification (MNO_{2g} and MNO_{3g}) is obtained by doing a nitrate and nitrite mass balance around the aerobic reactor of the system, as in Equations (C.7) and (C.8),

$$MNO_{2g} = (1+a+s)QNO_{2aer.} - (1+a+s)QNO_{2anox.} \qquad (\text{mgN-NO}_2/\text{d}) \qquad (\text{C.7})$$

$$MNO_{3g} = (1+a+s)QNO_{3aer.} - (1+a+s)QNO_{3anox.} \qquad (\text{mgN-NO}_3/\text{d}) \qquad (\text{C.8})$$

2) The nitrification oxygen demand is then given by Equation (C.9),

$$MO_n = 4.57MNO_{3g} + 3.43MNO_{2g} \qquad (\text{mgCOD/d}) \qquad (\text{C.9})$$

3) The carbonaceous oxygen demand (MO_C)in the aerobic reactor is determined in Equation (C.10),

$$MO_c = (OUR).V_a.24 - MO_n \qquad (\text{mgCOD/d}) \qquad (\text{C.10})$$

Where: OUR = oxygen utilization rate in the aerobic reactor (mgO/ ℓ /h)
V_a = aerobic reactor volume (ℓ)

ii) Equivalent oxygen demand for denitrification

During denitrification some influent biodegradable COD is oxidised with nitrate and nitrite. Stoichiometrically the equivalent amount of oxygen supplied during denitrification is different for nitrate and nitrite and therefore the equivalent oxygen demand per day for denitrification of nitrate and nitrite MO_d is given by:

$$MO_d = 2.86 MNO_{3d} + 1.71 MNO_{2d} \quad \text{(mgCOD/d)} \qquad \text{(C.11)}$$

Where:

2.86	= equivalent mass of oxygen demand in denitrifying one mgN of nitrate to N_2 (mgO/mgN-NO_3)
1.71	= equivalent mass of oxygen demand in denitrifying one mgN of nitrate to N_2 (mgO/mgN-NO_2)
MNO_{3d}	= mass of nitrate denitrified to nitrogen gas (mgN-NO_3/d)
MNO_{2d}	= mass of nitrate denitrified to nitrogen gas (mgN-NO_2/d)

iii) COD in waste sludge

The amount of COD that passes out of the system via the waste sludge is given by Equation (C.12):

$$MX_{svw} = f_{CV}.MX_v \quad \text{(mgCOD/d)} \qquad \text{(C.12)}$$

Where:

f_{CV}	= COD/VSS ratio o activated sludge (= 1.48mgCOD/mgVSS)
MX_v	= mass of sludge wasted per day (mgVSS/d)

iv) COD in effluent

This is given by the daily flow multiplied by the effluent COD concentration:

$$MS_{te} = Q.S_{te} \quad \text{(mgCOD/d)} \qquad \text{(C.13)}$$

v) COD balance

The percentage COD balance is then given by Equation (C.14),

$$\%COD\_balance = {100(MO_c + MO_d + MX_{svw} + MS_{te})}\Big/{MS_{ti}} \qquad \text{(C.14)}$$

APPENDIX D

CONSTRUCTION AND INTERPRETATION OF STATISTICAL PLOTS

D.1 INTRODUCTION

(After Muller *et al.*, 2003) Data from different tests could not be compared directly on a daily basis because of the variability in results from all the tests, due to variations in a multitude of factors that influence the data. Therefore a graphical approach was used to evaluate the data (Velz, 1950), to interpret the trends and compare the results between two test methods.

For a particular batch of wastewater, the data obtained from the different test methods were statistically analysed using a graphical procedure, to determine the mean, sample standard deviation (SSD), and standard deviation of the mean for the data set. This information could then be used to evaluate whether the difference between the means from two data sets is statistically significant at a selected confidence interval, or not.

D.2 CONSTRUCTION OF STATISTICAL PLOT

The experimental data is plotted using the procedure below:

- Arrange the data (n in number) in order of ascending magnitude.
- Assign a serial number "m" to each of the values (1, 2, 3,... n).
- Compute the y-axis plotting the position of each serial value, as the probability equal to or less than from the expression [m/(n+1)]. The x-axis plotting position is the actual value for the data.
- The probability curve is linearized and plotted; for this investigation the transformed rank probability method (Scientific Tables, 1975) was used to linearize the probability curve, see Fig. D1.

D.3 INTERPRETATION OF THE STATISTICAL PLOT

The data plotted can give an indication of whether the data is normally distributed or not:

- If a straight line can be fitted to the plot it indicates that the data have a normal distribution.
- If a straight line cannot be fitted to the plot, the data are not normally distributed.

If the data are normally distributed it indicates that a multitude of factors have each had an independent small influence on the measurements; if the data are not normally distributed it indicates that one factor has had a dominating influence.

From the above, provided a straight line can be fitted to the distribution (i.e. the data are normally distributed), is is possible to determine the mean and SSD graphically:

- The mean of the data plotted – this is determined as the x-value where the straight line of the distribution intercepts a vertical line extended from $y = 5$.
- The SSD of the sample, which provides a measure of the variation of the data – this is the difference between the mean (i.e. the x-value that gives $y = 5$, and the x value that gives $y = 4$, or $y = 6$).

D.4 TEST FOR STATISTICAL SIGNIFICANCE OF THE DIFFERENCES BETWEEN TWO MEAN VALUES

Visual comparison of two data (or data sets) is a common method of appraisal, to determine whether they differ. However, observed differences or similarities may not be significant as these may arise solely by chance. Statistics defines the expected variations due to chance, to determine whether the observed differences between two data have arisen by chance alone or are significant. In the graphical method, by plotting of two or more series of data on the same probability plot, a quick visual appraisal of similarities and differences can be obtained. To test whether the visual differences in the two series of data are statistically significant, a mathematical significance test is performed as follows:

- Plot the two or more distributions to test for normality as described above.
- If normal, obtain the mean (M) and the sample standard deviation (σ) of each series.
- Compute standard deviation of each mean:
  $SD(mean) = (\sigma/\sqrt{n})$
  Where n = number of data points.
- Compute the standard deviation of the difference between the two means:
  $SD(difference) = \sqrt{(SD\ mean1)^2 - (SD\ mean2)^2}$
- Compute the absolute value (i.e. positive) of the difference between the two means:
  $Mean\ (difference) = |mean1 - mean2|$
- Decide upon a confidence interval for the test for significance, e.g. 95% certainty or 99% or any other desired level of confidence.
- Apply the test for statistical significance of the difference.

For example, if 95% is selected as the confidence level, subtract from the difference between the two means [SD(difference)], i.e. [mean(difference) – 2*SD(difference)]. If a positive number is obtained it can be concluded that the difference between the two means is statistically significant at the selected level of confidence; if a negative value is obtained, then the difference between the two means was by chance alone, and it can be concluded that the apparent difference between the two means is NOT statistically different.

D.5 EXAMPLE ILLUSTRATION

An example plot is presented in Fig. D.1.

The mean of a set of values from an experiment is read off from the statistical graph as the value of x that gives $y = 5$, in this case 1.402mgCOD/mgVSS. The standard deviation of a set of values is calculated from the difference between the x-value that gives y = 5, and the x-value that gives y = 4 (or 6), as shown in Fig. D.1:

the x-value at y = 4 = 1.343,
therefore the standard deviation (σ) = 1.402 – 1.343 = 0.059mgCOD/mgVSS.

The standard deviation of the mean is the standard deviation divided by the square root of the number of values in the data set. In this case:

Number of data in set (n) = 26,
Therefore SD mean = $0.059/\sqrt{(26)}$ = 0.116 mgCOD/mgVSS.

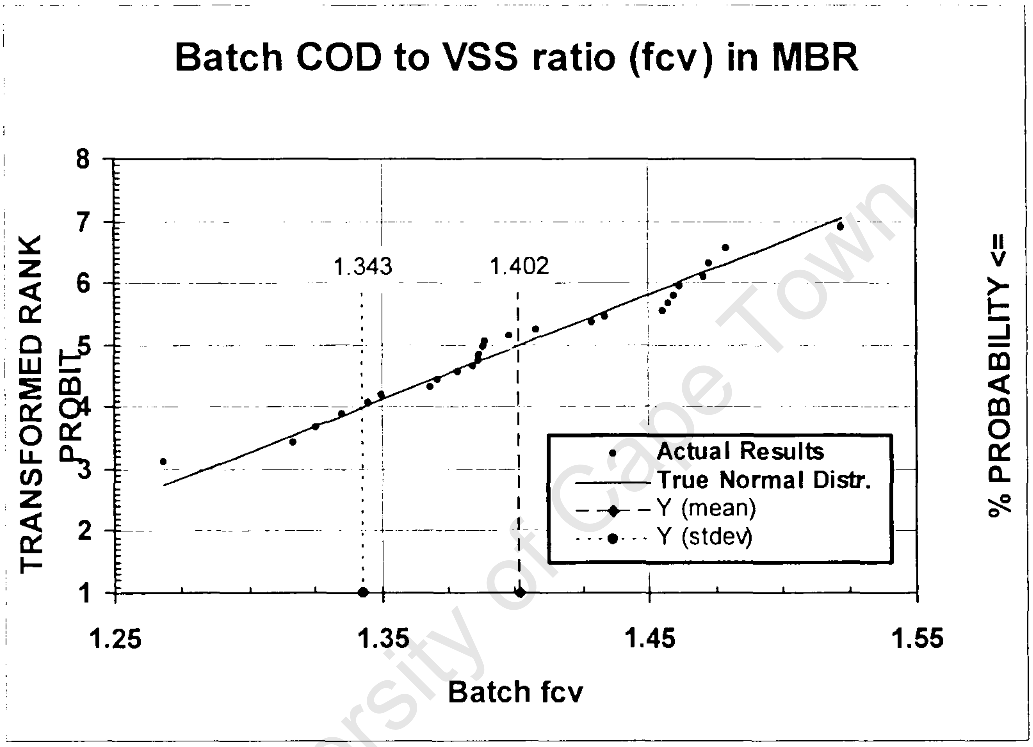

Figure D.1: *Example of a linearized probability graph (after Fig 4.14, Chapter 4: Statistical plot of the sewage batch average COD to VSS ratio (f_{CV}) in the MBR system)*

APPENDIX E

CAPE METROPOLITAN SCIENTIFIC SERVICES PATHOGEN COUNTS

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CITY OF CAPE TOWN

WATER SERVICES SCIENTIFIC SERVICES DEPARTMENT

LABORATORY REPORT

File Ref: CB6/M2.1.2

Telephone: (021) 684 1028/5

TO: UCT Water Research Group
Attention: Geoff Du Toit

BACTERIOLOGICAL TESTING OF EFFLUENT WATER SAMPLES

Sampling Date	Sample Code		Faecal Coliforms per 100 ml	*E Coli* per 100ml
2005-11-03	Conv UCT		6400	5700
2005-11-03	MBR UCT		10	10

KEY: *E coli* – *Escherichia coli*

Ingrid Thomson
for **HEAD: WATER SERVICES**

CITY OF CAPE TOWN

WATER SERVICES SCIENTIFIC SERVICES DEPARTMENT

LABORATORY REPORT

File Ref: CB6/M2.1.2

Telephone: (021) 684 1028/5

TO: UCT Water Research Group
Attention: Geoff Du Toit

BACTERIOLOGICAL TESTING OF EFFLUENT WATER SAMPLES

Sampling Date	Sample Code	Faecal Coliforms per 100 ml	*E Coli* per 100ml
2006-03-28	CONV UCT	560	340
2006-03-28	MBR UCT	<10	<10

KEY: *E coli – Escherichia coli*

Ingrid Thomson
for **HEAD: WATER SERVICES**

APPENDIX F

AERATION AND OXYGEN TRANSFER TESTING IN THE MBR SYSTEM

TABLE OF CONTENTS

Steady State Testing without membranes

date 14-Aug-06

Kla' = OUR/(beta.Cs - Cl)

Cs (20) = 9.07
beta = 1.0
theta = 1.024

Equation for Kla(20)
y = 0 9675x2 + 1 4474x + 32 601

Method : DO is calculated by taking readings from all over reactor for 2 minutes several times in an hour. The OUR is calculated from that in the OUR reactor, adjusted for difference in MLSS and hydraulic retention time

14.8.06

Run 1

AE Temp	17	**Reactors**	Vol	Cruc. Wt.	Dry wt.	Inc wt.	TSS	VSS		DO ave	6.3239
Rot	3.8	**Aerobic**	32	58 8461	59.9009		21096			OUR ave	16.045
Viscosity (80 1/s) (Pa.s)		**RE**	2 5	58.5241	59 5414		20346			OUR adj	16 045
OUR	14.9	17.18								Kla' (20)	4 7038
Set 1 - DO	5 97	6 48	6 52	6 33	6 41	6 48	6 46	6.32	6 23		
Set 2	6.14	6.2	6 17	6.46	6 51	6.41	6.27	6 38	6.53		
Set 3	6.21	6.41	6 2	6.11							
Set 4	6.25										

Run 2

AE Temp	17	**Reactors**	Vol	Cruc. Wt.	Dry wt.	Inc wt.	TSS	VSS		DO ave	5.3835
Rot	2.4	**Aerobic**	32	58.8461			21096	0		OUR ave	16 045
Viscosity (80 1/s) (Pa.s)		**RE**	2.5	58.5241			20346	0		OUR adj	16.045
OUR										Kla' (20)	3.7428
										Kla (20)	35.97
Set 1 - DO	5.02	5 61	5 77	5.21	5.31	5.44					
Set 2	5.09	5.63	5.8	5.17	5.48	5.56					
Set 3	5.05	5.66	5.02	5.26	5.44	5.6					
Set 4	5.25	5.74	4 99	5.33	5.39						

Run 3

AE Temp	17	**Reactors**	Vol	Cruc. Wt.	Dry wt	Inc wt	TSS	VSS		DO ave	3 4785
Rot	0.5	**Aerobic**	32	54.5313			21096	0		OUR ave	16.045
Viscosity (80 1/s) (Pa.s)		**RE**	2.2	53.2307			20346	0		OUR adj	16.045
OUR										Kla' (20)	2.6472
										Kla (20)	23 011
Set 1 - DO	3.01	2.96	3 15	3.22	3.42	3.44	3 39	3.41	3.34		
Set 2	3.38	3.72	3 68	3 69	3 71	3.78	3.83	3.85	3.61		
Set 3	3.47	3.43	3 5	3.42	3.51	3 61	3 52	3.39			
Set 4											

Run 4

AE Temp	17	**Reactors**	Vol	Cruc. Wt.	Dry wt.	Inc wt.	TSS	VSS		DO ave	5.6822
Rot	0.2	**Aerobic**	32	52.9256	53.7872		17232	1075744		OUR ave	21.95
Viscosity (80 1/s) (Pa.s)		**RE**	2 2	54.533	55 3811		16962	1107622		OUR adj	21.95
OUR	18 6	23.6	23 7	22.1	21.2	22.5				Kla' (20)	5 4755
										Kla (20)	20.567
Set 1 - DO	5.57	5.74	5 65	5.64	5.67	5.7	5.77				
Set 2	5.66	5.57	5.58	5.51	5.47	5.64	5.67				
Set 3	5.66	5.71	5 74	5.78	5.77	5.8	5.79				
Set 4	5.79	5.81									

Run 5

AE Temp	17	**Reactors**	Vol	Cruc. Wt.	Dry wt	Inc wt.	TSS	VSS		DO ave	6.73
Rot	1.4	**Aerobic**	32				17232	0		OUR ave	21.95
Viscosity (80 1/s) (Pa.s)		**RE**	2.2				16962	0		OUR adj	21 95
OUR										Kla' (20)	7.2374
										Kla (20)	23.709
Set 1 - DO	6 7	6.72	6.74	6.76	6.71	6.75	6.8	6.75	6.71		
Set 2	6 69	6 66	6 56	6.59	6.65	6 72	6 67	6.68	6.81		
Set 3	6.78	6.77	6.75	6.77	6 83	6.84	6.84				
Set 4											

Run 6

AE Temp	17	**Reactors**	Vol	Cruc. Wt	Dry wt.	Inc wt.	TSS	VSS		DO ave	7.7838
Rot	3.7	**Aerobic**	32				17232	0		OUR ave	21.95
Viscosity (80 1/s) (Pa.s)		**RE**	2.2				16962	0		OUR adj	21.95
OUR										Kla' (20)	10.7
										Kla (20)	29.732
Set 1 - DO	7.71	7.58	7 64	7.72	7.76	7 77	7.8	7.76			
Set 2	7.78	7.83	7.86	7.87	7.85	7.83	7.83	7.86			
Set 3	7.82	7.8	7.78	7.79	7.82						
Set 4											

Run 7

AE Temp	17	**Reactors**	Vol	Cruc. Wt	Dry wt.	Inc wt.	TSS	VSS		DO ave	9 0164
Rot	3.8	**Aerobic**	32	57.9526	58.5061		11070	1170122		OUR ave	13.592
Viscosity (80 1/s) (Pa.s)		**RE**	2.2				0	0		OUR adj	13.592
OUR	13.7	13.07	13.98	13.75	13.48	13.57				Kla' (20)	15.043
										Kla (20)	29.994
Set 1 - DO	8.86	9.03	9.06	9.09	9.1	9.13	9.1	9.12			
Set 2	9.13	9.11	9.1	9.03	9.02	9.06	9.03	8.97			
Set 3	8.94	8.92	8.91	8.92	8.86	8.87					
Set 4											

Run 8

AE Temp	17	**Reactors**	Vol	Cruc. Wt	Dry wt	Inc wt.	TSS	VSS		DO ave	8 744
Rot	1.4	**Aerobic**	32	57.9526	58.5061		11070	1170122		OUR ave	13.592
Viscosity (80 1/s) (Pa.s)		**RE**	2 2				0	0		OUR adj	13.592
OUR										Kla' (20)	11.745
Set 1 - DO	8 69	8.71	8.72	8.7	8.72	8.7	8.74	8.75			
Set 2	8.78	8.7	8.73	8.79	8.78	8.82	8.83				
Set 3											
Set 4											

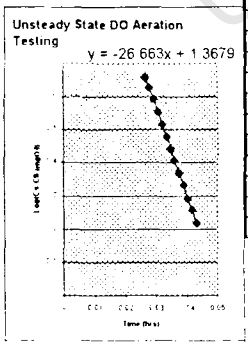
Unsteady State Testing

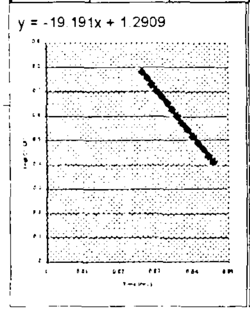
14.8.06

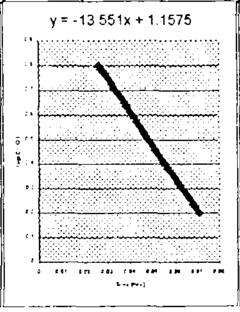
Cs(20): 9.07
Theta 1.024

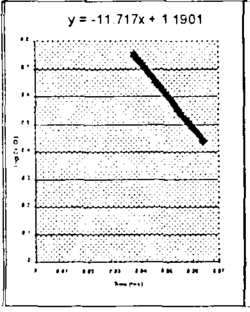
Testing without membranes

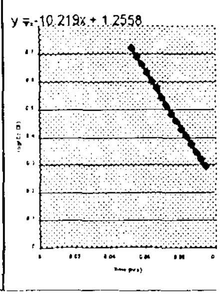
Rotameter reading	10.6			7			5.1			4			3	
Log (Cs-Cl gradient)	-26.7			-19.2			-13.6			-11.7			-10.2	
Kla (T)	61.4901			44.2176			31.3208			26.9451			23.4906	
Kla (20)	62.51945			44.95781			31.84511			27.39616			23.77082	
Temp	19.3			19.3			19.3			19.3			19.5	
Vol	32			32			32			32			32	
	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)
	0.001389	0.06	0.975414	0.001389	0.16	0.970794	0.001389	0.24	0.967062	0.001389	0.21	0.968465	0.002778	0.12
	0.002778	0.1	0.973572	0.002778	0.19	0.969398	0.002778	0.29	0.964713	0.002778	0.24	0.967062	0.005556	0.15
	0.004167	0.13	0.972185	0.004167	0.23	0.96753	0.004167	0.35	0.961878	0.004167	0.27	0.965654	0.008333	0.16
	0.005556	0.15	0.971258	0.005556	0.27	0.965654	0.005556	0.39	0.959977	0.005556	0.3	0.964242	0.011111	0.19
	0.006944	0.2	0.968932	0.006944	0.31	0.96377	0.006944	0.43	0.958068	0.006944	0.33	0.962825	0.013889	0.24
	0.008333	0.27	0.965654	0.008333	0.36	0.961403	0.008333	0.51	0.954224	0.008333	0.37	0.960928	0.016667	0.31
	0.009722	0.4	0.9595	0.009722	0.44	0.957589	0.009722	0.63	0.948394	0.009722	0.42	0.958546	0.019444	0.41
	0.011111	0.57	0.951319	0.011111	0.55	0.95229	0.011111	0.74	0.942981	0.011111	0.49	0.955188	0.022222	0.55
	0.0125	0.83	0.938501	0.0125	0.65	0.947415	0.0125	0.87	0.936495	0.0125	0.59	0.950346	0.025	0.77
	0.013889	1.18	0.920625	0.013889	0.86	0.936997	0.013889	1.05	0.927351	0.013889	0.68	0.945942	0.027778	1
	0.015278	1.58	0.899252	0.015278	1.02	0.928888	0.015278	1.26	0.916434	0.015278	0.79	0.940498	0.030556	1.29
	0.016667	1.99	0.876196	0.016667	1.24	0.917486	0.016667	1.48	0.904695	0.016667	0.94	0.932962	0.033333	1.62
	0.018056	2.38	0.853067	0.018056	1.53	0.901982	0.018056	1.71	0.892074	0.018056	1.07	0.926323	0.036111	1.99
	0.019444	2.82	0.825402	0.019444	1.79	0.887596	0.019444	1.91	0.880792	0.019444	1.24	0.917486	0.038889	2.4
	0.020833	3.28	0.794462	0.020833	2.09	0.870382	0.020833	2.18	0.865082	0.020833	1.41	0.908465	0.041667	2.75
	0.022222	3.72	0.76265	0.022222	2.46	0.848166	0.022222	2.44	0.849396	0.022222	1.59	0.898704	0.044444	3.16
	0.023611	4.17	0.727511	0.023611	2.8	0.826698	0.023611	2.69	0.83376	0.023611	1.79	0.887596	0.047222	3.52
	0.025	4.55	0.695449	0.025	3.14	0.804114	0.025	2.94	0.81754	0.025	1.99	0.876196	0.05	3.89
	0.026389	4.94	0.65988	0.026389	3.47	0.78101	0.026389	3.21	0.799315	0.026389	2.21	0.8633	0.052778	4.22
	0.027778	5.26	0.62835	0.027778	3.79	0.757367	0.027778	3.45	0.782446	0.027778	2.41	0.851235	0.055556	4.57
	0.029167	5.6	0.592135	0.029167	4.13	0.730752	0.029167	3.69	0.764895	0.029167	2.63	0.837565	0.058333	4.89
	0.030556	5.93	0.553837	0.030556	4.45	0.704118	0.030556	3.94	0.745826	0.030556	2.85	0.82345	0.061111	5.19
	0.031944	6.23	0.515824	0.031944	4.72	0.680301	0.031944	4.2	0.725064	0.031944	3.06	0.809534	0.063889	5.48
	0.033333	6.49	0.479953	0.033333	5	0.65414	0.033333	4.44	0.704976	0.033333	3.26	0.795854	0.066667	5.7
	0.034722	6.74	0.442421	0.034722	5.26	0.62835	0.034722	4.62	0.689275	0.034722	3.5	0.778847	0.069444	5.98
	0.036111	6.96	0.406476	0.036111	5.54	0.598749	0.036111	4.82	0.671138	0.036111	3.69	0.764895	0.072222	6.19
	0.0375	7.17	0.369146	0.0375	5.8	0.56933	0.0375	5.02	0.65221	0.0375	3.89	0.749707	0.075	6.41
	0.038889	7.36	0.332362	0.038889	6	0.54526	0.038889	5.2	0.634439	0.038889	4.08	0.73477	0.077778	6.6
	0.040278	7.55	0.292172	0.040278	6.22	0.517146	0.040278	5.41	0.612744	0.040278	4.27	0.7193	0.080556	6.78
	0.041667	7.7	0.257588	0.041667	6.43	0.488497	0.041667	5.58	0.594351	0.041667	4.46	0.703259	0.083333	6.93
	0.043056	7.86	0.217384	0.043056	6.61	0.462341	0.043056	5.76	0.573988	0.043056	4.68	0.683913	0.086111	7.09
	0.044444	7.97	0.187414	0.044444	6.77	0.437691	0.044444	5.93	0.553837	0.044444	4.83	0.670211	0.088889	7.26
	0.045833	8.1	0.149103	0.045833	6.92	0.413236	0.045833	6.1	0.532706	0.045833	5.02	0.65221	0.091667	7.37
	0.047222	8.2	0.117146	0.047222	7.05	0.390868	0.047222	6.24	0.514498	0.047222	5.17	0.637452	0.094444	7.49
	0.048611	8.31	0.079044	0.048611	7.19	0.365417	0.048611	6.38	0.495492	0.048611	5.34	0.620097	0.097222	7.59
	0.05	8.4	0.045175	0.05	7.3	0.344318	0.05	6.51	0.477067	0.05	5.49	0.604185	0.1	7.67
	0.051389	8.45	0.025151	0.051389	7.45	0.313788	0.051389	6.64	0.457825	0.051389	5.62	0.589907	0.102778	7.78
	0.052778	8.53	-0.00894	0.052778	7.57	0.287717	0.052778	6.76	0.439273	0.052778	5.77	0.572828	0.105556	7.86
	0.054167	8.56	-0.02245	0.054167	7.66	0.267083	0.054167	6.89	0.418239	0.054167	5.93	0.553837	0.108333	7.93
	0.055556	8.65	-0.06569	0.055556	7.75	0.245419	0.055556	6.99	0.401335	0.055556	6.07	0.536511	0.111111	8
	0.056944	8.7	-0.09172	0.056944	7.85	0.220009	0.056944	7.11	0.380143	0.056944	6.2	0.519778	0.113889	8.07
	0.058333	8.75	-0.1194	0.058333	7.94	0.195795	0.058333	7.2	0.363541	0.058333	6.3	0.506454	0.116667	8.13
	0.059722	8.79	-0.1429	0.059722	8.01	0.175982	0.059722	7.29	0.346279	0.059722	6.42	0.489905	0.119444	
	0.061111	8.82	-0.16139	0.061111	8.09	0.152173	0.061111	7.38	0.328303	0.061111	6.52	0.475616	0.122222	
	0.0625	8.87	-0.19408	0.0625	8.17	0.126982	0.0625	7.47	0.30955	0.0625	6.62	0.460841	0.125	
	0.063889	8.89	-0.20787	0.063889	8.21	0.113817	0.063889	7.55	0.292172	0.063889	6.75	0.44085	0.127778	
	0.065278	8.94	-0.24441	0.065278	8.27	0.093289	0.065278	7.63	0.274071	0.065278	6.85	0.42482	0.130556	
	0.066667	8.95	-0.25211	0.066667	8.32	0.075409	0.066667	7.7	0.257588	0.066667	6.92	0.413236	0.133333	
	0.068056	8.97	-0.26791	0.068056	8.37	0.056761	0.068056	7.77	0.240455	0.068056	7.03	0.394386	0.136111	
				0.069444	8.42	0.037276	0.069444	7.83	0.225212	0.069444	7.13	0.376508	0.138889	
				0.070833	8.46	0.021033	0.070833	7.92	0.201294	0.070833	7.21	0.361656	0.141667	
				0.072222	8.53	-0.00894	0.072222	7.97	0.187414	0.072222	7.27	0.350175	0.144444	
				0.073611	8.58	-0.03169	0.073611	8.02	0.173076	0.073611	7.37	0.330337	0.147222	
				0.075	8.6	-0.04114	0.075	8.06	0.161255	0.075	7.45	0.313788	0.15	
				0.076389	8.63	-0.0557	0.076389	8.11	0.146011	0.076389	7.53	0.296582	0.152778	
				0.077778	8.67	-0.07592	0.077778	8.17	0.126982	0.077778	7.59	0.283216	0.155556	
				0.079167	8.7	-0.09172	0.079167	8.21	0.113817	0.079167	7.65	0.269425	0.158333	
				0.080556	8.72	-0.10258	0.080556	8.26	0.096779	0.080556	7.69	0.259981	0.161111	
				0.081944	8.77	-0.13099	0.081944	8.3	0.08265	0.081944	7.74	0.247881	0.163889	
				0.083333	8.8	-0.14897	0.083333	8.34	0.068046	0.083333	7.77	0.240455	0.166667	
				0.084722	8.82	-0.16139	0.084722	8.37	0.056761	0.084722	7.83	0.225212	0.169444	











Testing with membranes

	1.8			0.5	26.7		0	14		10.3			7.1	
	-8.3			-6.8			-3.5			-27.7			-19.1	
	19.1149			15.6604			8.0605			63.7931			43.9873	
	19.34292			15.84721			8.156653			64.55408			44.51202	
	19.5			19.5			19.5			19.5			19.5	
	32			32			32			32			32	
log(Cs-Cl)	Time	D.O.	log(Cs-Cl)	Time	D.O.	log(Cs-Cl)	Time	D.O.	log(Cs-Cl)	Time	D.O.	log(Cs-Cl)	Time	D.O.
(mgO/l)	(hrs)	(mgO/l)	(mgO/l)	(hrs)	(mgO/l)	(mgO/l)	(hrs)	(mgO/l)	(mgO/l)	(hrs)	(mgO/l)	(mgO/l)	(hrs)	(mgO/l)
0.970812	0.002778	0.21	0.966611	0.004167	0.19	0.967548	0.005556	0.11	0.971276	0.001389	0.4	0.957608	0.001389	0.27
0.969416	0.005556	0.23	0.965672	0.008333	0.25	0.964731	0.011111	0.14	0.969882	0.002778	0.89	0.933488	0.002778	0.33
0.96895	0.008333	0.3	0.96237	0.0125	0.35	0.959995	0.016667	0.19	0.967548	0.004167	1.15	0.920124	0.004167	0.41
0.967548	0.011111	0.37	0.959042	0.016667	0.55	0.950365	0.022222	0.26	0.96426	0.005556	1.49	0.902003	0.005556	0.53
0.965202	0.013889	0.49	0.953277	0.020833	0.76	0.940019	0.027778	0.37	0.959042	0.006944	1.85	0.881956	0.006944	0.61
0.961896	0.016667	0.65	0.945469	0.025	1.04	0.925828	0.033333	0.49	0.953277	0.008333	2.28	0.856729	0.008333	0.74
0.957129	0.019444	0.85	0.935508	0.029167	1.4	0.906874	0.038889	0.68	0.943969	0.009722	2.71	0.829947	0.009722	0.87
0.950365	0.022222	1.05	0.925313	0.033333	1.75	0.887618	0.044444	0.93	0.931458	0.011111	3.14	0.801404	0.011111	1.02
0.93952	0.025	1.29	0.912754	0.0375	2.12	0.866288	0.05	1.2	0.917506	0.0125	3.58	0.770116	0.0125	1.18
0.927884	0.027778	1.6	0.895975	0.041667			0.055556	1.49	0.902003	0.013889	4.03	0.7356	0.013889	1.39
0.912754	0.030556	1.89	0.87967	0.045833	2.94	0.814914	0.061111	1.79	0.885362	0.015278	4.5	0.696357	0.015278	1.65
0.89487	0.033333	2.19	0.862132	0.05	3.29	0.790989	0.066667	2.07	0.869232	0.016667			0.016667	1.95
0.873902	0.036111	2.47	0.845099	0.054167	3.69	0.761929	0.072222	2.4	0.84942	0.018056	5.27	0.62325	0.018056	2.24
0.84942	0.038889	2.81	0.823475	0.058333	4.03	0.7356	0.077778	2.69	0.83123	0.019444	5.62	0.585462	0.019444	2.57
0.82737	0.041667	3.1	0.80414	0.0625	4.38	0.706719	0.083333	2.93	0.815578	0.020833	5.95	0.546544	0.020833	2.84
0.80003	0.044444	3.41	0.782473	0.066667	4.74	0.674862	0.088889	3.17	0.799341	0.022222	6.26	0.506506	0.022222	3.17
0.774518	0.047222	3.69	0.761929	0.070833	5.02	0.648361	0.094444	3.45	0.779597	0.023611	6.55	0.465384	0.023611	3.51
0.746635	0.05	4.01	0.737193	0.075			0.1	3.73	0.758913	0.025	6.82	0.423247	0.025	3.84
0.72016	0.052778	4.27	0.716004	0.079167	5.57	0.591066	0.105556	3.97	0.740363	0.026389	7.06	0.382019	0.026389	4.14
0.690197	0.055556	4.52	0.694606	0.083333	5.81	0.563482	0.111111	4.19	0.722635	0.027778	7.27	0.342425	0.027778	4.47
0.660866	0.058333	4.79	0.670247	0.0875	6.02	0.53782	0.116667	4.43	0.702431	0.029167	7.44	0.307498	0.029167	4.77
0.631445	0.061111	5.02	0.648361	0.091667	6.22	0.511885	0.122222	4.64	0.683948	0.030556	7.62	0.267174	0.030556	5.09
0.600974	0.063889	5.24	0.626341	0.095833	6.38	0.48996	0.127778	4.84	0.665582	0.031944	7.78	0.227889	0.031944	5.31
0.576342	0.066667	5.47	0.602061	0.1	6.56	0.463894	0.133333	5.09	0.641475	0.033333	7.93	0.187524	0.033333	5.61
0.542827	0.069444	5.67	0.579785	0.104167	6.74	0.436164	0.138889	5.26	0.624283	0.034722	8.06	0.149222	0.034722	5.81
0.515875	0.072222	5.89	0.553884	0.108333	6.89	0.411621	0.144444	5.44	0.605306	0.036111	8.17	0.113947	0.036111	6.07
0.485723	0.075	6.05	0.534027	0.1125	7.03	0.387392	0.15	5.62	0.585462	0.0375	8.29	0.071886	0.0375	6.27
0.457863	0.077778	6.22	0.511885	0.116667		0.97635	0.155556	5.8	0.564667	0.038889	8.38	0.03743	0.038889	6.45
0.429754	0.080556	6.41	0.485723	0.120833		0.97635	0.161111	5.97	0.544069	0.040278	8.46	0.004326	0.040278	6.63
0.404835	0.083333	6.57	0.462399	0.125		0.97635	0.166667	6.13	0.523748	0.041667	8.54	-0.03151	0.041667	6.79
0.376579	0.086111	6.71	0.440911	0.129167		0.97635	0.172222	6.26	0.506506	0.043056	8.61	-0.0655	0.043056	6.93
0.344394	0.088889	6.83	0.421606	0.133333		0.97635	0.177778	6.38	0.48996	0.044444	8.68	-0.10237	0.044444	7.06
0.322221	0.091667	6.96	0.399675	0.1375		0.97635	0.183333	6.48	0.475673	0.045833	8.73	-0.13076	0.045833	7.18
0.296667	0.094444	7.04	0.385608	0.141667		0.97635	0.188889	6.61	0.456368	0.047222	8.79	-0.16748	0.047222	7.3
0.27416	0.097222	7.17	0.36173	0.145833		0.97635	0.194444		0.97635	0.048611	8.82	-0.18708	0.048611	7.42
0.255275	0.1	7.27	0.342425	0.15		0.97635	0.2		0.97635	0.05		0.97635	0.05	7.52
0.227889	0.102778	7.33	0.330416	0.154167		0.97635	0.205556		0.97635	0.051389		0.97635	0.051389	7.63
0.206829	0.105556	7.44	0.307498	0.158333		0.97635	0.211111		0.97635	0.052778		0.97635	0.052778	7.72
0.187524	0.108333	7.52	0.290037	0.1625		0.97635	0.216667		0.97635	0.054167		0.97635	0.054167	7.8
0.16732	0.111111	7.61	0.269515	0.166667		0.97635	0.222222		0.97635	0.055556		0.97635	0.055556	7.88
0.146131	0.113889	7.67	0.255275	0.170833		0.97635	0.227778		0.97635	0.056944		0.97635	0.056944	7.95
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0.97635	0.122222	7.88	0.2014	0.183333		0.97635	0.244444		0.97635	0.061111		0.97635	0.061111	
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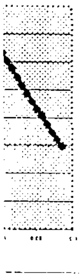

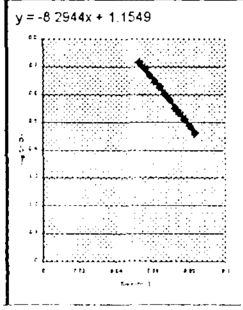

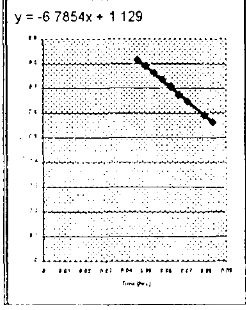

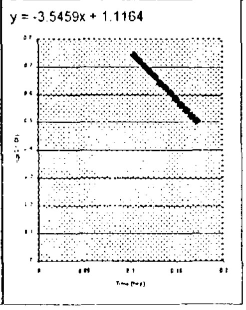

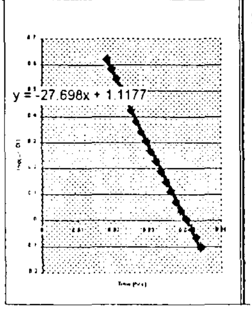

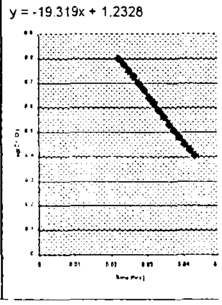

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	-11.8			-5.1			-3		
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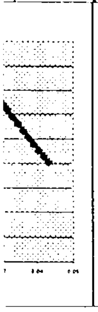
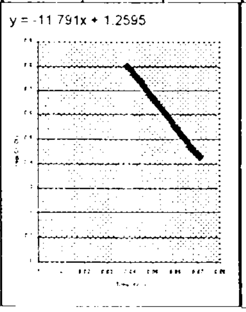
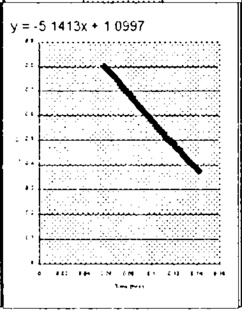
	27.49957			11.7453			6.909		
	19.5			20			20		
	32			32			32		
log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)	Time (hrs)	D.O. (mgO/l)	log(Cs-Cl) (mgO/l)
0.963788	0.001389	0.07	0.973128	0.002778	0.22	0.961525	0.008333	0.36	0.954831
0.960947	0.002778	0.1	0.97174	0.005556	0.24	0.960575	0.016667	0.48	0.949009
0.957129	0.004167	0.12	0.970812	0.008333	0.27	0.959146	0.025	0.65	0.940626
0.951338	0.005556	0.15	0.969416	0.011111	0.3	0.957712	0.033333	0.9	0.927996
0.947434	0.006944	0.2	0.96708	0.013889	0.32	0.956754	0.041667	1.23	0.910742
0.941015	0.008333	0.23	0.965672	0.016667	0.38	0.953866	0.05	1.64	0.888303
0.934499	0.009722	0.24	0.965202	0.019444	0.45	0.950472	0.058333	1.96	0.869947
0.926857	0.011111	0.28	0.963316	0.022222	0.54	0.946069	0.066667	2.34	0.847091
0.918555	0.0125	0.32	0.961422	0.025	0.62	0.942117	0.075	2.63	0.828801
0.907412	0.013889	0.39	0.958086	0.027778	0.75	0.935618	0.083333		
0.893207	0.015278	0.45	0.955207	0.030556	0.88	0.92902	0.091667	3.36	0.779033
0.876218	0.016667	0.52	0.951824	0.033333	1.07	0.919193	0.1	3.7	0.753751
0.859139	0.018056	0.58	0.948902	0.036111	1.27	0.908603	0.108333	4.02	0.728532
0.83885	0.019444	0.69	0.943495	0.038889	1.44	0.899393	0.116667	4.33	0.70262
0.821514	0.020833	0.78	0.93902	0.041667	1.68	0.88605	0.125	4.63	0.67598
0.799341	0.022222	0.89	0.933488	0.044444	1.89	0.874029	0.133333	4.9	0.650521
0.775247	0.023611	1.02	0.926857	0.047222	2.11	0.861068	0.141667		
0.750509	0.025	1.13	0.921167	0.05	2.38	0.844614	0.15	5.37	0.602298
0.726728	0.026389	1.29	0.912754	0.052778	2.59	0.83137	0.158333	5.57	0.580035
0.698971	0.027778	1.43	0.905257	0.055556	2.83	0.815724	0.166667	5.74	0.560169
0.672099	0.029167	1.58	0.897076	0.058333	3.05	0.800868	0.175	5.91	0.539352
0.641475	0.030556	1.82	0.883662	0.061111	3.24	0.787616	0.183333		0.971841
0.619094	0.031944	2.05	0.870404	0.063889	3.42	0.774677	0.191667		0.971841
0.586588	0.033333	2.26	0.856729	0.066667	3.62	0.759834	0.2		0.971841
0.563482	0.034722	2.52	0.841985	0.069444	3.8	0.746026	0.208333		0.971841
0.53146	0.036111	2.72	0.829304	0.072222	3.99	0.73096	0.216667		0.971841
0.505151	0.0375	2.96	0.813582	0.075	4.17	0.716187	0.225		0.971841
0.480008	0.038889	3.16	0.80003	0.077778	4.36	0.700028	0.233333		0.971841
0.45332	0.040278	3.37	0.785331	0.080556	4.52	0.685938	0.241667		0.971841
0.428136	0.041667	3.61	0.767898	0.083333	4.69	0.67045	0.25		0.971841
0.404835	0.043056	3.81	0.752817	0.086111	4.84	0.656309	0.258333		0.971841
0.382019	0.044444	4	0.737988	0.088889	5.01	0.639705	0.266667		0.971841
0.359837	0.045833	4.21	0.720967	0.091667	5.12	0.628613	0.275		0.971841
0.336462	0.047222	4.43	0.702431	0.094444	5.3	0.609829	0.283333		0.971841
0.311756	0.048611	4.64	0.683948	0.097222	5.41	0.597936	0.291667		0.971841
0.290037	0.05	4.8	0.669318	0.1	5.55	0.582313	0.3		0.971841
0.26482	0.051389	4.96	0.654177	0.102778	5.66	0.569631	0.308333		0.971841
0.243041	0.052778	5.13	0.637491	0.105556	5.81	0.551718	0.316667		0.971841
0.222719	0.054167	5.29	0.621177	0.108333	5.93	0.536836	0.325		0.971841
0.2014	0.055556	5.45	0.604227	0.111111	6.02	0.525329	0.333333		0.971841
0.181846	0.056944	5.61	0.586588	0.113889	6.15	0.508152	0.341667		0.971841
0.158365	0.058333	5.75	0.570544	0.116667	6.23	0.497233	0.35		0.971841
0.97635	0.059722	5.89	0.553684	0.119444	6.31	0.486033	0.358333		0.971841
0.97635	0.061111	6.01	0.539077	0.122222	6.43	0.468672	0.366667		0.971841
0.97635	0.0625	6.14	0.522446	0.125	6.49	0.459724	0.375		0.971841
0.97635	0.063889	6.27	0.505151	0.127778	6.6	0.442824	0.383333		0.971841
0.97635	0.065278	6.38	0.48996	0.130556	6.68	0.430107	0.391667		0.971841
0.97635	0.066667	6.51	0.471293	0.133333	6.76	0.417006	0.4		0.971841
0.97635	0.068056	6.61	0.456368	0.136111	6.84	0.403497	0.408333		0.971841
0.97635	0.069444	6.7	0.442481	0.138889	6.91	0.391323	0.416667		0.971841
0.97635	0.070833	6.79	0.428136	0.141667	6.99	0.376977	0.425		0.971841
0.97635	0.072222	6.89	0.411621	0.144444	7.03	0.369623	0.433333		0.971841
0.97635	0.073611	6.99	0.394453	0.147222		0.971841	0.441667		0.971841
0.97635	0.075	7.08	0.3784	0.15		0.971841	0.45		0.971841
0.97635	0.076389	7.16	0.363614	0.152778		0.971841	0.458333		0.971841
0.97635	0.077778	7.23	0.35025	0.155556		0.971841	0.466667		0.971841
0.97635	0.079167	7.3	0.336462	0.158333		0.971841	0.475		0.971841
0.97635	0.080556	7.36	0.324284	0.161111		0.971841	0.483333		0.971841
0.97635	0.081944	7.41	0.313869	0.163889		0.971841	0.491667		0.971841
0.97635	0.083333	7.46	0.303198	0.166667		0.971841	0.5		0.971841
0.97635	0.084722	7.51	0.292256	0.169444		0.971841	0.508333		0.971841

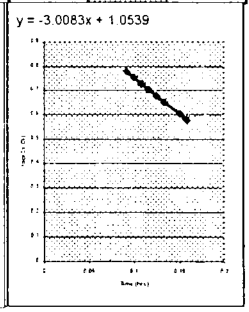




y = -11.791x + 1.2595



y = -5.1413x + 1.0997



y = -3.0083x + 1.0539

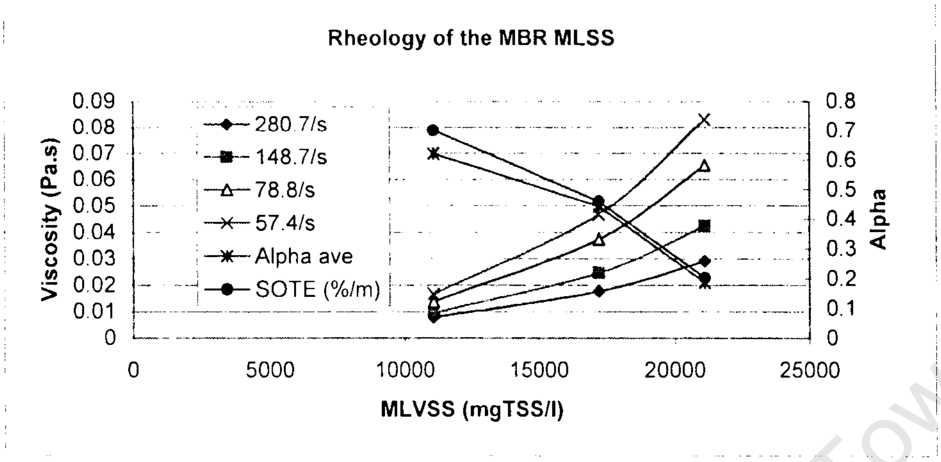
Appendix F-3: Summarized Rheology Results

Rheology readings

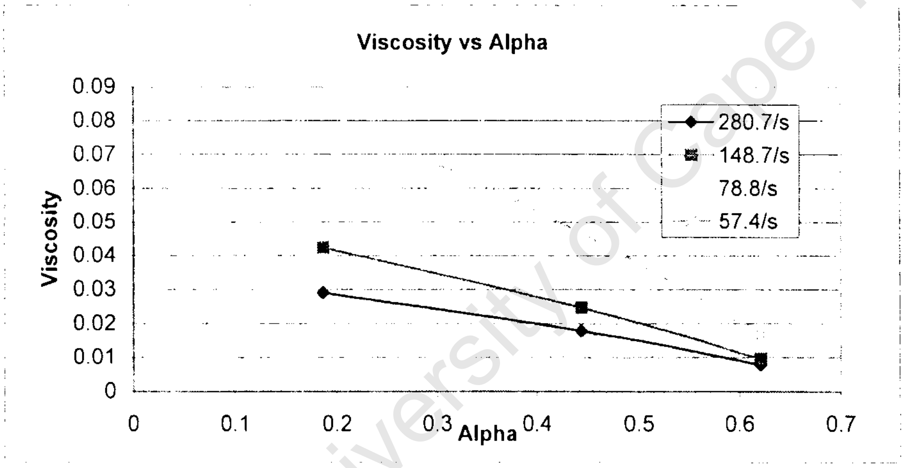
tested: 14 August 2006

Sample ID	Viscosity @ shear rate				MLSS	Ave Alpha	SOTE
#	280.7/s	148.7/s	78.8/s	57.4/s	mgTSS/l		%/m
A	0.0291	0.04239	0.06547	0.0831	21096	0.186	0.203
B	0.0178	0.0247	0.0373	0.0468	17232	0.444	0.46
C	0.0079	0.0096	0.0138	0.0166	11070	0.621	0.701
D	0.00537	0.0029	0.0015	0	n/a	n/a	n/a

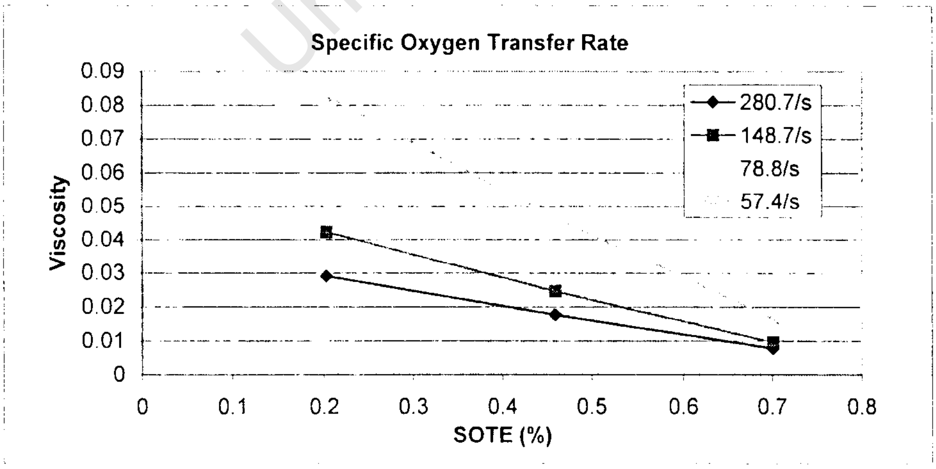
Plot A



Plot B



Plot C



Appendix F-4: Rheometric Testing

Data Series Information

Name:	Sample A 1
Sample:	Sample A
Operator:	VGF & GS
Remarks:	Received 15 Aug 2006
Number of Intervals:	1
Application:	US200/32 V2.43 21001629-33024
Device:	MC1+ SN701754
Measurement Date:	8/15/2006
Measurement Time:	16:38 PM
Measuring Systems:	Z2 DIN (45mm)

Calculating Constants:	
- Csr:	1.2946486
- Css:	3.9172248
- Start Delay Time [s]:	2.924
- Measurement Type:	2

Interval:	1
Number of Data Points:	30

Time Setting:	30 Meas. Pts. Meas. Pt. Duration 5 s

Measuring Profile:	
Shear Rate	d(gamma)/dt = 1E+3 ... 0.1 1/s Log

Meas. Pts.	Shear Rate [1/s]	Shear Stre [Pa]	Viscosity [Pa·s]	Speed [1/min]	Torque [µNm]	Status []
1	1,000	23.08	0.02308	772.6	5,892	M-M+
2	727.9	15.51	0.0213	562.2	3,959	M-
3	529.8	11.66	0.02201	409.2	2,977	M-
4	385.6	9.627	0.02497	297.9	2,458	M-
5	280.7	8.179	0.02914	216.8	2,088	M-
6	204.3	7.124	0.03486	157.8	1,819	M-
7	148.7	6.304	0.04239	114.9	1,609	M-
8	108.3	5.674	0.05241	83.61	1,448	M-
9	78.8	5.159	0.08547	60.87	1,317	M-
10	57.36	4.764	0.08305	44.3	1,216	M-
11	41.74	4.448	0.1066	32.24	1,135	M-
12	30.39	4.188	0.1378	23.47	1,069	M-
13	22.12	3.919	0.1772	17.08	1,000	M-
14	16.1	3.767	0.2339	12.44	961.5	
15	11.72	3.591	0.3065	9.05	916.7	
16	8.534	3.477	0.4074	6.592	887.6	
17	6.214	3.366	0.5416	4.8	859.2	
18	4.515	3.261	0.7223	3.488	832.5	
19	3.291	3.141	0.9544	2.542	801.9	
20	2.39	2.992	1.252	1.846	763.8	
21	1.748	2.877	1.646	1.35	734.4	
22	1.271	2.739	2.155	0.9818	699.1	
23	0.9116	2.519	2.764	0.7042	643.2	
24	0.6689	2.448	3.66	0.5167	624.9	
25	0.4909	2.114	4.307	0.3792	539.8	M-
26	0.3834	1.966	5.128	0.2962	501.9	M-
27	0.383	1.855	4.843	0.2958	473.5	M-
28	0.3938	1.816	4.611	0.3042	463.5	M-
29	0.3884	1.618	4.165	0.3	413	M-
30	0.3938	1.554	3.947	0.3042	396.8	M-

Name:	Sample B 1
Sample:	Sample B
Operator:	VGF & GS
Remarks:	Received 15 Aug 2006
Number of Intervals:	1
Application:	US200/32 V2.43 21001629-33024
Device:	MC1+ SN701754
Measurement Date:	8/15/2006
Measurement Time:	16:53 PM
Measuring Systems:	Z2 DIN (45mm)

Calculating Constants:	
- Csr:	1.294649
- Css:	3.917225
- Start Delay Time [s]:	1.342
- Measurement Type:	2

Interval:	1
Number of Data Points:	30

Time Setting:	30 Meas. Pts. Meas. Pt. Duration 5 s

Measuring Profile:	
Shear Rate	d(gamma)/dt = 1E+3 ... 0.1 1/s Log

Meas. Pts	Shear Rate [1/s]	Shear Stre [Pa]	Viscosity [Pa·s]	Speed [1/min]	Torque [µNm]	Status []
1	1,000	17.81	0.01781	772.5	4,548	M-M+
2	728	11.96	0.01644	562.2	3,054	M-
3	529.8	8.075	0.01524	409.2	2,061	M-
4	385.6	6.032	0.01564	297.9	1,540	M-
5	280.7	4.994	0.01779	216.8	1,275	M-
6	204.3	4.278	0.02094	157.8	1,092	M-
7	148.7	3.671	0.02468	114.9	937	M-
8	108.3	3.267	0.03018	83.62	834	M-
9	78.81	2.935	0.03724	60.88	749	M-
10	57.37	2.683	0.04676	44.31	685	M-
11	41.75	2.49	0.05963	32.25	636	M-
12	30.39	2.345	0.07715	23.48	599	M-
13	22.12	2.211	0.09995	17.09	565	M-
14	16.1	2.086	0.1296	12.43	532.6	M-
15	11.72	1.975	0.1685	9.055	504.3	M-
16	8.534	1.908	0.2236	6.592	487.1	M-
17	6.214	1.832	0.2949	4.8	467.8	M-
18	4.52	1.834	0.4058	3.492	468.2	M-
19	3.291	1.712	0.5201	2.542	436.9	M-
20	2.39	1.665	0.6968	1.846	425.1	M-
21	1.742	1.563	0.8969	1.346	399	M-
22	1.268	1.555	1.227	0.9792	396.9	M-
23	0.917	1.45	1.581	0.7083	370.2	M-
24	0.6851	1.439	2.101	0.5292	367.5	M-
25	0.4963	1.384	2.789	0.3833	353.4	M-
26	0.4046	1.528	3.778	0.3125	390.2	M-
27	0.3884	1.281	3.299	0.3	327.1	M-
28	0.3884	1.181	3.042	0.3	301.6	M-
29	0.3825	1.03	2.693	0.2955	263	M-
30	0.3884	0.9426	2.427	0.3	240.6	M-

Name:	Sample C 1
Sample:	Sample C
Operator:	VGF & GS
Remarks:	Received 15 Aug 2006
Number of Intervals:	1
Application:	US200/32 V2.43 21001629-33024
Device:	MC1+ SN701754
Measurement Date:	8/15/2006
Measurement Time:	17:03 PM
Measuring Systems:	Z2 DIN (45mm)

Calculating Constants:	
- Csr:	1.294649
- Css:	3.917225
- Start Delay Time [s]:	4.005
- Measurement Type:	2

Interval:	1
Number of Data Points:	21

Time Setting:	30 Meas. Pts. Meas. Pt. Duration 5 s

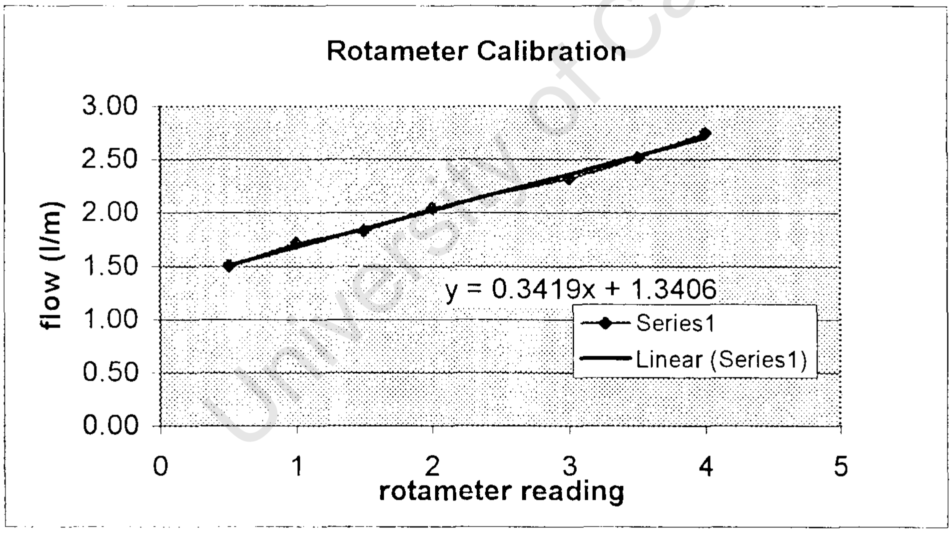
Measuring Profile:	
Shear Rate	d(gamma)/dt = 1E+3 ... 0.1 1/s Log

Meas. Pts.	Shear Rate [1/s]	Shear Stre [Pa]	Viscosity [Pa·s]	Speed [1/min]	Torque [µNm]	Status []
1	1,000	11.72	0.01172	772.5	2,993	M-M+
2	727.9	7.566	0.01039	562.2	1,931	M-
3	529.8	5.004	0.009444	409.2	1,277	M-
4	385.6	3.494	0.00906	297.9	892	M-
5	280.7	2.223	0.007918	216.8	567.4	M-
6	204.3	1.736	0.008498	157.8	443.3	M-
7	148.7	1.43	0.009615	114.9	365	M-
8	108.3	1.234	0.01139	83.62	314.9	M-
9	78.8	1.091	0.01384	60.87	278.5	M-
10	57.37	0.9514	0.01658	44.32	242.9	M-
11	41.75	0.8882	0.02128	32.25	226.8	M-
12	30.4	0.8115	0.0267	23.48	207.2	M-
13	22.13	0.6832	0.03088	17.09	174.4	M-
14	16.11	0.5863	0.0364	12.44	149.7	M-
15	11.72	0.5564	0.04747	9.054	142	M-
16	8.539	0.592	0.06933	6.596	151.1	M-
17	6.214	0.324	0.05214	4.8	82.71	M-
18	4.515	0.2894	0.06409	3.488	73.88	M-
19	3.285	0.4103	0.1249	2.537	104.8	M-
20	2.39	0.1668	0.0698	1.846	42.58	M-
21	1.742	0.2762	0.1585	1.346	70.5	M-
22	1.265	0.7315	0.5781	0.9773	186.7	M-
23	0.917	0.6002	0.6544	0.7083	153.2	M-
24	0.6797	0.5657	0.8323	0.525	144.4	M-
25	0.4801	0.5624	1.172	0.3708	143.6	M-
26	0.3834	0.5629	1.468	0.2962	143.7	M-
27	0.383	0.6251	1.632	0.2958	159.6	M-
28	0.3938	0.6405	1.626	0.3042	163.5	M-

Rotameter Calibration

Method: A five litre calibrated bucket is filled with water and held upside down under water. The rotameter is set at a certain value and for a set period of time flow is directed into the bucket, then removed. The bucket is lifted until the inner level and outer level are the same. The volume displaced divided by the time it took is the flow in litres/second.

Rotameter Setting		0.5	1	1.5	2	3	3.5	4
5s	5	2000	2400	2550	2800	3250	3500	3750
	5	2100	2400	2600	2900	3200	3500	3800
	5	2200	2450	2600	2800	3200	3500	3900
ave flow (l/m)		25.2	29.0	31.0	34.0	38.6	42.0	45.8
7s	7					4500	4900	
	7					4600	4900	
	7					4500	4900	
ave flow (l/m)						38.9	42.0	
8s	8			4000	4550			
	8			4000	4600			
	8			4000	4500			
ave flow (l/m)				30.0	34.1			
10s	10	4100	4750					
	10	4200	4700					
	10	4200	4600					
		25.0	28.1					
ave flow (l/m)		25.1	28.6	30.5	34.1	38.7	42.0	45.8
ave flow (m3/h)		1.51	1.71	1.83	2.04	2.32	2.52	2.75



APPENDIX G

40 DAY LONG SLUDGE AGE MBR DAILY MEASUREMENTS

TABLE OF CONTENTS

40 Day Sludge Age Daily Measurements

	batch		COD			TKN			FSA		TSS			VSS			Qi	Qw	OUR	NO3				NO2				P					Recycles		COD/VSS	TKN/VSS
Day	batch		Inf	Aer	Eff	Inf	Aer	Eff	Inf	Eff	AN	AX	AE	AN	AX	AE	(l)	(l)	mgO/l/hr	AN	AX	AE	E	AN	AX	AE	E	INF	AN	AX	AE	EFF	a	r	fcv	fN
1	19-Sep-06	Batch 1	983.7	17649.3	24.3	107.5	1010.8	2.3	79.4	2.0	6568	17276	16696	5676	15664	15630	80	1.5	64.9	0.0	0.0	5.7	10.7	0.0	0.0	0.8	0.5	31.9	68.4	88.1	29.4	13.5	3.00	1.20	1.13	0.06
2	20-Sep-06		980.0	12386.9	18.2	115.8	991.2	2.1	81.8	2.9	6238	13002	15366	5282	10528	12442	80	1.5	65.8	0.0	0.0	6.9	12.1	0.0	0.0	1.1	2.3	35.1	69.4	51.9	14.1	15.7	3.00	1.20	0.99	0.08
3	21-Sep-06		1157.7	16353.9	28.3	105.1	949.2	2.0	82.5	1.5	6876	17940	14806	5972	14962	12128	80	1.5	61.2	0.0	0.0	0.0	3.6	0.0	0.0	2.5	1.5	41.6	78.4	46.3	10.4	14.1	3.00	1.20	1.35	0.08
4	22-Sep-06		1113.2	16434.9	32.4	101.5	963.2	2.2	74.5	1.2	7304	17722	16780	5980	14326	15758	80	1.5	66.5	0.0	0.0	4.1	7.2	0.0	0.0	1.4	0.5	44.4	72.5	55.0	8.5	10.7	3.00	1.20	1.04	0.06
5	23-Sep-06		1303.5	18216.0	12.1	99.0	1190.0	0.8	71.0	1.9	4331	14172	16034	3741	11852	12672	80	1.5	86.9	0.0	0.0	0.0	11.3	0.0	0.1	2.6	0.4	47.5	80.9	34.7	11.6	12.3	3.00	1.20	1.44	0.09
6	24-Sep-06		1218.4	18216.0	26.3	102.9	1092.0	0.6	78.7	2.5	6870	17798	17944	5748	13274	12688	80	1.5	72.2	0.0	0.0	1.8	11.5	0.0	0.0	3.8	1.6	60.6	92.8	69.1	32.9	13.5	3.00	1.20	1.43	0.09
	Average		**1126.1**	**16542.8**	**23.6**	**105.3**	**1032.7**	**1.7**	**78.0**	**2.0**	**6364**	**16318**	**16271**	**5400**	**13434**	**13553**	**80**	**1.5**	**69.6**	0.0	**0.0**	**3.1**	**9.4**	**0.0**	**0.0**	**2.1**	**1.1**	**53.5**	**94.7**	**70.9**	**16.0**	**14.5**	**3.0**	**1.2**	**1.230**	**0.077**
8	26-Sep-06	Batch 2	1303.5	15220.5	26.3	99.8	1024.8	0.5	73.5	0.2	6138	14834	17702	5318	12298	14340	80	1.5	74.0	0.0	0.3	5.6	12.6	0.0	0.1	5.6	2.3	45.0	79.6	59.4	17.6	13.5	3.00	1.20	1.06	0.07
9	27-Sep-06		1181.4	18708.5	60.5	126.1	1044.4	2.0	86.4	0.3	6866	12230	18170	5776	9886	14578	80	1.5	97.0	0.0	0.9	11.5	22.3	0.0	0.1	12.3	1.1	35.8	65.6	47.1	15.9	17.5	3.00	1.20	1.28	0.07
10	28-Sep-06		1201.5	18869.8	40.3	129.9	1075.2	1.9	102.5	0.8	6620	14570	18486	5600	11838	15664	80	1.5	75.5	0.0	0.0	0.0	23.1	0.0	0.1	1.3	0.2						3.00	1.20	1.20	0.07
11	29-Sep-06		1153.2	19998.7	20.2	130.9	1061.2	1.9	93.4	0.7	7748	13912	18988	6498	11486	15470	80	1.5	78.6	0.0	0.2	18.2	21.3	0.0	0.1	3.7	1.3	38.9	63.3	68.8	20.3	15.4	3.00	1.20	1.29	0.07
12	30-Sep-06		1229.8	19514.9	44.4	130.6	1248.8	1.8	111.4	1.6	6956	14518	19468	5836	12024	15328	80	1.5	87.5	0.0	0.0	0.0	25.4	0.0	0.3	1.0	0.2	36.3	61.5	34.7	17.2	18.8	3.00	1.20	1.27	0.08
13	**Average**		**1213.9**	**18462.5**	**38.3**	**123.5**	**1090.9**	**1.6**	**93.4**	**0.7**	**6866**	**14013**	**18563**	**5806**	**11506**	**15076**	**80**	**1.5**	**82.5**	0.0	**0.3**	**7.1**	**20.9**	**0.0**	**0.1**	**4.8**	**1.0**	**37.8**	**89.8**	**100.6**	**67.4**	**20.8**	**3.0**	**1.2**	**1.221**	**0.072**
16	4-Oct-06	Batch 3	1096.0	16400.0	14.0	127.1	1134.0	2.1	102.8	0.7	7192	12870	15150	5966	10392	11592	80	1.5	92.7	0.0	0.2	13.1	28.7	0.0	0.2	4.8	0.2	37.2	70.1	62.8	30.2	18.1	3.00	1.20	1.41	0.10
17	5-Oct-06		1108.0	20880.0	14.0	123.1	1103.2	2.2	103.0	0.4	7182	11656	15776	6048	9516	12688	80	1.5	85.8	0.0	0.0	0.0	17.9	0.0	0.2	1.7	0.9	53.3	85.0	49.1	23.4	25.2	3.00	1.20	1.64	0.09
18	6-Oct-06		1088.0	16320.0	26.0	119.8	1187.2	1.5	99.4	0.2	6730	13072	14282	5708	10604	11266	80	1.5	88.1	0.0	1.9	20.8	19.2	0.0	0.1		0.2	52.7	99.8	56.6	28.6	19.5	3.00	1.20	1.45	0.11
19	7-Oct-06		1028.0	16800.0	32.0	111.3	1005.2	2.2	102.9	0.2	7464	12056	15132	6253	10056	12948	80	1.5	86.8	0.0	0.0	6.1	17.9	0.0	0.1		0.3	41.6	82.6	41.6	20.7	18.0	3.00	1.20	1.30	0.08
20	8-Oct-06						0.0	0.0		0.0																		45.8	83.8	103.5	15.9	18.6				
21	9-Oct-06		1012.0	18000.0	40.0	125.0	1195.6	0.4	105.6	0.1	6404	13054	14660	5302	10596	11680	80	1.5	79.8	0.0	1.7	28.2	34.1	0.0	0.1		0.1	36.4	47.9	30.4	13.2	15.0	3.00	1.20	1.54	0.10
22	10-Oct-06		1024.0	18080.0	38.0	114.8	1262.8	1.3	93.2	0.5	6200	11910	15622	5212	9772	12598	80	1.5	88.1	0.0	1.7	26.4	30.3	0.0	0.1	1.3	0.1						3.00	1.20	1.43	0.10
23	**Average**		**1059.3**	**17746.7**	**27.3**	**120.2**	**1148.0**	**1.6**	**101.2**	**0.4**	**6862**	**12436**	**15104**	**5748**	**10156**	**12129**	**80**	**1.5**	**86.9**	0.0	**0.9**	**15.8**	**24.7**	**0.0**	**0.1**	**2.6**	**0.3**	**44.5**	**78.2**	**57.3**	**22.0**	**19.1**	**3.0**	**1.2**	**1.462**	**0.095**
25	15-Oct-06	Batch 4	1189.4	18144.0	32.3	132.3	1111.6	2.9	102.2	0.4	5810	12318	17220	5044	10088	13668	80	1.5	99.3	0.0	0.0	15.5	23.7	0.0	0.1	2.3	1.2						3.0	1.2	1.33	0.08
26	16-Oct-06		1181.4	17660.2	50.4	123.9	1190.0	2.2	106.4	1.8	6232	12490	15714	5268	10124	12438	80	1.5	82.1	0.0	0.0	16.0	20.1	0.0	0.0	1.5	0.8						3.0	1.2	1.42	0.10
27	17-Oct-06		999.9	19998.7	42.3	132.7	1131.2	3.1	98.8	1.3	5790	13912	17312	4872	11486	13892	80	1.5	86.0	0.0	0.1	23.0	26.3	0.0	0.1	2.0	0.7						3.0	1.2	1.44	0.08
28	18-Oct-06		923.3	19031.0	28.2	108.2	1290.8	2.9	89.9	0.8	5046	12280	15630	4376	10298	12554	80	0.0	85.5	0.0	0.0	18.4	27.5	0.0	0.0	1.6	0.9						3.0	1.2	1.51	0.10
30	20-Oct-06		840.3	20442.4	50.5	114.4	1066.8	2.0	90.4	0.6	6378	12826	19006	5240	10252	14432	80	1.5	108.7	0.0	0.0	17.5	22.3	0.0	0.1	3.1	1.7						3.0	1.2	1.41	0.07
31	21-Oct-06		812.0	16887.2	44.4	129.8	910.0	0.3	91.4	0.1	5360	9862	16230	4460	7996	12832	80	1.5	113.4	0.0	0.0	17.2	34.0	0.0	0.1	1.7	0.8						3.0	1.2	1.31	0.07
32	22-Oct-06		824.2	17776.0	48.5	115.6	985.6	2.0	97.4	0.6	4248	9680	16420	3670	7950	13024	80	1.5	117.9	0.0	0.2	19.6	37.6	0.0	0.1	5.1	0.8						3.0	1.2	1.36	0.08
33	**Average**		**967.2**	**18562.8**	**42.4**	**122.4**	**1098.0**	**2.2**	**96.7**	**0.8**	**5552**	**11910**	**16790**	**4704**	**9742**	**13263**	**80**	**1.3**	**99.0**	**0.0**	**0.0**	**18.2**	**27.4**	**0.0**	**0.1**	**2.5**	**1.0**						**3.0**	**1.2**	**1.40**	**0.08**