35

UNIVERSITY OF CAPE TOWN
Department of Civil Engineering
Water Research Group

THE EFFECT OF A LARGE ANOXIC MASS FRACTION AND CONCENTRATIONS OF NITRATE AND NITRITE IN THE PRIMARY ANOXIC ZONE ON LOW F/M FILAMENT BULKING IN NUTRIENT REMOVAL ACTIVATED SLUDGE SYSTEMS

by

Eustina V. Musvoto
BSc. Engineering (Hons.)-Civil
University of Zimbabwe.

Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Engineering at the University of Cape Town.

September, 1992

DECLARATION BY CANDIDATE

I

EUSTINA VONGAI MUSVOTO

hereby declare that this thesis is my own work and has not been submitted for a degree at another University.

September 1992

SYNOPSIS

Two surveys on South African plants by Blackbeard *et al*. in 1986 and 1988 showed that filamentous bulking is a major problem in nutrient removal activated sludge systems. Controlling the proliferation of filamentous organisms by keeping the DSVI of the sludge to relatively low values (<100 mℓ/g) would permit significantly higher flows (50 to 100%) to be treated in existing plants resulting in huge capital savings. The possibility of such savings has been the motivation behind the research into the control of low F/M filament bulking.

The two surveys indicated that the principal filaments causing bulking are the so called low F/M (Food/micro-organism ratio) ones (Jenkins *et al*., 1984). Work by Gabb *et al*. (1989a) showed that the selector effect which was the promoted specific control procedure for low F/M filament bulking, did not control low F/M filament bulking. This finding prompted a comprehensive follow-up research programme into the causes and control of low F/M filament bulking in nitrogen (N) and nutrient (N&P) removal plants. Completed research in this programme has shown that in fully aerobic and in fully anoxic systems, low F/M filament bulking was ameliorated but that in intermittently aerated N removal systems, low F/M filament bulking tended to be promoted, a phenomenon exacerbated as the anoxic mass fraction increased. It was observed that the periods of poor settleability were associated with high concentrations of nitrate and nitrite in the anoxic zone immediately before the aerobic zone.

The research presented in this thesis focuses on the effect of the magnitude of the (1) anoxic mass fraction and (2) nitrate and nitrite concentrations in the anoxic zone immediately before the aerobic zone on low F/M filament bulking in N&P removal MUCT systems. Accordingly two MUCT N&P removal systems , MUCT1 and MUCT2 each with 15% anaerobic, 65% anoxic and 20% aerobic mass fractions, were set up. Both systems were operated identically except that nitrate was dosed to the second anoxic reactor of MUCT1 for a period of time and nitrite to MUCT2 for a period of time: MUCT1 was operated for 340 days and nitrate was dosed to the second anoxic

5. In the MUCT1 system, which received the nitrate dose:

   5.1 Before dosing of nitrate, the DSVI of the sludge decreased from a start up value of 164 to 80 mℓ/g in 128 days. The nitrate and nitrite concentrations in the outflow of the second anoxic reactor were very low i.e <0,5 mgNO_3-N/ℓ and <0,2 mgNO_2-N/ℓ. The dominant filaments were of the low F/M type i.e. 0092 and 0914 with 021N as the secondary filament and 0041, *Microthrix parvicella, H.hydrossis* and 0803 present as incidental filaments. The presence of 021N, which normally occurs due to septic wastewaters, was found to be an artefact caused by the sewage turning septic in the storage tanks due to cold room malfunction and to improper cleaning of the transport container.

   5.2 Upon dosing 720 mgNO_3-N/d (equivalent to 72 mgN/ℓ influent, effectively increasing the influent TKN/COD ratio to 0,16 mgN/mgCOD) to the second anoxic reactor, the DSVI increased slowly reaching 176 mℓ/g in 111 days. The nitrate and nitrite concentrations in the outflow of the second anoxic reactor increased from <0,5 mgNO_3-N/ℓ and <0,2 mgNO_3-N/ℓ respectively to between 2 and 10 mgNO_3-N/ℓ and between 1,5 and 3 mgNO_2-N/ℓ respectively. The increase in nitrite concentration with nitrate dosing is acceptable because in this investigation as well as in those of Clayton *et al.* (1989) and Stern and Marais (1974), it was found that nitrite is formed at a slow rate 0,060 mgNO_2-N/(mgAVSS.d) while nitrate is being denitrified, and that only when the nitrate concentration reaches low values (< 1 mgNO_3-N/ℓ) does nitrite removal commence. The same dominant filaments, i.e. 0092 and 0914 were identified with *M.parvicella* and 0041 as secondary filaments and 0803, 021N and H.hydrossis present as incidental filaments.

   5.3 After cessation of nitrate dosing the DSVI declined from 176 to 91 mℓ/g in 69 days. A few days after cessation of nitrate dosing the nitrate and nitrite concentrations in the outflow of the second anoxic reactor decreased to similarly low values (<0,5 $mgNO_3$-N/ℓ and <0,2 $mgNO_2$-N/ℓ respectively) as observed earlier before nitrate dosing. The same low F/M filaments identified earlier as dominant were present.

6. In the MUCT2 system, which received the nitrite dose:

    6.1 Before nitrite dosing, the DSVI decreased slowly from a start up value of 131 to 90 mℓ/g in 118 days. The concentrations of nitrate and nitrite in the outflow of the second anoxic reactor were very low <0,2 $mgNO_2$-N/ℓ and <0,7 $mgNO_3$-N/ℓ. The filamentous organisms identified as dominant were of the low F/M type namely 0092 with 021N, 0041 and *H.hydrossis* as the secondary filaments and *M.parvicella*, 0041, *H.hydrossis* and 021N also present as incidental filaments.

    6.2 Upon dosing 900 $mgNO_2$-N/d (equivalent to 90 mgN/ℓ influent effectively increasing the influent TKN/COD ratio to 0,17 mgN/mgCOD) to the second anoxic reactor the DSVI initially increased sharply from 90 to 116 mℓ/g in 11 days and thereafter more slowly reaching 174 mℓ/g, 39 days later. The nitrite and nitrate concentrations in the outflow of the second anoxic reactor increased from <0,2 $mgNO_2$-N/ℓ and <0,7 $mgNO_3$-N/ℓ respectively to between 10 and 20 $mgNO_2$-N/ℓ and to between 0,5 and 3 $mgNO_3$-N/ℓ respectively. The increase in nitrate concentrations in the second anoxic reactor during nitrite dosing was surprising and could only be caused by (1) errors in the analytical procedure when nitrite is the principal NO_x^- species in the NO_2^- and NO_3^- determination or (2) a reduction in the nitrate denitrification rate in the presence of high concentrations of nitrite. The possibility of the later cause was tested in a batch test and it was found that high nitrite concentrations (10-20 $mgNO_2$-N/ℓ) do not interfere with the nitrate denitrification rate; however, significant nitrite denitrification does not commence until nitrate denitrification is virtuallly complete. From this it was concluded that the increase in nitrate concentration was an artefact and the cause for the increase in DSVI is increased nitrite concentration which occured also with nitrate dosing (see 5.2 above). The dominant filaments identified were the same low F/M ones namely 0092, with 021N as the secondary filament and *M.parvicella* present as the incidental filament.

6.3 Because the nitrite concentration entering the aerobic reactor in MUCT2, (in which the DSVI increased relatively fast) was higher than in MUCT1, (in which the DSVI increased relatively slowly), it appears that the higher the nitrite concentration entering the aerobic zone, the faster the low F/M filament proliferation.

6.4 The response to nitrite dosing cessation was not studied.

From the above observations it would appear that low and high concentrations of nitrite in the anoxic reactor before the aerobic reactor ameliorate and promote bulking caused by low F/M filaments respectively. The anoxic mass fraction in itself does not affect low F/M filament bulking but it affects the concentration of nitrate and nitrite in the anoxic reactor before the aerobic reactor. This provides strong supporting evidence for the cause of low F/M filament bulking in N and N&P removal systems proposed by Casey *et al.* (1992a,b).

ACKNOWLEDGEMENTS

I wish to express my appreciation and gratitude to the following:

- Professor George Ekama, my supervisor for his sustained interest and guidance during the laboratory investigation and write up.
- Mr Taliep Lakay, for his invaluable help in running the experimental system and laboratory investigation.
- Professor G v R Marais for his support and interest throughout the investigation period.
- Dr M C Wentzel and T G Casey for sound advice both during the investigation period and write up.
- Mrs Mara Segal and Mrs Lee Boyd, principal and senior professional officers of the Johannesburg City Health Department at Cydna Laboratories for doing the filamentous organisms identifications.
- Messrs Eike von Geurard, Denis Botha and the Civil Engineering workshop staff for constructing, maintaining and servicing the laboratory equipment.

Acknowledgement is also due to the Beit Trust for financial support throughout the study period.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Filamentous bulking occurs when filamentous organisms are present in excessive numbers and extend from flocs into the bulk solution. They interfere with the compaction and settling of the activated sludge either by producing a very diffuse floc structure or by causing bridging between flocs. This results in a sludge with poor settleability i.e low settling velocity and low solids concentration in the return activated sludge (RAS). In severe cases overflow of the sludge with the effluent occurs. Bulking not only causes these problems in the activated sludge process, but it also causes poor dewaterability of the waste activated sludge. Clearly bulking not only adversely affects the efficiency of the secondary settling tank but also the efficiency of the sludge treatment units at the plant. While controlling or eliminating bulking at plants will certainly be beneficial for sludge handling, by far the most significant impact would be on the activated sludge process itself. It has been estimated that if the sludge settleability could be controlled at Diluted Sludge Volume Indices (DSVI) below 100 mℓ/g, 50 to 100% more wastewater could be treated in existing plants leading to enormous savings (Ekama and Marais, 1986a). This single factor is the principal driving motive behind the research to establish the causes and control of filamentous bulking.

With regard to the influence of filamentous organisms on sludge settleability, Lee *et al.* (1983) correlated the total extended filament length (TEFL) and settleability in terms of the DSVI and showed that filamentous organisms begin to dominate the settling behaviour of the sludge at TEFL longer than 30 km/g corresponding to a DSVI greater than 150 mℓ/g. On this basis therefore, a bulking sludge can be deemed as one with a DSVI > 150 mℓ/g. The traditional sludge volume index (SVI) is not as discriminating as the DSVI in identifying a bulking sludge due to its lack of consistency in relation to TEFL (Lee *et al.*, 1983) and to its acute sensitivity to solids concentration. However taking note of reported data it is roughly accepted that an SVI between 100 and 200 mℓ/g is possibly a bulking sludge and an SVI > 200 mℓ/g usually is.

From two surveys on South African plants by Blackbeard *et al.*, (1986, 1988) six filamentous organism types were identified as the major causes of bulking. In the first survey of mainly N removal plants, the six dominant filament types in decreasing order of frequency were type 0092 dominant in 34% of the plants, type 0914 in 24%, *Microthrix Parvicella* in 20%, type 1851 in 17%, type 0675 in 16% and type 0041 in 14%. Although in a different order, these six filaments were the most frequently dominant types in the second survey done in 1988 on 33 biological N&P removal plants, i.e. 0092 dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *M.parvicella* in 33%, 0914 in 33% and 1851 in 21%. Of the six most dominant filaments identified in South African plants, types 0092, *M.parvicella*, 0675 and 0041 are classified as low food/micro-organism (F/M) ratio which tend to proliferate in long sludge age plants (Jenkins *et al.*, 1984). Types 0914 and 1851 were also classified as low F/M by Blackbeard *et al.*, (1986, 1988) due to their frequency of appearance with the so called low F/M filaments.

Research into specific methods of controlling bulking caused by these filaments has received research attention at the University of Cape Town over the past eight years starting with a four year research programme by Gabb *et al.*, (1985-1988). In the work by Gabb *et al.*, (1989) which in particular examined the effect of aerobic, anoxic and anaerobic selectors on low F/M filaments, it was found that although aerobic and anoxic selectors were promoted as the specific method for low F/M filament control, these did not do so. This finding, details of which are given in Chapter 2, placed the bulking research back into an exploratory stage. Accordingly a comprehensive research programme was initiated in 1989 to develop specific control methods of low F/M filament bulking in N and N&P removal plants focusing on the influence on low F/M filament proliferation of the following parameters:

(1) the RBCOD and PBCOD fraction of the sewage
(2) alternating unaerated-aerated conditions
(3) fully aerobic and fully anoxic systems
(4) magnitude of the unaerated mass fraction and nitrate and nitrite concentration in the anoxic zone.
(5) sludge age

(6) different plant configurations

Casey *et al.* (1990,1991), Warburton *et al.* (1991), Ketley *et al.* (1991) and Hulsman *et al.* (1992) investigated *inter alia* the effect of the magnitude of the anoxic mass fraction and concentration of nitrate during the anoxic period in intermittently aerated and pre and post denitrification nitrogen removal systems. It was observed that in fully anoxic and in intermittently aerated N removal systems at low anoxic mass fractions (0-25%), and very high anoxic mass fractions (90-100%), low F/M filament bulking was ameliorated. Also in MUCT systems with low (<20%) and high (approximately 40%) anoxic mass fractions, the DSVI (and therefore the bulking by low F/M filaments) was low (<100 mℓ/g) and high (>200 mℓ/g) respectively (see Casey *et al.*, 1992c). Also, it was observed that the periods of poor settleability (high DSVI and therefore bulking) were associated with periods of high concentrations of nitrate and nitrite in the anoxic zone prior to the aerobic zone. Because (1) the anoxic mass fraction governs the degree of denitrification that can be achieved and therefore is linked to the nitrate and nitrite concentrations in the system, and (2) fully anoxic conditions did not bulk, it was decided to investigate the effect of very large (65%) anoxic mass fractions in MUCT N&P removal systems.

In accordance with the above, the research reported in this thesis investigates the influence of a large anoxic mass fraction (65%) in biological N&P removal MUCT systems on low F/M filament bulking in particular the effect of low and high nitrate and nitrite concentrations in the anoxic zone prior to the aerobic zone.

Chapter 2 of this thesis gives a comprehensive literature review so that the objectives of the investigation presented in this thesis can be placed in the context of the current status of the research into low F/M filament bulking in N and N&P removal systems. In Chapter 3 the experimental investigation is described in detail and in Chapter 4 the conclusions of the investigation are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 PREAMBLE

A comprehensive literature review into specific bulking control has recently been compiled by Casey *et al*(1992b) and it is not the intention in this chapter to do another separate review. Rather, for convenience to the reader, this review is presented in this chapter to allow the reader to place the objectives of the investigation presented in this thesis in context with the current status of the bulking research.

2.2 INTRODUCTION

There are two approaches to bulking control, (1) non-specific and (2) specific. With non-specific control some toxicant, usually chlorine, but ozone and hydrogen peroxide can also be used, is dosed into the activated sludge system. Because the filamentous organisms extend beyond the flocs into the liquid, they are more sensitive to the toxicant and therefore are selectively killed; in contrast the floc-formers survive the toxicant because they find protection inside the sludge flocs. By the selective killing of the filaments, their numbers are reduced and the bulking is ameliorated. The toxicant affects all the filaments irrespective of type and for this reason is called non-specific.

The principal non-specific bulking control procedure is by chlorination. This procedure is well documented in the literature such as in the bulking control manual of Jenkins *et al.* (1984). The method has been tested for biological N&P removal systems (Lakay *et al.*, 1988) and found to be satisfactory provided the guidelines set down by Jenkins *et al.* (1984) are followed. But chlorination has the drawback that undesirable compounds such as trihalomethanes and chlorinated hydrocarbons tend to form which pose a potential health risk. To reduce this van Leeuwen (1988) and van Leeuwen and Pretorius (1988) investigated the use of ozone for bulking control in an N&P removal pilot plant. They concluded ozonation successfully controls filamentous bulking and imparts a few additional benefits i.e. (1) improves the removal of organic substances, (2) aids nitrification and to some degree biological excess P removal (BEPR) and (3) produces an effluent that is more suitable for reuse than activated sludge treatment without ozonation. The problem with non-specific bulking control is that as soon as toxicant dosing ceases, the filaments regrow and inexorably bulking conditions return. This is because non-specific bulking control deals with the symptoms of bulking, i.e. reduces the filaments, but does not remove the causes of the filament proliferation on a permanent basis. With specific bulking control the causes of filament proliferation are sought to be eliminated on a permanent basis.

2.3 SPECIFIC BULKING CONTROL

Specific control of bulking focuses on identifying and eliminating the conditions that promote the proliferation of the specific nuisance filaments causing the bulking problem. Once the conditions are identified, through the types of filaments present in the sludge, it may be possible to create environmental conditions in the activated sludge plant such that the growth of filamentous organisms is inhibited or suppressed. If successful, the method provides a permanent solution to the particular bulking situation.

Five conditions in the activated sludge system have been identified that lead to filamentous organism proliferation (Jenkins *et al.*, 1984), viz. low DO, low Food to Micro-organism ratio (F/M or equivalently long sludge age), nutrient deficiency, septic influent and low pH; each condition favours the growth of certain filamentous organism types. From the surveys of activated sludge plants in South Africa (Blackbeard *et al.*, 1986, 1988) it was found that the most frequently dominant filamentous organisms in South African activated sludge plants belong to the low F/M group. This is not unexpected because most plants in South Africa are operated at long sludge ages (>15 days).

2.4 LOW F/M BULKING CONTROL - SOME BACKGROUND

2.4.1 Chudoba's selection criterion

Chudoba *et al.* (1973a) proposed an organism selection criterion as an explanation of the occurrence or non-occurrence of filamentous bulking. This criterion is based on competition between the floc-formers and the filaments for the mutually limiting soluble substrate, as follows: In the Monod formulation for the specific rate of growth of organisms, filamentous organisms have lower values for both the maximum specific growth rate (μH) and the half saturation coefficient (K_s) than floc-formers. Consequently at low substrate concentrations the filamentous organisms have a higher specific growth rate than floc-formers and at high substrate concentrations, a lower specific growth rate (Fig 2.1).

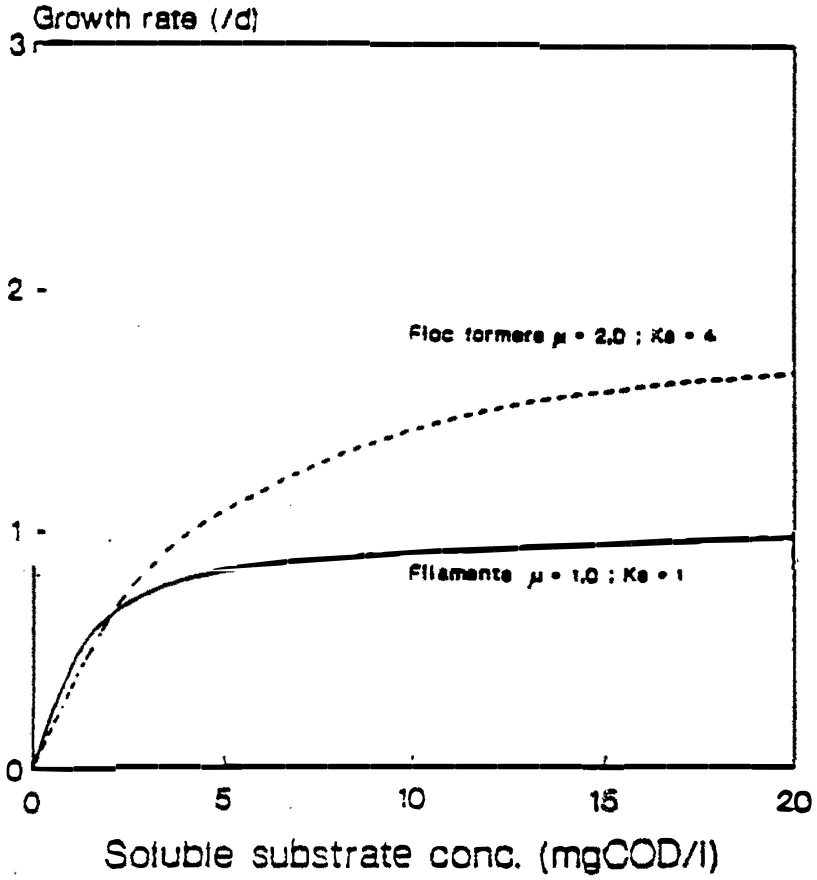


Fig 2.1 Monod specific growth rate functions for filaments and floc-forming organisms illustrating the selection criterion of Chudoba *et al.* (1973a).

Over the past 15 years the selection criterion has provided a framework for research into the causes of bulking and its control by specific methods. Results, reported by a number of investigators who have measured the Monod constants of various filaments and floc-formers, appear to fit within the structure of the selection criterion: van den Eynde *et al.* (1982a) showed that in general, organisms with high μ_H rates have high K_s values and ones with low μ_H rates have low K_s values. Slijkhuis (1983) measured the μ_H of *Microthrix parvicella* (one of the principal filaments causing low F/M bulking) to be 1,66/d; this is considerably lower than a μ_H of 4,33/d measured by Richard *et al.* (1981) for a floc-former isolated from activated sludge. Palm *et al.* (1980) extended the selection criterion to incorporate limiting nutrients: For some filaments (the low DO ones),the limiting nutrient is apparently oxygen whereas for others the limiting nutrient is the soluble substrate concentration surrounding the organism, as originally conceived by Chudoba *et al.* (1973a).

With regard to low DO bulking, Hao *et al.* (1983) and Lau *et al.* (1984) confirmed the work of Palm *et al.* (1980): From dual species studies they showed that low DO filaments (*Sphaerotilus natans*, Type 1701) and floc-formers can be selectively grown by manipulating the DO concentration: if high, the floc-former dominates, if low, the filament dominates.

With regard to bulking in long sludge age (low F/M) systems, Chudoba *et al.* (1973a,b) tested the selection criterion with pure soluble substrate: They controlled the substrate concentration surrounding the organism by having different configurations for the activated sludge system. For example, in a single reactor completely mixed system, the substrate concentration would be low throughout the reactor whereas in a multi-reactor plug flow system the substrate concentration would be high in the upstream section and low in the downstream section. They found that in aerobic single reactor completely mixed systems filamentous organisms proliferated causing bulking whereas in aerobic multi-reactor plug flow systems filamentous organisms did not proliferate and a good settling sludge was maintained. From this work, Chudoba *et al.* (1973b) developed the selector reactor for bulking control. The selector reactor is a small aerated reactor upstream of the main aerated reactor and receives the influent and underflow recycle. In the selector reactor, the substrate concentration is high and, in terms of the selection criterion, the floc-formers should grow faster than the filaments, and, usually will utilize practically all of the soluble substrate; the mass of soluble substrate that passes through the selector is a very small fraction of that available to the floc-formers in the selector so that filament growth will be restricted and insufficient to cause bulking. Although the filament categorization into 5 causative groups was not yet developed, -this only emerged in 1984 with the work of Jenkins *et al.* -it should be noted that even though the systems operated by Chudoba *et al.* (1973a,b) were long sludge age or low F/M ones, the filaments causing the bulking were not low F/M filaments: They were principally one of the low DO filaments, i.e *S.natans*.

The work by Chudoba *et al.* (1973a,b) stimulated research into the control of bulking in low F/M (long sludge age) systems. Most of this research was conducted on fully aerobic systems, at laboratory scale with real or synthetic sewage as influent. In this research it was found that good settling (non-bulking) was produced in systems with;

(1) compartmentalization of the aeration reactor while maintaining continuous feeding of waste water (Chudoba *et al.*, 1974; Rensink *et al.*, 1982; Wu *et al.*, 1984);

(2) batch or intermittent feeding to completely mixed aeration basins (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982a,b; Eikelboom, 1982; Rensik *et al.*, 1982; Goronszy, 1979; Goronszy and Barnes, 1979; Barnes and Goronszy, 1980; Chiesa and Irvine, 1982, 1985; Jenkins *et al.*, 1983; Ekama and Marais, 1986b; Still *et al.*, 1986; van Niekerk, 1985; van Niekerk *et al.*, 1987);

(3) small aerated mixing reactors (aerobic selectors) ahead of the main completely mixed aeration reactor, receiving the influent and underflow streams (Grau *et al.*, 1982; Lee *et al.*, 1982; Jenkins *et al.*, 1983; Daigger *et al.*, 1985; Still *et al.*, 1986; van Niekerk, 1985; van Niekerk *et al.*, 1987).

Like in the investigation of Chudoba *et al.* (1973a,b), in a large number of the investigations cited above, bulking in long sludge age (low F/M) systems was not caused by low F/M filaments; in most, bulking was caused by *S.natans* which is a low DO filament. This raises the question of the appropriateness of the system modification approach for controlling low F/M filaments. It appears that in the bulking research, controlling bulking in low F/M systems became the focus rather than controlling bulking by low F/M filaments. These are two distinctly different objectives because bulking in a low F/M system is not necessarily caused by low F/M filaments. As a result of this difference, the reader's attention is drawn to clearly distinguish between the two terms in the remainder of this review; low F/M bulking is bulking in a low F/M system with the filaments causing the bulking unspecified, i.e. could be *S.natans*, whereas low F/M filament bulking is bulking caused specifically by the low F/M filaments but this condition need not necessarily be in a low F/M system.

2.4.2 Stimulation of selector effect - aerobic conditions

A common characteristic of the three types of systems outlined above is that a soluble COD (<0,45 μm) concentration gradient is induced either in time (i.e. in batch or intermittently fed systems, type 2) or in space (i.e. in compartmentalized or selector reactor systems, types 1 and 2). Some of the investigators concluded that Chudoba's selection criterion does not completely account for the suppression of filamentous organism proliferation and that other factors also play an important part. For example;

(1) Many investigators (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982a,b; Eikelboom, 1982; Jenkins *et al.*, 1983; Daigger *et al.*, 1985; Ekama and Marais, 1986b; Still *et al.*, 1986; van Niekerk *et al.*, 1987) using real or synthetic sewage, provided experimental evidence that systems incorporating the 3 modifications cited above, stimulate in the sludge soluble COD or, more correctly, readily biodegradable COD (RBCOD) and oxygen uptake rates that are much higher than in sludge grown in single reactor completely mixed systems with a constant flow and load. They speculated that the soluble COD (RBCOD) concentration gradient induced by the 3 modifications stimulates the growth of floc-forming organisms with high substrate uptake rates which finds no counterpart in the growth of filamentous

organisms with the result that the filamentous organisms are unable to compete successfully for substrate.

(2) Chiesa and Irvine (1982) proposed that the alternating feed-starve conditions induced by the three modifications stimulated development of floc-formers with a higher starvation resistance than filamentous organisms.

The significance of these factors in bulking control in low F/M (long sludge age) systems is not yet clear but in any event is not really of much consequence. From a practical point of view, provided the system modification approach works and controls the bulking problem, it can be implemented for this purpose; the detailed explanation and mechanism will follow hand in hand with practical experience; the urgency is in controlling the bulking problems in many activated sludge plants, in particular the low F/M filament bulking problems so common in biological N and N&P removal plants, not only in South Africa but also in other countries.

2.4.3 Application of selector effect under anoxic conditions

The system modification approach for bulking control in low F/M systems also was applied by incorporating initial anoxic selectors into N removal activated sludge systems. The need for this arises out of the desirability for denitrification for N removal. If an aerobic selector receiving the influent and underflow recycle streams is placed ahead of a nitrification-denitrification system, most of the influent RBCOD will be utilized in the aerobic selector. This will result in a significant loss in denitrification - as much as 50% - in that the influent RBCOD will be utilized with oxygen in the aerobic selector rather than with nitrate in the primary anoxic reactor. If the selector can be anoxic, the RBCOD will be utilized with nitrate and no loss in denitrification will occur, and if the anoxic selector functions, then the conditions for good N removal and selector bulking control are simultaneously met. In laboratory, pilot and full scale work, Heide and Pasveer (1974); Bailey and Thomas (1975); Cooper *et al.* (1977); Tomlinson and Chambers (1979); Wagner (1982); Price (1982); Cooper and Boon (1983) and Shao (1986) reported that in nitrifying activated sludge systems, incorporation of initial anoxic mixing zones/selectors ahead of the main aeration reactor, reduced bulking and had a beneficial influence on sludge settleability. However in this work, the filaments were not specified, or where specified, were not low F/M types. In evaluating anoxic selectors for bulking control in laboratory scale low F/M systems receiving real sewage, Lee *et al.* (1982), reported that incorporation of two anoxic selectors in series, each 1/74th of the total system volume, did not control bulking. Lee *et al.* sized the selectors in accordance with the volume that would be required to control bulking with aerobic selectors. Based on measurements of soluble COD through the system, they found that not all the soluble biodegradable COD (RBCOD) was taken up in the selectors. In follow-up laboratory research, Shao (1986) concluded that (1) anoxic selectors controlled bulking in low F/M systems provided that they removed practically all the RBCOD, (2) RBCOD and nitrate uptake rates were significantly higher in the systems incorporating anoxic selectors than systems without anoxic selectors, (3) uptake rate of RBCOD is slower under anoxic conditions than under aerobic conditions so that anoxic selectors should be sized larger than aerobic selectors.

From this research, it would appear that anoxic selectors also are effective for controlling bulking in low F/M systems, but it needs to be pointed out that the filaments present in the laboratory systems operated by Lee *et al.* and Shao were not low F/M ones but 021N, *Thiothrix* and *S.natans*. Consequently it is still not clear whether or not aerobic or anoxic selectors will control the low F/M filaments.

In work on denitrification, Bailey and Thomas (1975) and Arkley and Marais (1981) found that as the hydraulic retention time of an initial (primary) completely mixed anoxic reactor increased, so sludge settleability in long sludge age systems (20 days) deteriorated. In Arkley and Marais' work, the anoxic zone had sizes, zero (completely aerobic) 39, 50 and 70% of the total system volume. These large anoxic zones cannot be considered selectors in that even though they probably did remove virtually all the RBCOD they almost definitely would not have stimulated a rapid RBCOD uptake rate. Instead of a single large completely mixed primary anoxic reactor, Cooper and Boon (1983) installed a channel type anoxic zone by replacing the surface aerators with stirrers in 25% of the aeration basin (normal anoxic hydraulic retention time 2,5h) and a good settling sludge (SVI < 100 mℓ/g) was maintained. In this work on denitrification, the filamentous organisms were not identified so it is difficult to come to any firm conclusion regarding the effect of the different anoxic conditions on the low F/M filaments.

2.4.4 Conclusion - influence of selector effect on low F/M filaments uncertain

From the evidence presented in this review so far, it appears that a conclusion widely held is that the selector effect, i.e the stimulation of a rapid RBCOD uptake rate in an aerobic or anoxic selector, through system modification which introduces a RBCOD concentration gradient in the system, stimulates the growth (or adaptation) of floc-formers with high RBCOD uptake rates, thus enabling them to successfully compete against the filaments for substrate. While this may be the mechanism of control over certain filamentous organisms, and from the literature it appears that *S.natans*, *Thiothrix* and 021N are controlled by this mechanism, there is no conclusive evidence that the low F/M filaments are controlled by this mechanism. Because this mechanism has gained considerable credibility as a means of controlling bulking in low F/M systems, its influence on sludge settleability and the low F/M filaments so common in long sludge age biological N and N&P removal systems was thoroughly investigated at laboratory scale by Gabb *et al.* (1989a).

2.5 UNIVERSITY OF CAPE TOWN INVESTIGATION-PHASE 1

2.5.1 Experimental investigation

In this investigation, which extended over a period of 4 years, many types of laboratory scale activated sludge systems were operated. As a starting point (phase 1), the type of experiments reported in the literature were repeated to see if the same results could be obtained. This would serve as a useful reference. The types of systems operated were:

* fully aerobic constant feed single reactor completely mixed (O/CFCM) and intermittently fed fill and draw (O/IFFO) systems.

* fully aerobic constant feed completely mixed systems with (O/CFCM/SEL) and without (O/CFCM) aerobic selector reactors.

The need for denitrification required the stimulation of the selector effect in anoxic selectors to be investigated. This was done by operating and evaluating anoxic-aerobic constant feed single reactor completely mixed (AO/CFCM) and intermittently fed fill and draw (AO/IFFD) systems that are similar to the fully aerobic O/CFCM and O/IFFD systems cited above except that alternating periods of aeration (3h) and non aeration (1h) were imposed on the systems.

These systems were operated at 20 days sludge age, were fed Mitchell's Plain raw sewage and were started up with low F/M filament bulking sludge (DSVI > 250 mℓ/g) from the Mitchell's Plain N removal plant containing *M. parvicella*, 0675, 0041, 0092 and *Nocardia*. Conclusions drawn from these first phase experiments were:

2.5.1.1. *Stimulation of selector effect*

The alternating feed-starve conditions imposed by (i) intermittent feeding to completely mixed reactor systems, either fully aerobic (O/IFFD) or anoxic aerobic (AO/IFFD) and by (ii) aerobic selector reactors incorporated in fully aerobic continuously fed completely mixed systems (O/CFCM/SEL) stimulated in the mixed liquor a selector effect, i.e. a high readily biodegradable (or dissolved < 0.45 μm filtered) COD (RBCOD) uptake rate. The RBCOD uptake rates were 2 to 3 times higher than in systems that did not incorporate alternating feed-starve conditions (O/CFCM and AO/CFCM). If the condition during which the RBCOD was taken up was aerobic, the high RBCOD uptake rate gave rise to an associated high initial oxygen utilization rate (OUR) under batch conditions; if the condition was anoxic, it gave rise to an associated high (initial) nitrate uptake rate (NUR) under batch conditions.

The selector effect could be stimulated in a sludge (or lost) over a period less than a sludge age in long sludge age (> 20d) systems by introducing (or eliminating) alternating feed-starve conditions. Acquisition of the selector effect by a sludge under aerobic or anoxic alternating feed-starve conditions imposed by the IFFD and CFCM/SEL systems is in agreement with reported results in the literature.

2.5.1.2. *Purely aerobic conditions appear to ameliorate bulking by low F/M filaments*

Low F/M filament bulking sludge (DSVI's > 250 mℓ/g) containing, usually, in varying proportions, 0092, *M.parvicella*, 0914, 0675, 1851 and 0041, from long sludge age full scale (N removal) plants, when used to start up the laboratory scale long sludge age (>15d) activated sludge systems under fully aerobic conditions and the particular anoxic-aerobic conditions i.e. 1h anoxic 3h aerobic, invariably ceased bulking (DSVI < 80 mℓ/g) within a month irrespective of whether or not the system stimulated the selector effect. Evidently, in long sludge age fully aerobic systems, and in the particular alternating anoxic-aerobic systems, the selector effect was irrelevant because the low F/M filament proliferation was suppressed both when the selector effect was present or absent.

2.5.1.3. *Bulking caused by* Sphaerotilus natans (S.natans)

In fully aerobic, and in the particular alternating anoxic-aerobic, long sludge age systems, in which there is no selector effect (i.e. O/CFCM and AO/CFCM) when bulking was observed, it was not due to low F/M filaments but due to *S.natans* and *Thiothrix*. According to Jenkins *et al.* (1984) *S.natans* sorts into the low DO group and *Thiothrix* into septic sewage or nutrient deficient groups. Curiously in the South African surveys of full scale N and N&P removal plants *S.natans* had not, and *Thiothrix* only rarely, been observed to cause bulking.

2.5.1.4. S.natans *bulking apparently caused by seeding*

Regular and thorough cleaning of the influent feed lines eliminated the *S.natans* bulking problems in the laboratory systems. From this it was concluded that *S.natans* proliferation in the laboratory systems was caused by seeding from *S.natans* attached growth on the influent feed line walls. This artefact may also have been present in the many laboratory scale studies throughout the world cited above because numerous investigators have reported the proliferation of *S.natans* in their low F/M (long sludge age) laboratory systems under a wide range of operating conditions.

anoxic reactors very little RBCOD enters the aerobic reactor for growth of *S.natans*. In terms of this explanation, selectors, whether aerobic, anoxic or anaerobic, control *S.natans* proliferation either by (i) removing RBCOD under conditions in which *S.natans* cannot function (anaerobic or anoxic selectors or (ii) stimulating high RBCOD uptake in floc-former which then can compete successfully against *S.natans* (aerobic selectors). With regard to *Thiothrix*, this organism is variously reported as obligate aerobic or facultative. If it is obligate aerobic, its proliferation is controlled in the same two ways as *S.natans* described above. If it is facultative, anaerobic reactors, anoxic and aerobic selectors should control its proliferation. The literature supports this conclusion; *Thiothrix* is controlled by anaerobic reactors (Wanner *et al.*, 1987b), anoxic selectors (Shao, 1986) and aerobic selectors (van Niekerk *et al*, 1987).

2.5.2.3 *Low F/M filaments appear not to require RBCOD for proliferation*

From the above discussion it can be seen that with respect to the filaments *S.natans, Thiothrix* and 021N there is consistency of behaviour among the anaerobic reactor as metabolic selector and aerobic and anoxic selectors as competitive (or kinetic) selectors in that in all three, RBCOD is taken up preferentially by floc-formers at the expense of the filaments. The observation that the anaerobic reactor in its function as a metabolic selector, does not control the proliferation of low F/M filaments in N&P removal systems, raises the question whether or not aerobic and anoxic selectors will be able to control low F/M filament proliferation through competitive or kinetic selection. Because aerobic and anoxic selectors and anaerobic reactors permit removal of influent RBCOD by floc-formers through competitive or metabolic selection, but that despite this low F/M filament continue to proliferate in N&P removal systems, it would appear that the low F/M filaments do not require RBCOD for growth like *S.natans, Thiothrix* and 021N do. If the low F/M filaments are able to grow on COD other than RBCOD, i.e. the particulate biodegradable COD (PBCOD), then because the PBCOD passes through the aerobic/anoxic selectors and anaerobic reactors, the proliferation of these filaments would not be controlled by aerobic and anoxic selectors. Based on this reasoning the second phase of the investigation of Gabb et al. (1989a) focused on checking whether or not aerobic selectors would suppress low F/M filament proliferation.

2.6 UNIVERSITY OF CAPE TOWN INVESTIGATION - PHASE 2

2.6.1 Confirmation that selector effect is not important in ameliorating low F/M filament bulking

Before the efficacy of aerobic (or anoxic) selectors on suppressing low F/M filament proliferation through competitive selection could be checked, it was necessary to devise a laboratory system other than an N&P removal one, wherein low F/M filaments proliferated. To do this, attention was focused on unaerated/aerated systems, because it was evident from the first phase of the investigation and from the bulking surveys that low F/M filaments proliferate in full scale unaerated/aerated systems, irrespective of whether these were biological N&P removal systems or N removal only systems. Accordingly in this second phase of the investigation fully aerobic and various kinds of unaerated/aerated systems were operated.

Initially three single reactor systems were started up with a low F/M filament bulking sludge harvested from a laboratory scale N&P removal (Modified UCT) system. All three systems were operated at the same sludge age (20d) and received the same sewage (Mitchell's Plain raw) as the parent MUCT system. Two of the systems were intermittently fed once daily while the third was continuously fed. One of the intermittently fed systems was anaerobic for the first 6h after feeding (nitrate concentration lasted only for the first 30 minutes) and aerobic for 16h, and finally settling for 2h. The other intermittently fed system, and continuously fed system, were maintained fully aerobic for 24h. In the two fully aerobic systems, the DSVI declined steadily from a start up value of around 200 mℓ/g to below 60 mℓ/g over a period of two to three sludge ages. Over the same period, the DSVI in the intermittently fed anaerobic-aerobic system and in the parent MUCT system remained high between 180 and 200 mℓ/g.

These experiments confirmed that (1) continuous aeration inhibits the growth of most of the low F/M filaments, in particular *M.parvicella*, 0092 and 0914 irrespective of whether or not alternating feed-starve conditions prevail (intermittently or continuously fed), and (2) an initial anoxic-anaerobic period of 6h during which all the RBCOD is removed from the liquid phase, followed by an aerobic period of 16h, at a DO of 6 mgO/ℓ and the anaerobic (9,6h), anoxic (11,2h), aerobic (14,4h) sequence of the parent MUCT system allows low F/M filaments to proliferate and cause bulking. However, it was not clear how the continuation of bulking by low F/M filaments in the intermittently fed anaerobic/aerobic system fits in with the amelioration of low F/M filament bulking observed in the anoxic-aerobic (AO/IFFD) and continuously fed (AO/CFCM) systems operated in phase 1 of the investigation (see 2.5.1.2 above). Nevertheless it was concluded from these experiments, and from the survey of filamentous organisms in full scale plants, that low F/M filaments proliferate in plants that have alternating aeration non-aeration either in different reactors or in different stages of the same reactor.

2.6.2 Proliferation of low F/M filaments in laboratory scale intermittent aeration systems

In an attempt to grow low F/M filaments in laboratory systems other than N&P removal ones, long sludge age single reactor continuously fed completely mixed systems with intermittent aeration (1 minute air on, in a ten minute cycle with peak DO of 2,0 mgO/ℓ) and fed real sewage were set up to mimic full scale Carousel or Orbal type N removal plants which were known from the survey to stimulate low F/M filament proliferation. In the laboratory intermittent aeration systems it was found that most of the low F/M filaments proliferated, in particular *M.parvicella* and 0092 but also 0914, 0041, 0675 and 1851. Switching the systems from intermittent to continuous aeration invariably caused a sharp decline in bulking (<10 days) with a concomitant reduction in low F/M filaments over less than a sludge age; switching back to intermittent aeration caused slow regrowth (~3 months) of the low F/M filaments and associated bulking, confirming that the low F/M filaments respond very strongly to the presence or absence of unaerated periods in the system.

2.6.3 Aerobic selectors do not control low F/M filament proliferation

Having established that low F/M filaments proliferated in laboratory intermittent aeration systems, it became possible to check, by setting up an experimental and control single reactor, continuously fed completely mixed intermittently aerated system whether or not aerobic selectors control low F/M filaments (Gabb *et al.*, 1989a). With a correctly sized multi-compartment aerobic selector installed on the experimental system, it was found that the selector effect did not control most of the low F/M filaments. The DSVI remained above 250 mℓ/g in both systems for more than 5 sludge ages (100 days). The presence of the selector effect in the experimental system sludge was verified by doing (i) batch tests to check that a rapid RBCOD and oxygen uptake rates had been stimulated, (ii) soluble COD profiles in the selector reactors to see that all the RBCOD was taken up in the selectors and (iii) microscopic examination which confirmed that numerous Zoogloea colonies had formed. Switching the control system to continuous aeration caused the DSVI to decrease sharply in 10 days, with a concomitant decline in low F/M filaments, while the DSVI in the experimental system with the selector reactors remained high.

2.6.4 Implications of the phase 2 investigation results

2.6.4.1 *Consistency of effect of aerobic selectors and anaerobic reactors*

The observation that aerobic selectors did not control bulking by low F/M filaments in particular, 0092, *M.parvicella*, 0675 and 0041, resolved the inconsistency with respect to the low F/M filaments in the behaviour between metabolic selection in anaerobic reactors (in N&P removal plants) and kinetic selection in aerobic selectors: In N&P removal plants anaerobic reactors which stimulate preferential removal of influent RBCOD by floc-formers (Wentzel *et al.*, 1985) did not control low F/M filament proliferation; aerobic (and by implication presumably also anoxic) selectors promote preferential removal of influent RBCOD by stimulating the selector effect also did not control low F/M filament proliferation.

2.6.4.2 *Confirmation that low F/M filaments do not require RBCOD for proliferation*

It would appear that the *influent RBCOD does not play an important role in the growth of low F/M filaments in long sludge age systems*. It would seem then that the possibility exists that the low F/M filaments utilize particulate biodegradable COD (or its hydrolysis products) originating either from the influent or self-generated by death and lysis of organisms (Ekama and Marais, 1986b).

2.6.4.3 *Conditions promoting nutrient removal appear to promote low F/M filament bulking*

Low F/M filaments appear to proliferate in systems that expose the sludge mass to alternating anoxic-aerobic periods as in anaerobic-anoxic-aerobic multi reactor N&P removal systems and completely mixed intermittently aerated N removal systems (ditch type plants). When these systems, or sludge harvested from these systems, are exposed to purely aerobic conditions by continuous aeration, the low F/M filament bulking is ameliorated and sludge settleability improved (DSVI < 80 mℓ/g). From this it would appear that the anaerobic-anoxic conditions that are required to stimulate biological N or N&P removal also stimulate proliferation of low F/M filaments in long sludge age systems; fully aerobic conditions which inhibit low F/M filament proliferation also inhibit biological N or N&P removal. Consequently to effect specific control over the low F/M filaments, some environmental condition needs to be found that will lead to exclusion of the filaments but retention of the organisms and conditions that effect biological nutrient removal.

2.6.4.4 *Anoxic-aerobic conditions apparently stimulate low F/M filament proliferation*

It was considered most likely that it is the anoxic-aerobic alternation that leads to the low F/M filament proliferation because this is a common feature in N&P removal and completely mixed ditch-type N removal systems. No answers were offered by Gabb *et al.* (1989a) as to the effects of magnitude of anoxic mass fraction and its position in the configuration, length of anoxic retention time (actual or nominal), duration of the anoxic-aerobic cycles in intermittent aeration systems, concentration of nitrate during the anoxic periods, frequency of alternation between anoxic and aerobic periods and the effect of the low DO concentrations which arise from the "lead-in" to anoxic conditions in intermittent aeration systems.

2.7 NEW RESEARCH DIRECTIONS

The finding that the selector effect did not control low F/M filament bulking placed this research back into an exploratory stage. As a consequence a central task of the bulking research programme since 1989 was to establish and pursue new directions of research. By considering the implications of the research reviewed above, investigations were initiated to determine the influence of the following factors on low F/M filament bulking:

1. Which components in the influent wastewater are responsible for bulking by the low F/M filaments? Because the influent RBCOD apparently does not play an important role in the sense that they can proliferate without it, can the low F/M filaments utilize the influent particulate biodegradable COD (PBCOD)? It is anticipated that the influent PBCOD does play a role in the growth of the low F/M filaments because this COD is not significantly reduced in selector reactors (whether aerobic or anoxic) and anaerobic reactors and therefore passes through to the anoxic and aerobic zones of the system. For the purpose of identifying the role of the influent PBCOD and RBCOD, it may be necessary to develop and refine an artificial sewage of known composition, which supports the growth of the low F/M filaments. The artificial sewage can be fed to nutrient removal and completely mixed intermittent aeration systems to compare the filament populations that develop with the artificial sewage with those in similar systems receiving real sewage. The constituents of the artificial sewage can be manipulated to observe the influence of the RBCOD and PBCOD on the low F/M filaments. Additional to developing an artificial sewage, real sewage can be readily separated into its RBCOD and PBCOD constituents by modern ultra-filtration techniques. The RBCOD and PBCOD, appropriately reconstituted to its original volume with tap water, can be fed to various laboratory scale N and N&P removal systems to observe the effect of the substrate on the low F/M filaments and system performance.

2. If PBCOD only supports the growth of the low F/M filaments, do the filaments utilize hydrolysis products of the PBCOD in the liquid generated by other organisms or are they able to hydrolyse and utilize PBCOD directly themselves? Are the low F/M filaments able to utilize (either directly or indirectly) the substrate originating from the lysis of dead organisms in the biomass (Ekama and Marais, 1986b)? If influent PBCOD, or its hydrolysis derivatives, can be

utilized by the low F/M filaments, what causes the filaments to proliferate under unaerated-aerated conditions but not purely aerated conditions?

3. Due to the strong influence of the periodic unaerated-aerated conditions in biological N and N&P removal plants - most likely the anoxic conditions because this is common to both N and N&P removal plants - investigate the influence of the characteristics of the anoxic reactor on low F/M filament bulking, such as;

(i) size - because low F/M filaments proliferate (DSVI > 300 mℓ/g) in anoxic-aerobic systems with large anoxic fractions (50-70%) and not (DSVI < 80 mℓ/g) in purely aerated systems (0% unaerated) is there a trend that the greater the anoxic fraction, the higher the DSVI? From Arkley and Marais (1981), this would appear to be the case; unfortunately in their work the filaments were not identified, but probably these were low F/M ones because *S.natans, Thiothrix* or 021N are rarely found in laboratory multi reactor anoxic-aerobic (N removal) or anaerobic-anoxic-aerobic (N&P removal) systems in which all the influent is discharged into the anoxic or anaerobic reactors. Can the low F/M filaments proliferate under fully anoxic conditions?

(ii) position - i.e. as a primary anoxic reactor receiving the influent flow and before the aerobic reactor or as a secondary anoxic reactor after the aerobic reactor.

(iii) type - i.e. anoxic reactors in compartments separated from the aerobic reactor or forming part of single intermittent aeration ditch type reactors which are anoxic where the DO is close to zero.

(iv) nitrate - investigate the effect of the nitrate concentration in the anoxic zone on the proliferation of low F/M filaments

(v) frequency of alternation between anoxic and aerobic conditions - in the intermittent aeration systems the aeration cycle establishes the number of times the sludge is switched between anoxic and aerobic conditions, and in multi reactor anoxic aerobic systems this is established by the recycle ratios; does this frequency of alternation between the anoxic and the aerobic conditions have an influence on the low F/M filament proliferation?

(vi) low DO conditions - in intermittent aeration systems do the low DO conditions leading to anoxic conditions promote the low F/M filament proliferation?

4. Because the low F/M filaments appear to proliferate in long sludge age systems, at what sludge age is their proliferation suppressed so that sludge settleability is at most a DSVI of 100 mℓ/g? Is N and N&P removal possible at this sludge age?

5. Attempt to control bulking by low F/M filaments in different system configurations which incorporate biological N&P removal. For example;

(i) a system configuration which minimizes utilization of influent PBCOD under anoxic conditions (but not that generated by organism death and lysis) is the Johannesburg system, with anaerobic and aerobic zones following sequentially and an anoxic zone in the underflow recycle stream for denitrification of the return sludge to the anaerobic reactor. If such a system inhibits proliferation of low F/M filaments compared to a MUCT system, it would indicate that the filaments utilize influent PBCOD, or a derivative of influent PBCOD, under anoxic conditions.

(ii) sludge ages in N and N&P removal plants are long (>20 days) principally to ensure nitrification. Wanner *et al.* (1988) investigated the influence of fixed media in the aerobic zone of N and N&P removal plants on the nitrification rate. With this approach it may be possible to maintain a long aerobic sludge age on the fixed media nitrification while the suspended sludge has a sludge age sufficiently short to suppress low F/M filament proliferation.

2.8 UNIVERSITY OF CAPE TOWN INVESTIGATION-PHASE 3

The above research areas are clearly wide ranging and in order to investigate them, a second comprehensive laboratory research investigation was commenced in 1989. The research presented in this thesis forms part of this phase 3 investigation and in order to place it in the context of this investigation, a brief review of its progress relevant to this thesis is given below.

2.8.1 The development of an artificial sewage feed supporting low F/M filament growth by Gabb *et al.* (1988).

This work followed 3 steps:

(1) Chemical Composition: Nutritional requirements insofar as readily (RBCOD) and particulate (PBCOD) biodegradable COD constituents were concerned were established from the literature for many of the activated sludge bacteria. In addition the chemical constituent analyses of domestic sewage reported in the literature were examined. The composition of Mitchell's Plain raw sewage was important because this was the sewage fed to the laboratory scale activated sludge systems which were compared with the systems fed artificial sewage. From this information and measured principal constituents of Mitchell's Plain raw sewage (COD, Organic N, $NH4^+$, fats and oils, RBCOD and PBCOD), an artificial sewage was formulated which was progressively refined after experimentation on activated sludge systems in steps (2) and (3) below.

(2) Kinetic response: The correct proportions of RBCOD and PBCOD were determined by comparing the batch test results with artificial sewage and with Mitchell's Plain raw sewage. RBCOD and PBCOD proportions were varied until they matched those of the raw sewage.

(3) Microbiological Response: The ability of the low F/M filaments to proliferate in the systems fed the artificial sewage was evaluated. For this purpose experimental laboratory systems were operated receiving the artificial sewage, both with identical control systems receiving Mitchell's Plain raw sewage. It was found that an unaerated-aerated (6 hours unaerated, 16 hours aeration, 2 hours settling) intermittently fed fill and draw (IFFD) system receiving artificial sewage feed on occasion promoted the abundant growth of the following filaments; types 0092, 0914, 0041, 0675, 0803, *Haliscomenobacter hydrossis* and *Nostocoida limicolla II*. In the surveys of Blackbeard *et al.* (1986, 1988), all of these filaments had been observed in bulking sludge of full scale plants (the first four named more common than the last three). During these experiments the inorganic nutrient concentrations of the artificial sewage were adjusted to prevent these being growth limiting.

2.8.2 The work of Casey *et al.* (1990) with artificial sewage

The artificial sewage developed by the procedure above was later used in experiments by Casey *et al.* (1990) with only the RBCOD and PBCOD proportions being varied. The following observations were made on intermittently aerated single completely mixed reactor systems:

(1) low F/M filaments, in particular *H.hydrossis* and 1851 but also 0092, 0041 and 0675, proliferated to exceptionally high DSVI's (>600 mℓ/g) irrespective of whether the feed comprised only RBCOD or PBCOD. The only difference was that with RBCOD their proliferation was more explosive and rapid than with PBCOD.

(2) Changing the aeration pattern from intermittent (anoxic/aerobic) to continuous (aerobic) caused amelioration of bulking by the low F/M filaments - specifically *H.hydrossis* and 1851.

(3) Changing the systems from continuous to intermittent aeration caused proliferation of low F/M filaments specifically *H.hydrossis* and 1851.

(4) *M.parvicella* did not grow in the systems irrespective of whether or not fats and oils were excluded from the artificial sewage. In similar intermittent aeration systems receiving real sewage, *M.parvicella* is often the dominant one (Warburton *et al.*, 1991 see below).

(5) Reducing the amount of nitrate added to the systems so that the effluent nitrate concentration was < 5,0 mgN/ℓ caused an amelioration of bulking (DSVI down from 680 mℓ/g to 150 mℓ/g) and a reduction of low F/M filaments, specifically *H.hydrossis*.

Casey *et al.* (1990) also found that in switching to artificial sewage feed in a MUCT system containing low F/M filaments developed on real sewage, caused the DSVI of the sludge to decrease from 191 mℓ/g to 83 mℓ/g in 51 days. In an attempt to reseed the system with low F/M filaments, 10% of the MLSS mass in the system was replaced daily with mixed liquor from MUCT systems fed real sewage containing low F/M filament bulking sludge for 5 consecutive days. This caused a temporary increase in the DSVI, but when seeding ceased the DSVI decreased again indicating the low F/M filaments were unable to grow in a typical MUCT system receiving the artificial sewage feed. The same conclusions were arrived at by Gabb *et al.* (1988).

2.8.3 The work of Warburton *et al.* (1991) with intermittently aerated systems fed real sewage

Warburton *et al.* (1991) investigated the effect of (1) nitrate concentration during the anoxic period, (2) varying the anoxic mass fraction, and (3) varying the sludge age on low F/M filament bulking in continuously fed intermittently aerated single completely mixed reactor systems receiving real sewage as feed. The following conclusions were drawn:

(1) the nitrate concentration during the anoxic period did influence the DSVI; high nitrate levels (effluent nitrate concentrations between 30 and 50 mgN/ℓ) were associated with increases in the DSVI whereas low nitrate levels (effluent nitrate concentrations < 5,0 mgN/ℓ) led to a decrease in the DSVI. However even

under low nitrate conditions the low F/M filaments, particularly 0092 and *M.parvicella*, were able to proliferate to the extent of causing bulking (i.e. DSVI 200 mℓ/g and higher).

(2) Increasing the aerobic mass fraction from 30% to 70% (reducing the anoxic mass fraction from 70 to 30%) led to a decrease in the DSVI from 200-400 mℓ/g down to 120-150 mℓ/g. The low F/M filaments present in the systems were *M.parvicella*, *H.hydrossis*, 0092 and 0041.

(3) Sludge age did influence the DSVI: at short sludge ages (<10 days) the DSVI was lower than at long (>10 days) sludge ages. However the low F/M filaments still proliferated sufficiently abundantly even at very short sludge ages (5d) to cause bulking (DSVI>150 mℓ/g).

(4) While low anoxic nitrate concentrations, short sludge ages and small anoxic mass fractions tend to discourage proliferation, the only factor to date which ameliorated the low F/M filament bulking and yielding DSVI's <100 mℓ/g was continuous aeration.

2.8.4 The work of Ketley *et al.* (1991) with intermittently aerated systems fed artificial and real sewage

With artificial sewage feed, Ketley *et al.* (1991) examined the effect on the low F/M filaments of

(1) fully anoxic conditions, and
(2) the magnitude of the nitrate concentration during the anoxic period

and with real sewage feed examined the effect of

(1) fully anoxic conditions, and
(2) the frequency of exposure to alternating anoxic-aerobic conditions.

All the experimental systems operated were long sludge age (15 days) continuously fed single completely mixed reactor N removal systems, either intermittently aerated or fully anoxic. The single reactor form avoided the complexity of biological excess P removal in multi reactor systems and, as was demonstrated earlier, intermittently aerated single reactor systems were found to consistently promote the proliferation of low F/M filaments in the activated sludge with artificial and real sewage.

From their work with artificial sewage Ketley *et al.* (1991) concluded that:

(1) In intermittently aerated systems (70% anoxic mass fraction), low nitrate concentrations during the anoxic period led to amelioration of bulking by filaments 1851 and 1701 (of which only the former is a low F/M one). However the production of polymeric material in the sludge could have played a role in the reduction of the DSVI.

(2) Under fully anoxic conditions, only *H.hydrossis* was able to proliferate to the extent of causing bulking; other low F/M filaments declined.

Because *H.hydrossis* is a filament of little consequence in full scale systems, Ketley *et al.* repeated the experiments with real sewage. From these experiments it was concluded that:

(1) Low F/M filaments were unable to proliferate under fully anoxic conditions to cause bulking and the excessive growth of *H.hydrossis* with artificial sewage was not a true reflection of that filament's growth under the same conditions when fed real sewage.

(2) Increasing the frequency of alternation between anoxic and aerobic conditions from 48 cycles/d (30 minute cycles) to 1 cycle every 3 days (3 day cycles) had no ameliorating effect on the low F/M filament bulking.

(3) Stimulation or suppression of low F/M filament proliferation could be reproduced repeatedly by switching from intermittent aeration (stimulation) to either fully aerobic or fully anoxic conditions (suppression) respectively, with fully aerobic conditions leading to more rapid decreases in DSVI than fully anoxic conditions.

2.8.5 The work of Hulsman *et al.* (1992) with compartmentalized N removal systems fed artificial and real sewage.

Hulsman *et al.* (1992) with artificial and real sewage fed to two reactor anoxic-aerobic systems, examined the effect on low F/M filament proliferation of:

(1) the type of anoxic zone i.e. compartmentalized into a separate reactor as distinct from single reactor intermittent aeration systems,
(2) the size of the anoxic mass fraction,
(3) the position of the anoxic reactor relative to the aerobic reactor i.e. as primary anoxic reactor receiving influent and underflow recycle streams (pre-denitrification, MLE) or as a secondary anoxic reactor receiving effluent from the aerobic reactor (post denitrification, Wuhrmann),
(4) the frequency of anoxic-aerobic alternation per day and
(5) the system MLVSS concentration.

The following conclusions were made by Hulsman *et al.* (1992)

(1) Filamentous organism proliferation in these systems was much less severe than in intermittently aerated systems operated under similar conditions, but was more severe than in fully anoxic or fully aerobic systems operated under similar conditions.

(2) Changing the size of the anoxic reactor of the MLE system from 70 to 54% and back again from 54 to 74% did not significantly affect the low F/M proliferation and the sludge settleability remained below 125 mℓ/g under both conditions.

(3) Positioning the anoxic reactor after the aerobic reactor did, but only to a small degree, decrease the DSVI for artificial sewage from 200 to 150 mℓ/g and for real sewage from 130 to 100 mℓ/g.

2.8.6 The work of Casey *et al.* (1992a,b) on MUCT systems using real sewage

Using real sewage feed it was found possible to manipulate the sludge settleability (DSVI) to high and low values, hence low F/M proliferation in MUCT systems by:

(1) Manipulating the anoxic sludge mass fraction. In a pair of MUCT systems, one with a high anoxic mass fraction (15% anaerobic, 20% first anoxic and 32% second anoxic and 33% aerobic), the other, with a low anoxic mass fraction (15% anaerobic, 20% first anoxic and 32+33=65% aerobic) the DSVI was high (200-250 mℓ/g) in the former and low (100-150 mℓ/g) in the latter.

(2) Manipulating the influent TKN concentration with ammonium dosing to the influent. At low TKN/COD ratio (no ammonium dosing) the concentration of nitrate generated to be denitrified by the anoxic reactors was such that the nitrate and nitrite concentrations leaving the anoxic reactors was very low (< 5 mgN/ℓ). At high TKN/COD ratios (with ammonium dosing) complete denitrification in the anoxic reactors (mainly the second anoxic) was no longer possible leading to high concentrations of nitrate and nitrite leaving the anoxic reactor (>10 mgN/ℓ). With ammonium dosing the DSVI increased (from 100 to 280 mℓ/g) and without ammonium dosing the DSVI decreased (from 250 to 170 mℓ/g).

2.8.7 The bulking hypothesis proposed by Casey *et al.* (1992a,b)

From the experiments reviewed above, Casey *et al.* (1992a,b) concluded that a major factor influencing low F/M filament proliferation was intermittent aeration conditions, causing the organisms to be alternately exposed to aerobic conditions (where oxygen serves as terminal electron acceptor) and anoxic conditions (where NO_3^- or NO_2^- serve as terminal electron acceptor). From this it was proposed that a possible cause for the low F/M filament proliferation lay in *the requirement for the sludge mass to switch* *between aerobic and anoxic metabolic pathways, this switching providing some competitive advantage to the filamentous organisms at the expense of the floc-forming organisms.* With this proposal as a basis, attention was focused on denitrification pathways.

Payne (1973) proposed the general denitrification pathway

$$\mathrm{NO_3^-} \longrightarrow \mathrm{NO_2^-} \longrightarrow \mathrm{NO} \longrightarrow \mathrm{N_2O} \longrightarrow \mathrm{N_2}$$

nitrate nitrite nitric oxide nitrous oxide nitrogen gas

Initially denitrification was considered a strictly anoxic process, occurring only in the total absence of oxygen. However, subsequently it has been demonstrated quite convincingly in pure cultures that denitrification can continue under aerobic conditions, albeit at a lower rate [Pichinoty and d'Ornano (1961), Showe and De Moss (1968), Krul and Veeningen (1977), Robertson and Kuenen (1984)]. Pure culture studies have also demonstrated that one or more of the intermediates in the denitrification pathway have an inhibitory effect on the aerobic utilization of substrate with oxygen as terminal electron acceptor. Krul (1976) in pure culture studies on a denitrifying organism isolated from activated sludge, cultured under anoxic conditions and tested under aerobic conditions, concluded that the accumulation of the intermediate nitric oxide (NO) during denitrification caused a measurable and prolonged inhibition of oxygen utilization under subsequent aerobic conditions. Curiously, this inhibition could be demonstrated for a pure culture of an isolate from activated sludge but not for a mixed culture of activated sludge.

Some controversy arose as to whether the inhibitory effect was due to NO_2^- or NO, but recent work has concluded that the inhibitory effect is due to NO and not NO_2^-. However, the degree of inhibition is exacerbated by the presence of NO_2^- and NO_3^- (Kučera *et al.*, 1987; Carr and Ferguson, 1990).

With this basis Casey *et al.* (1992a,b) proposed the following explanation for the proliferation of low F/M filaments in N and N&P systems: Floc-formers are inhibited under aerobic conditions by denitrification intermediates accumulated under the preceding anoxic conditions; the denitrification intermediate causing the inhibition is NO. For this explanation to be valid requires the low F/M filaments to denitrify only as far as NO_2^- and therefore do not accumulate NO, and the floc-formers to denitrify completely to N_2 and thereby accumulate NO under certain conditions. Under this hypothesis, low F/M filament bulking can be expected to take place if nitrate and nitrite removal in the anoxic reactor is incomplete. In this event, the floc-forming organisms would still have NO accumulated in their enzyme systems causing oxygen uptake inhibition in them upon entering the aerobic reactor. If nitrate and nitrite reduction is complete, then low F/M filament bulking would not be expected because then the NO intermediate will have been denitrified also and oxygen uptake inhibition in the floc-formers will not take place. Experimental work by Casey *et al.* (1991, 1992a,b) on sludge from fully anoxic and fully aerobic systems supported this hypothesis.

2.8 SCOPE OF THIS THESIS

From the investigations outlined above all the indications show that the bulking by low F/M filaments in intermittent anoxic-aerobic and compartmentalized N and N&P removal systems is associated with the magnitude of the anoxic mass fraction and the concentration of nitrate and nitrite in the anoxic zone. Because (1) fully anoxic systems did not bulk and (2) the anoxic mass fraction governs the degree of denitrification that can be obtained and therefore is linked to the nitrate and nitrite concentrations in the system, the research presented in this thesis investigates the effect of very large anoxic mass fractions (65%) and the nitrate and nitrite concentration in the anoxic reactor preceding the aerobic reactor in MUCT N&P removal systems on the proliferation of low F/M filaments. In order to achieve this two MUCT N&P removal systems with 15% anaerobic, 65% anoxic and 20% aerobic mass fractions receiving real sewage were set up. With these two systems the effect of

(1) low and high nitrate concentrations in the second anoxic reactor and
(2) low and high nitrite concentrations in the second anoxic reactor

on the proliferation of low F/M filaments was examined.

The experimental investigation and the results of the research are presented in the next chapter.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 EXPERIMENTAL SET-UP

In accordance with the objectives outlined in Chapter 1, two MUCT systems were set up with 20% aerobic, 65% anoxic and 15% anaerobic mass fractions. The systems were operated under constant flow and load steady state conditions details of which are shown in Table 3.1. The investigation extended over a total of 340 days, with day 1 being the day the first system, MUCT1, was started; the second system, MUCT2, was started on day 171 and operation of both systems stopped on day 340. Fig 3.1 shows a schematic layout of the two MUCT systems. A number of changes were made to the systems during the investigation period and these are discussed separately below for each system.

The experimental investigation was conducted on the two systems in 3 stages.

MUCT1

Stage 1:	Effect of the large anoxic mass fraction resulting in very low nitrate and nitrite concentrations in the second anoxic reactor.
Stage 2:	Effect of dosing nitrate into the second anoxic reactor ensuring high concentrations of nitrate and nitrite in this reactor.
Stage 3:	Effect of withdrawing the nitrate dose to restore the conditions of stage 1.

MUCT2

Same as MUCT1 except nitrite instead of nitrate was dosed into the second anoxic reactor and stage 3 was not done.

In the investigation the following parameters were measured daily on each system viz:

1. Unfiltered influent and filtered effluent COD concentrations.
3. Filtered reactor and effluent nitrate concentrations.
4. Filtered reactor and effluent nitrite concentrations.

5. Unfiltered influent, filtered reactor and filtered effluent total phosphorus concentrations.
6. MLSS and MLVSS concentrations in the aerobic reactor.
7. Oxygen utilization rate (OUR) in the aerobic reactor.
8. Aerobic sludge settleability in DSVI.
9. Filament identification on sludge from aerobic reactor every 3 to 4 weeks.
10. Anoxic batch tests on sludge entering the second anoxic reactor during periods of marked change in DSVI to measure the denitrification rates.
11. Random ammonium concentrations in the aerobic reactor and effluent.

The experimental results are first discussed separately below for each system followed by a comparison of the response of the two systems.

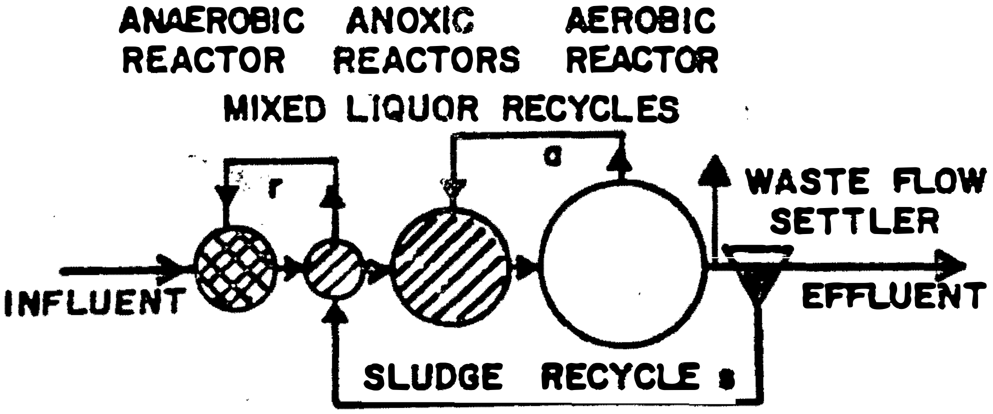


Fig 3.1 Schematic layout of the MUCT system.

Table 3.1: Initial design and operating parameters for the two laboratory scale MUCT systems (MUCT1 and MUCT2)

Parameter	Value
Sludge age (d)	20
Temperature (°C)	20
pH of mixed liquor	7.2-8.2
DO in aerobic recycle (mgO/ℓ)	2.5-4
Influent raw sewage:	
Source	Mitchell's Plain
Flow (ℓ/d)	10
COD concentration (mgCOD/ℓ)	1000
Readily biodegradable COD (mgCOD/ℓ)	155-250*
TKN concentration (mgN/ℓ)	60-100*
Phosphate-P concentration (mgP/ℓ)	15-24*
Reactor Volumes (l);Mass fractions (%)	
Anaerobic	6 ; 15
1st anoxic	4 ; 20
2nd anoxic	9 ; 45
Aerobic	4 ; 20
Unaerated mass fraction	19 ; 80
Recycles:	
Underflow (s-recycle)	1:1
Mixed liquor - Aerobic to 2nd anoxic (a-recycle)	3:1**
Mixed liquor - 1st anoxic to anaerobic (r-recycle)	1:1
MLVSS concentration (mg/ℓ)	3000
MLSS concentration (mg/ℓ)	3600

Notes

* Value varied between sewage batches

** Initial value for first system 2:1 but increased to 3:1 on day 28.

3.2 EXPERIMENTAL RESULTS: MUCT1

From day 1 to day 129, this system was operated under the conditions shown in Table 3.1. From day 120 to day 237, nitrate was dosed into the second anoxic reactor to increase the nitrate load on it to in excess of its denitrification potential. All the operational changes made to this system are set out in Table 3.2.

The results of the parameters measured to monitor the performance of the system are graphically shown in the following figures.

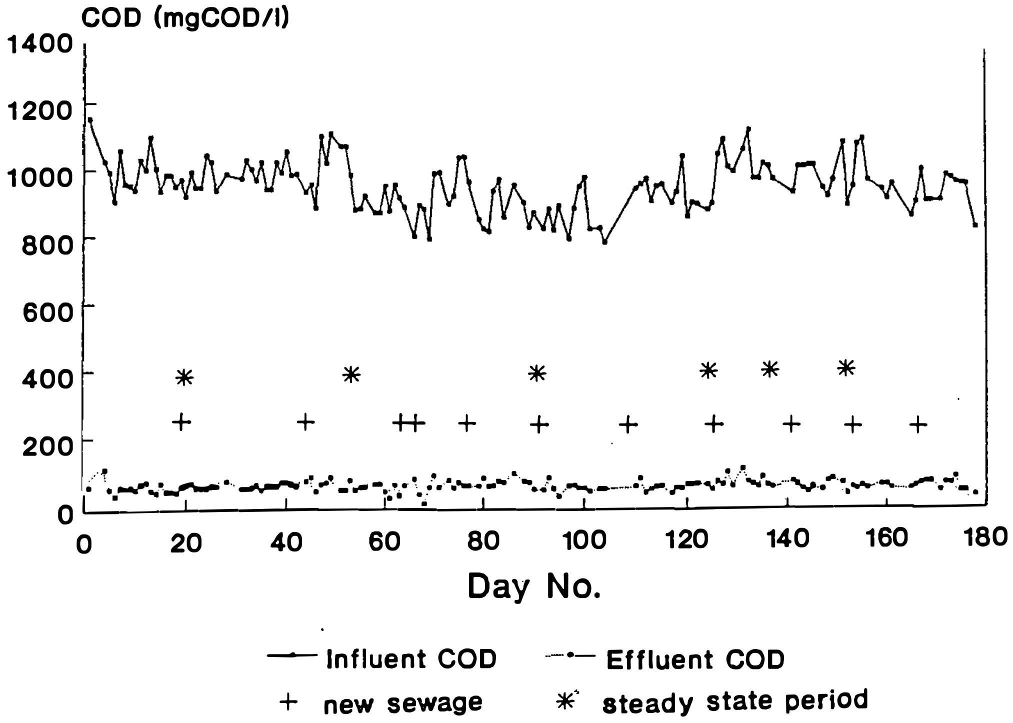
Fig 3.2	Influent and effluent COD concentration (mgCOD/l)
Fig 3.3	Influent and effluent TKN concentration (mgN/ℓ)
Fig 3.4	Influent TKN and effluent nitrate concentration (mgN/ℓ)
Fig 3.5	Influent TKN and effluent nitrite concentration (mgN/ℓ)
Fig 3.6	MLSS and MLVSS concentration (mg/ℓ)
Fig 3.7	Phosphorus removal/litre influent (mgP/ℓ)
Fig 3.8	Oxygen Utilization Rate (OUR) (mgO/ℓ/h)
Fig 3.9	Sludge settleability in DSVI (mℓ/g) and filament ID

The results shown graphically in Figs. 3.2 to 3.9 are listed in Appendix A. Before these results are discussed in terms of the objectives of the investigation, it is first necessary to check the reliability of the data by means of nitrogen and COD mass balances and by a kinetic response evaluation. In order to do this the 340 day test period was divided into 13 steady state periods; these periods were selected on the basis of a significant change between consecutive sewage batches or an operational change. During the 340 days 21 sewage batches were fed to the system and the times of these changes of sewage batches are indicated in Figs 3.2 and 3.3. The changes in system operation (see Table 3.2) as well as the steady state periods are also shown in Figs 3.2 and 3.3.

Table 3.2: Operational changes made to the MUCT1 system.

Day	Change	Reason
1	Set up system with initial design parameters: a-recycle 2:1, s-recycle 1:1, r-recycle 1:1	
28	a-recycle increased to 3:1	To ensure more nitrate is recycled to the 2nd anoxic reactor for denitrification.
129	Dose 720 mgNO_3-N/d to 2nd anoxic reactor	To ensure presence of excess nitrate in the 2nd anoxic reactor so as to observe the effect on DSVI.
239	Stop nitrate dose to 2nd anoxic reactor	Observe effect of nitrate limitation on DSVI which had increased due to nitrate dosage.
340	Terminate operation	Investigation complete.

(a)



(b)

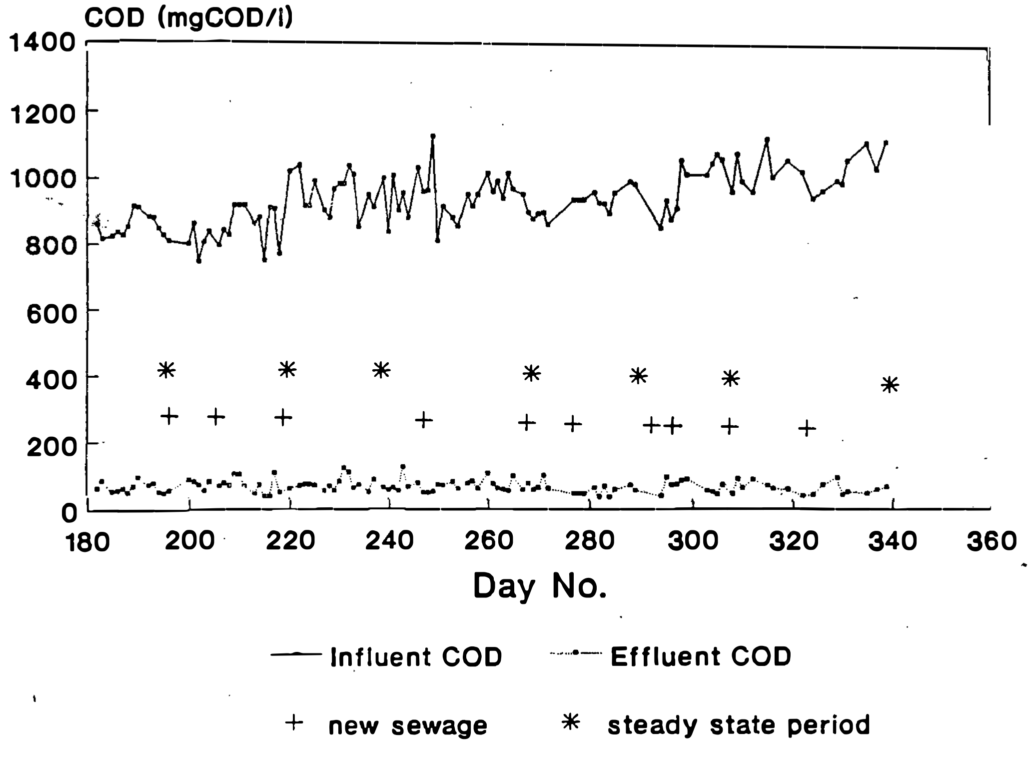
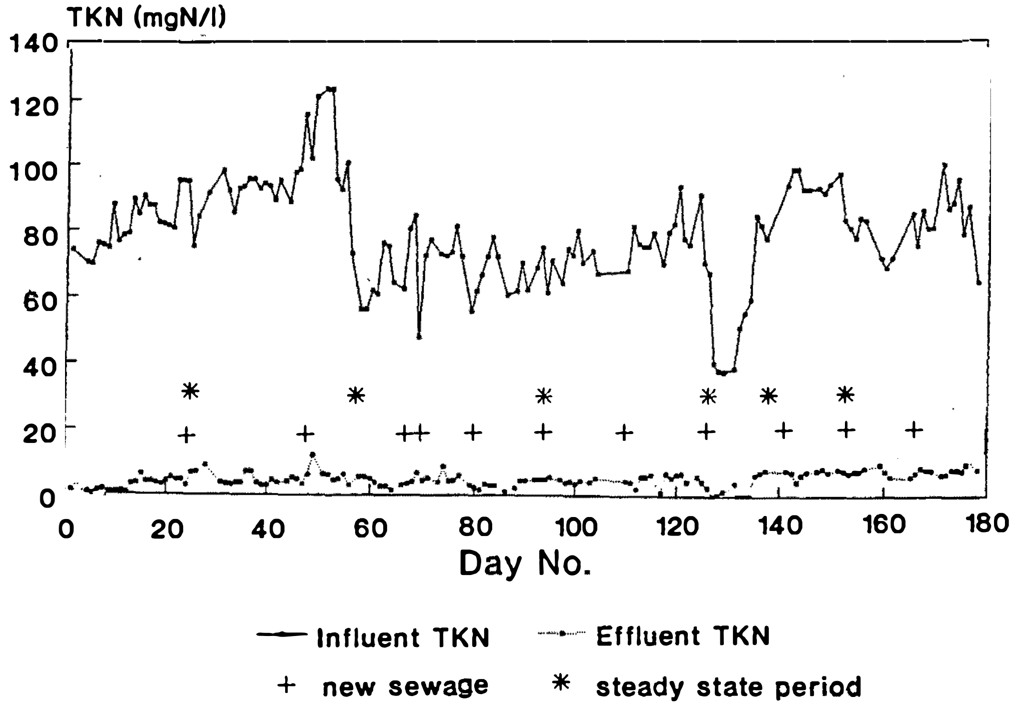


Fig 3.2 The daily influent and effluent COD concentrations from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)



(b)

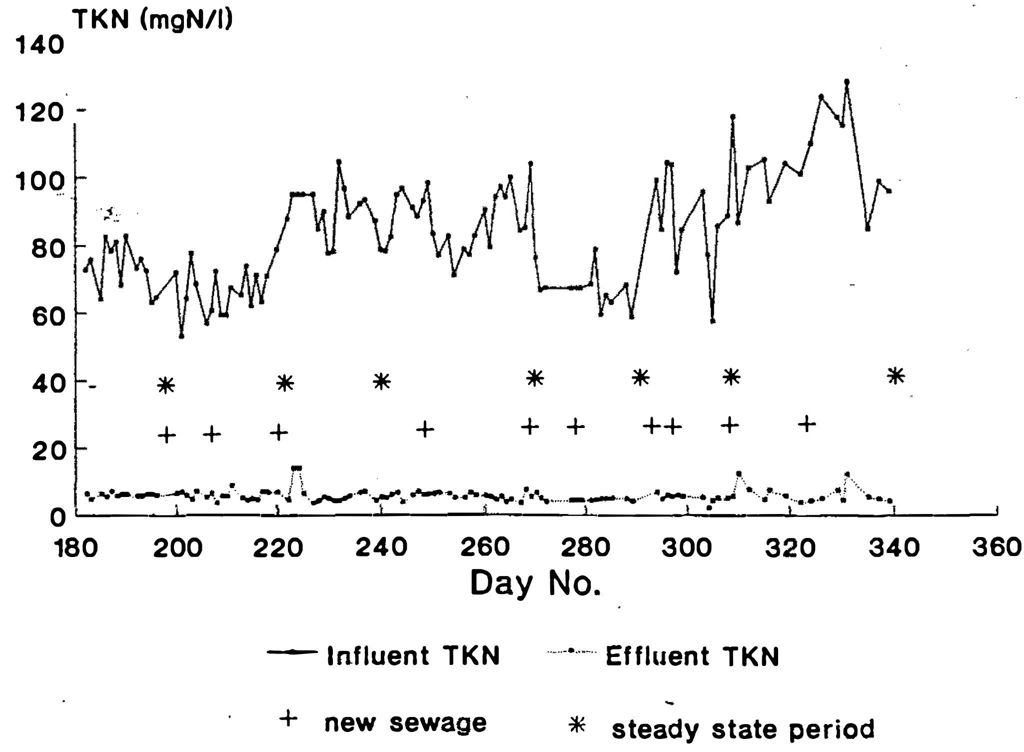
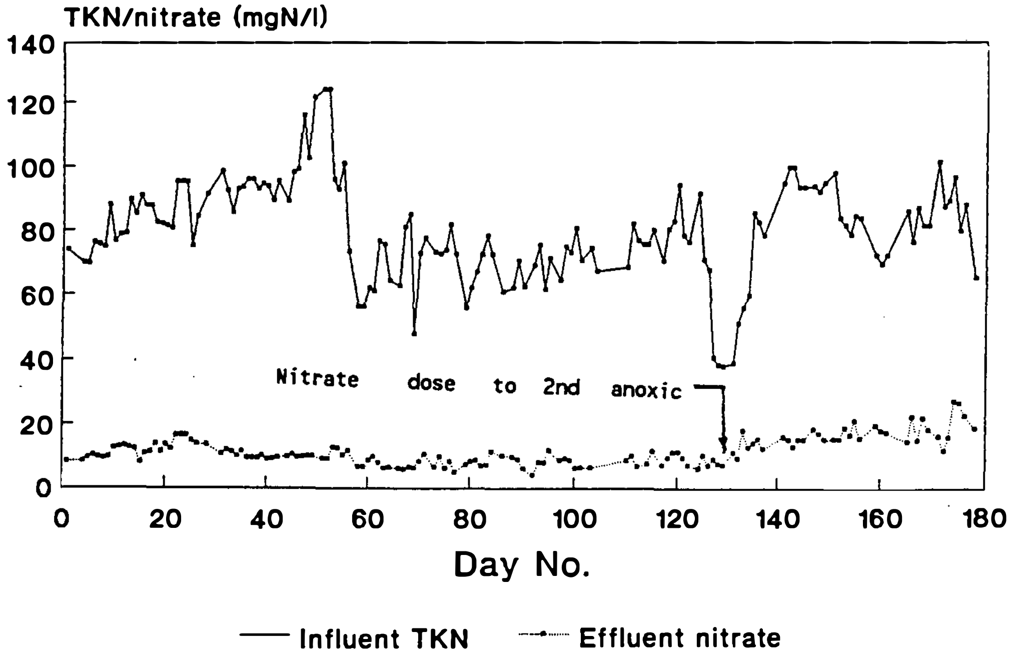


Fig 3.3 The daily influent and effluent TKN concentrations from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)



(b)

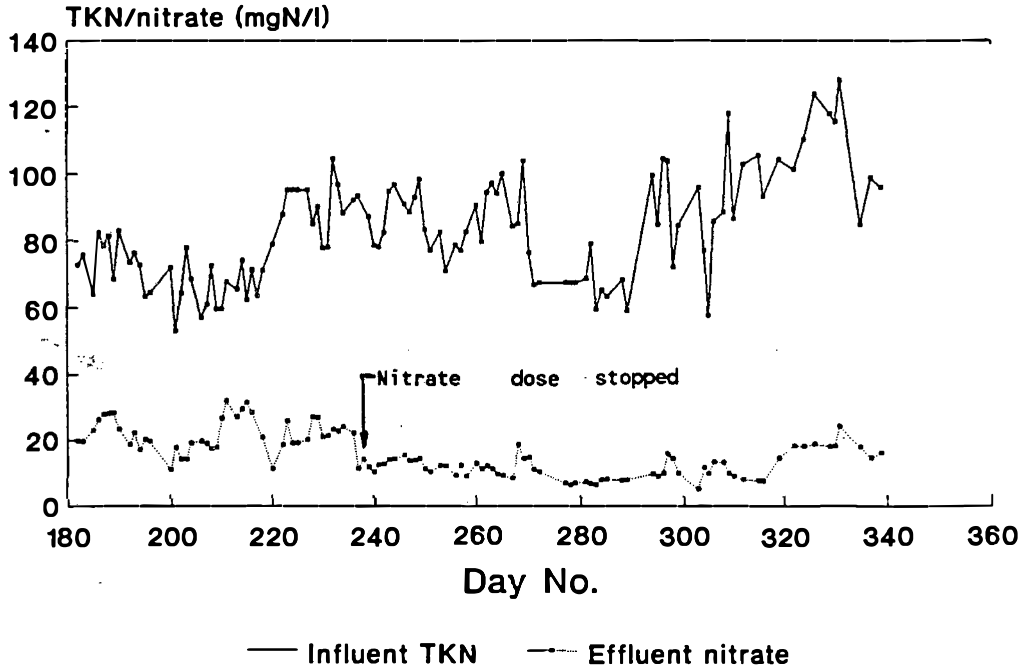


Fig 3.4. The daily influent TKN and effluent nitrate concentrations from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)

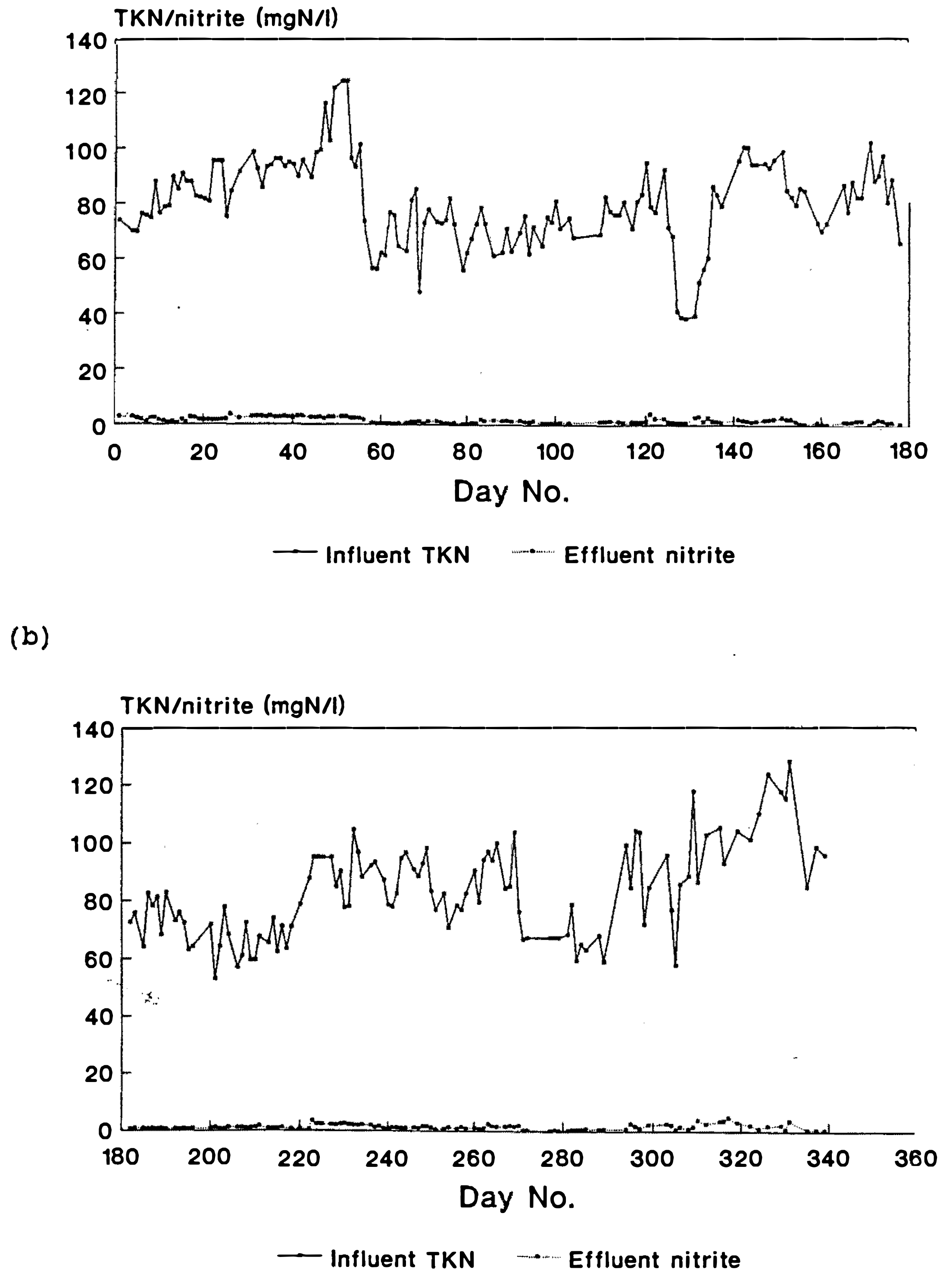
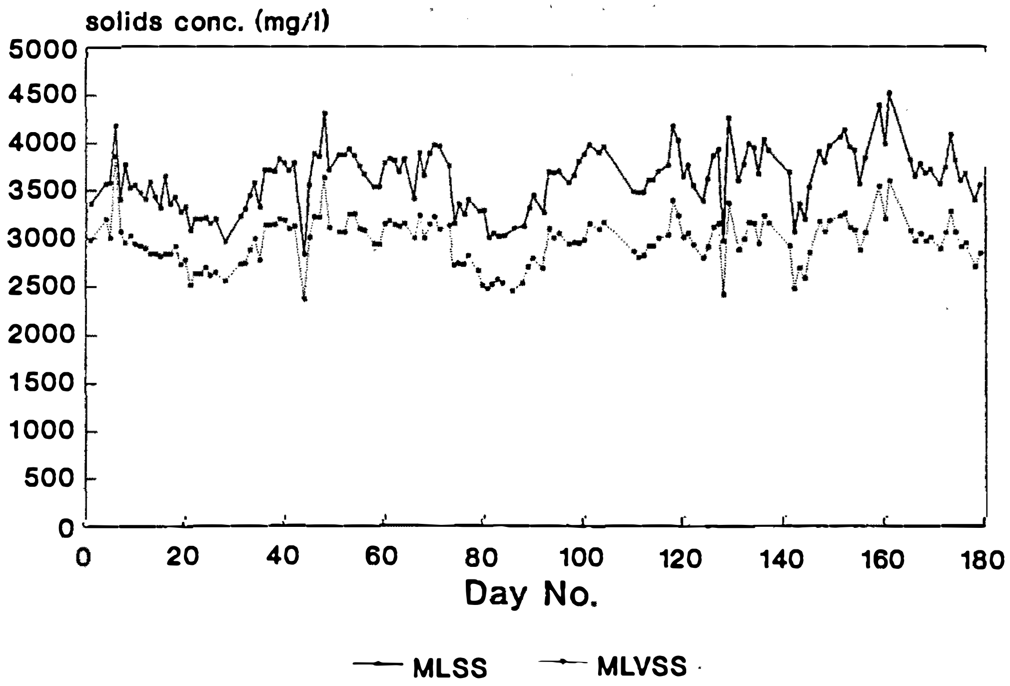


Fig 3.5 The daily influent TKN and effluent nitrite concentrations from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)



(b)

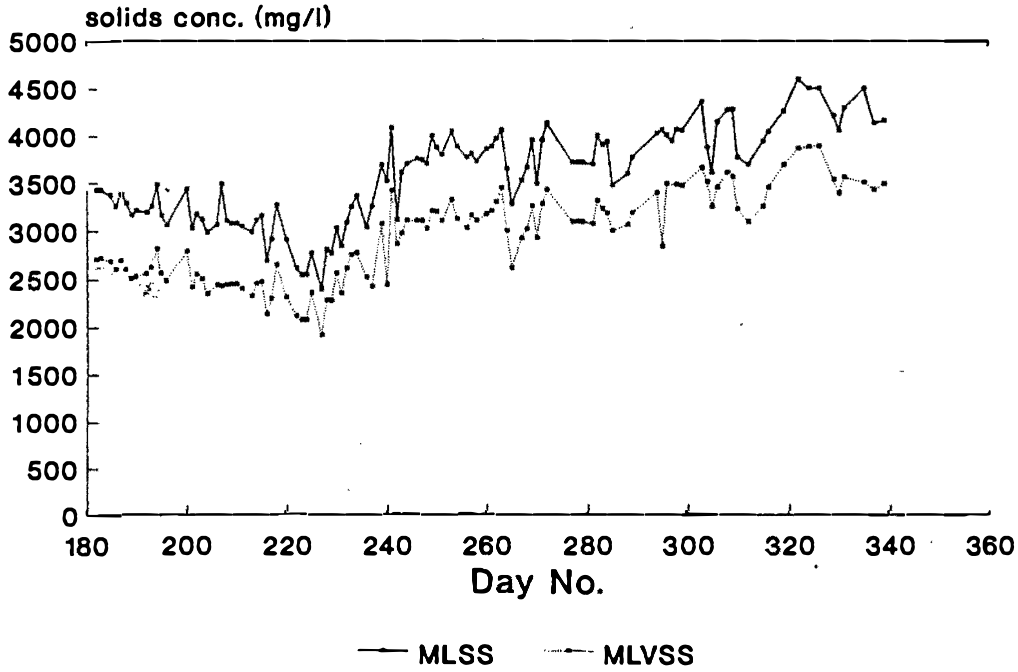
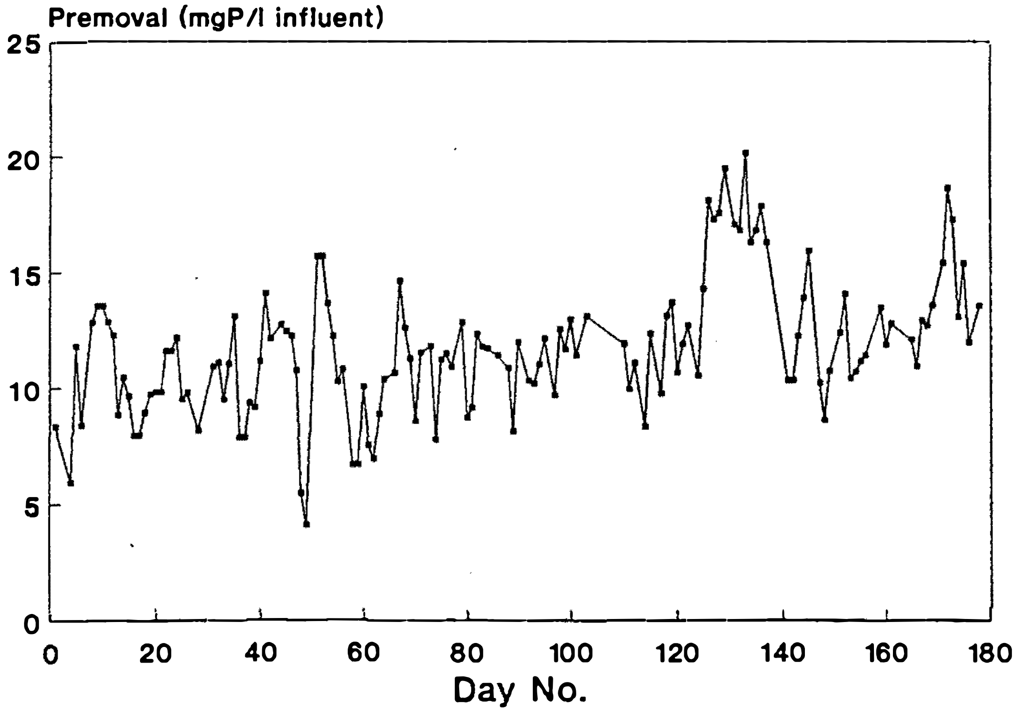


Fig 3.6 The daily MLSS and MLVSS concentrations from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)



(b)

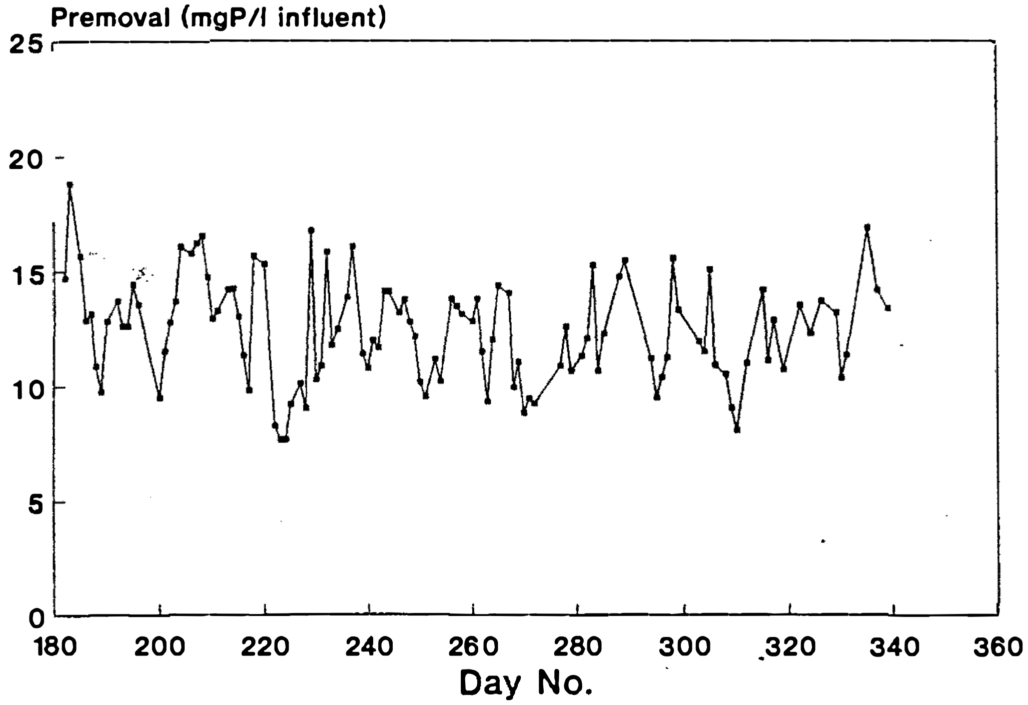
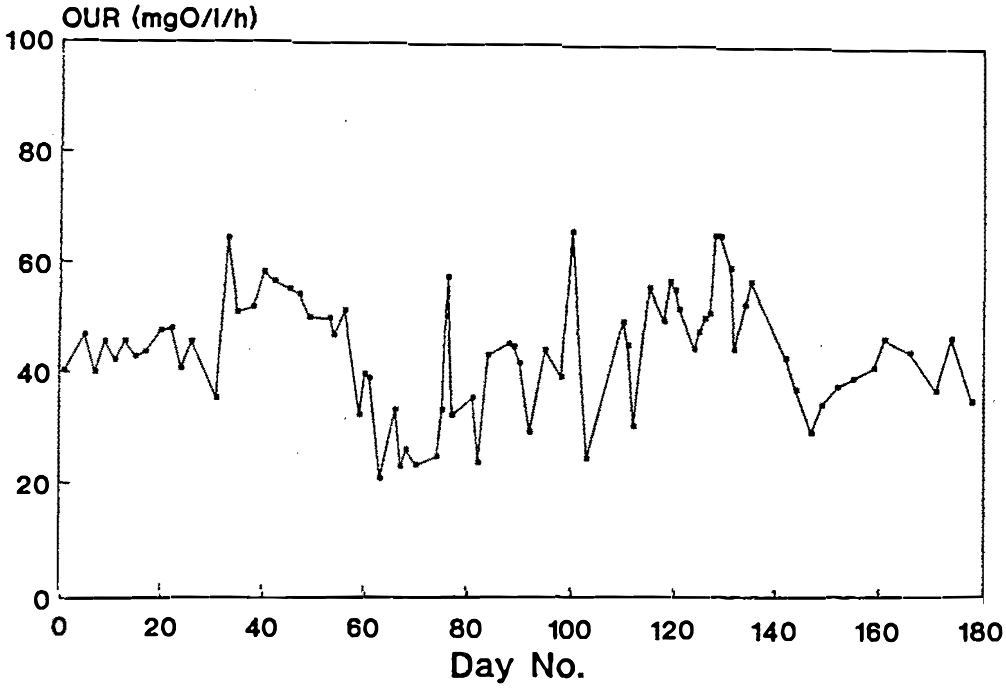


Fig 3.7. The daily P removal (per litre influent) from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.

(a)



(b)

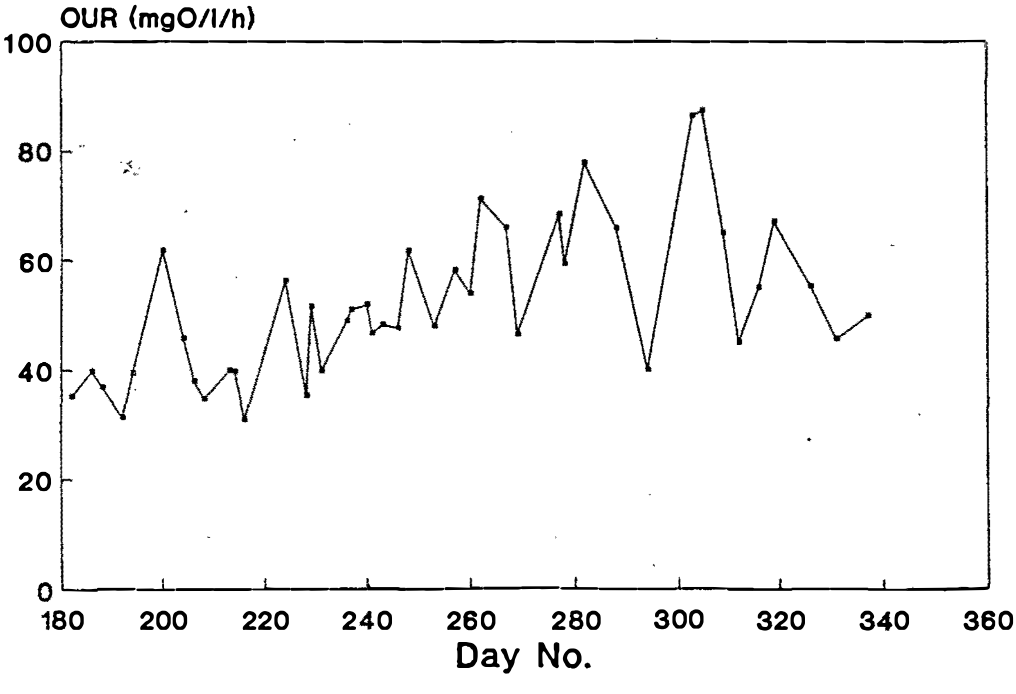
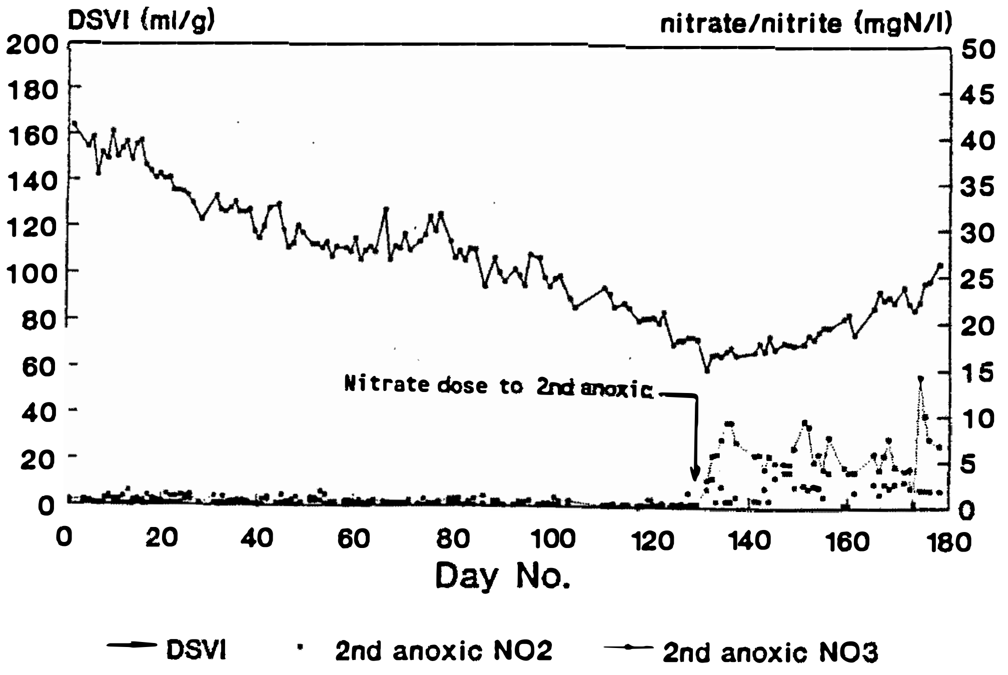
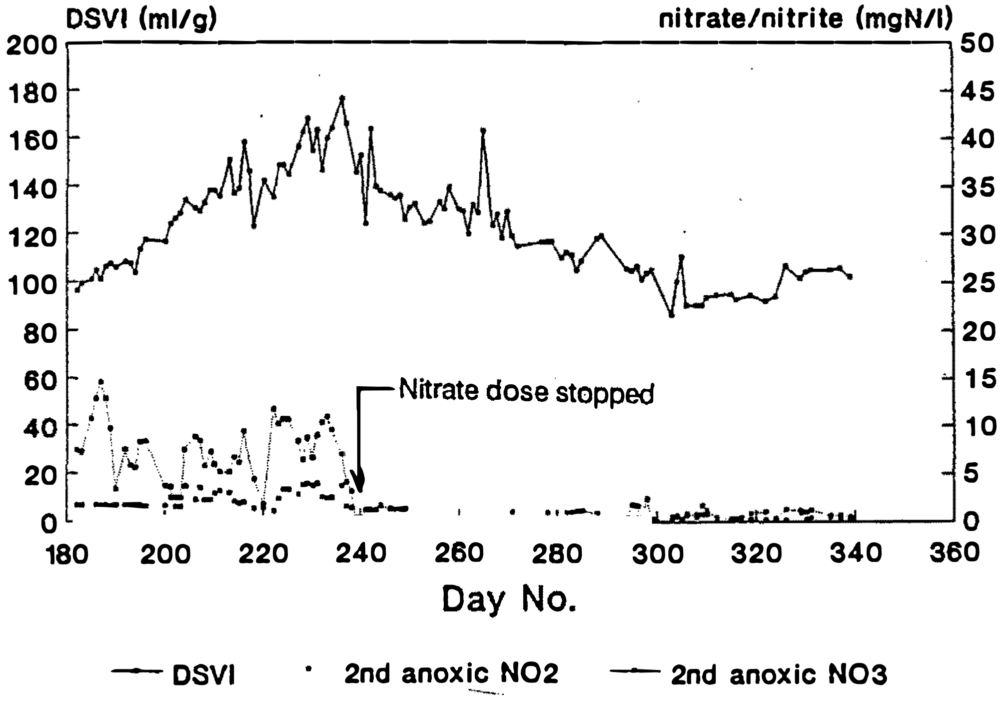


Fig 3.8 The oxygen utilization rate measured in the aerobic reactor from (a) day 0 to 180 and (b) day 180 to 360 for the MUCT1 system.



Day No.	DSVI	Dominant Filament	Secondary Filament	Other Filaments Present	Relative Amount of Filaments	Remarks
61	105	0092	021N	0041 M parvicella H hydrossis	Common to v. common	Bridging present algae and diatoms
119	82	0092	021N	H.hydrossis M.parvicella 0041	V. common	

Fig 3.9a Sludge settleability in DSVI from day 0 to 180 for the MUCT1 system. Also shown on this figure are the filament identifications done every 3 to 4 weeks.



Day No.	OSVI	Dominant Filament	Secondary Filament	Other Filaments Present	Relative Amount of Filaments	Remarks
181	96	0914	0092 Beggiatoa	M parvicella 0041;H.hydrossis Flexibacter	Common	Bridging between flocs present but not common
202	126	0092	M.parvicel	0803,0041 H.hydrossis	Abundant	Bridging common
237	165	0092	0041	M.parvicella 0803,021N	Common	
270	129	0092	021N	0803;0041 M.parvicella	V.common	Bridging present
308	91	0092	021N	M.parvicella 0041;0675 H.hydrossis Thiothrix sp.	Common to very common	Bridging common

Fig 3.9b Sludge settleability in DSVI from day 180 to 340 for the MUCT1 system. Also shown on this figure are the filament identifications done every 3 to 4 weeks.

3.2.1 Mass balances

In order to test the accuracy of the measured system response data, nitrogenous material (N) and carbonaceous material (COD) mass balances were performed on the average response data of the system for each steady state period and the results of these are shown in Table 3.3. These balances operate on the principle that the N and COD that enter the system should be accounted for by the N and COD that leave the system. N and COD balances ranging from 95% to 105% are accepted as good balances and indicate that the experimental data are acceptable. Reliable balances are obtained when a prolonged steady state period is achieved in the systems. Details of the procedure to determine N and COD balances is given in Appendix B.

Table 3.3: Nitrogen and COD mass balances for the MUCT1 system.

Period	Day to	Day	Nitrogen	COD
1	1	22	98	82
2	23	55	99	86
3	56	92	106	81
4	93	125	106	95
5	126	137	104	116
6	138	152	101	91
7	153	196	106	101
8	197	220	114	103
9	221	239	92	99
10	240	269	107	90
11	270	290	108	120
12	291	308	110	114
13	309	340	110	112
Weighted average			105	106

3.2.1.1 *The N mass balance*

Nitrogen balances ranging from 92 to 110% were obtained giving a weighted average of 105% over the whole investigation. Ten periods out of the 13 show N balances greater than 100% which shows that more N was accounted for as leaving the system than that entering it. These N balances are satisfactorily accurate but it was noted that these tend to be somewhat higher than obtained in the past for other systems operated in the laboratory (see Clayton *et al.*, 1989; Ketley *et al.*, 1991 and Hulsman *et al.*, 1992) where acceptable nitrogen balances were also obtained but tended to be somewhat less than 100%.

The reason for these higher or lower N mass balances is that the N balance is very sensitive to the nitrate and nitrite concentration leaving the anoxic reactors especially at high recycle ratios: e.g. for the MUCT systems operated in this investigation (a-recycle = 3:1) a 1 mgN/ℓ difference in the nitrate concentration of the outflow of the second anoxic reactor makes a 5% difference on the N mass balance.

3.2.1.2 *The COD mass balance*

COD balances ranging from 82% to 120% were obtained with a weighted average of 106%. Six out of the 13 steady state periods show balances greater than 100% like in the case of N balances. The COD balances are good indicating reliable data were obtained but unusual compared to other systems run in the laboratory because they tend to be above 100% rather than below 100%. Warburton *et al.* (1991), Ketley *et al.* (1991) and Hulsman *et al.*, (1992) who all operated N removal systems (not N&P removal systems as in this investigation) all found poor COD mass balances. This was attributed to the effect of the large anoxic mass fraction (50-70%) in some of the systems which they said led to lower COD recoveries than in fully aerobic systems.

In contrast to N removal systems, Clayton *et al.* (1989) obtained good COD mass balances (94%) with MUCT N&P removal systems with a 35% anoxic sludge mass fraction. These systems like the ones operated in this investigation displayed unusually high MLSS and MLVSS concentrations leading to a high estimated value of the unbiodegradable particulate COD fraction (f_{up}) (See below section 3.2.2). In view of this, good COD mass balances are obtained in MUCT systems irrespective of the size of the anoxic sludge mass fraction due to higher than expected (from WRC, 1984) MLSS and MLVSS masses accumulating in these systems (in this case 30% higher;

see section 3.2.2). The acceptable N and COD mass balances obtained indicate that reliable experimental data were obtained and no significant error was made in the operation and analytical procedures during the investigation.

3.2.2 Estimation of the values of the soluble and particulate unbiodegradable fractions of the sewage and the active fraction of the VSS

As mentioned above in the COD balances (section 3.2.1.2) the higher than expected MLVSS concentrations obtained in the MUCT systems compared to N removal systems (fed with the same Mitchell's plain raw sewage) prompted an estimation of the sewage characteristics f_{us} and f_{up}, ie the soluble and particulate unbiodegradable COD fractions. Usually for the MUCT systems values of the MLVSS concentrations measured were considerably higher than those predicted using the WRC (1984) recommended values of f_{up} and f_{us} (i.e. 0,13 and 0,05 respectively) in the steady state equations. This is because the poly phosphate organisms contribute more to the MLVSS mass per COD mass utilized by them than the ordinary heterotrophs (Wentzel *et al.*, 1990a). However because Clayton *et al.* (1989) used the WRC (1984) procedure to calculate the f_{up} value, for comparative purposes this approach also is initially adopted in this section. Thereafter the f_{up} values are recalculated with the aid of the Wentzel *et al* (1990) model for BEPR systems and compared with the WRC (1984) f_{up} values.

For the WRC (1984) model theoretically the total mass of volatile suspended solids $M(X_v)$ in an activated sludge system receiving a certain wastewater is given by (WRC, 1984)

$$M(X_v) = R_sM(S_{ti})\{(1-f_{up}-f_{us})Y_h(1+fb_hR_s)/(1+b_hR_s) + f_{up}/f_{cv}\} \qquad (3.1)$$

where

$M(X_v)$ = mass of volatile suspended solids in the system (mgVSS)

R_s = sludge age (d)

$M(S_{ti})$ = mass of total influent COD per day (mgCOD/d)

f_{us} = soluble unbiodegradable fraction of influent sewage

f_{up} = particulate unbiodegradable fraction of the influent sewage

Y_h = heterotrophic organism yield coefficient
= 0,45 mgVSS/mgCOD

f = unbiodegradable fraction of active mass
= 0,20 mgVSS/mgVSS

b_h = endogenous mass loss rate for heterotrophic organisms
= 0,24/d (at 20^{0}C)

f_{cv} = COD to VSS ratio of volatile sludge mass
= 1,48 mgCOD/mgVSS

The measured mass of VSS ie $M(X_v)$ is found from the measured MLVSS concentration and the total process volume V_p taking due consideration that the anaerobic reactor has a lower MLVSS concentration than the subsequent reactors.

$$M(X_v) = X_{va}[(V_p-V_{an})+V_{an}/(1+r)] \qquad (3.2)$$

where

X_{va} = MLVSS concentration in aerobic reactor (mg/ℓ)
V_p = total volume of reactors
V_{an} = volume of anaerobic reactor
r = recycle ratio to anaerobic reactor

The value of f_{us} in Equation 3.1 can be estimated from the filtered effluent COD (S_{te}): since the influent RBCOD is rapidly utilized and the PBCOD becomes adsorbed and enmeshed in the sludge and removed from the system via the daily sludge waste then the filtered effluent COD is wholly unbiodegradable influent COD (van Haandel *et al.*, 1981).

The f_{us} value is therefore given by

$$f_{us} = S_{te}(\text{filtered})/S_{ti} \qquad (3.3)$$

The f_{up} value is then calculated by trial and error till the theoretical and measured $M(X_v)$

values correspond.

Knowing f_{us} and f_{up}, the active volatile solids mass in the system $M(X_a)$ is calculated as follows

$$M(X_a) = (1-f_{us}-f_{up})M(S_{ti})Y_hR_s/(1+b_hR_s) \qquad (3.4)$$

and the active fraction

$$f_{av} = M(X_a)/M(X_v) \qquad (3.5)$$

The measured average MLVSS concentrations for the 13 steady state periods are all higher than those calculated with the usual value of f_{up} of 0,13. The MLVSS also changed during the investigation and was lower during periods when nitrate was dosed to the second anoxic reactor than when nitrate was not dosed. The values of f_{up} estimated for each steady state period are shown in Table 3.4.

Table 3.4: Values of the unbiodegradable particulate COD fraction estimated for each steady state period.

Period	Day From	Day To	X_v	f_{us}	f_{up}[2]	f_{up}[3]
1	1	22	2926	0,066	0,30	0,28
2	23	55	2980	0,069	0,30	0,30
3	56	92	2858	0,075	0,33	0,33
4	93	125	3059	0,072	0,36	0,39
5[1]	126	137	3116	0,078	0,31	0,32
6[1]	138	152	2943	0,069	0,29	0,29
7[1]	153	196	2890	0,071	0,32	0,33
8[1]	197	220	2440	0,082	0,28	0,27
9[1]	221	239	2350	0,078	0,21	0,18
10	240	269	2818	0,076	0,30	0,31
11	270	290	3195	0,070	0,39	0,41
12	291	308	3417	0,072	0,40	0,42
13	309	340	3564	0,066	0,38	0,39

Note:
1. Nitrate dosed to 2nd anoxic reactor.
2. f_{up} calculated with WRC (1984) model.
3. f_{up} calculated with Wentzel *et al.* (1990) model.

The f_{up} value decreases from 0,36 during period 4 (prior to nitrate dosing to the second anoxic reactor) to 0,21 during period 9 (end of nitrate dosing period). The value increases again to 0,4 from period 10 to period 13 after stopping nitrate dosing. This trend in f_{up} is as a result of the MLVSS concentration changing in the same pattern. The average f_{up} and f_{us} values over the whole investigation are 0,32 and 0,073 respectively giving an active fraction with respect to the volatile suspended solids f_{av} of 0,15.

The biological excess phosphorus removal (BEPR) steady state model of Wentzel *et al.*, 1990) separates poly P organisms from non-Poly P organisms and the f_{up} values with this model were also calculated. To simplify the calculation it was assumed that all the influent RBCOD was used for the growth of Poly P organisms and the slowly biodegradable COD (SBCOD) by the non-Poly P heterotrophic organisms. The average f_{up} remained the same as the one calculated using WRC (1984) at f_{up}=0,32.

The f_{up} value obtained for the system is much higher than that recommended for raw municipal sewage of f_{up} = 0,13 (WRC, 1984). Clayton *et al.* (1989) using the WRC (1984) method also measured high values of f_{up} in a laboratory MUCT system; for this system, which had an unaerated sludge mass fraction of 51% they found an average f_{up} of 0,20. They explained the higher than expected MLVSS concentrations as due to the feeding procedure which involved breaking up of coarse material by rubbing it through the sewage sieve thereby adding additional particulate material to the sewage fed compared to feeding sewage that passes through the sieve normally. However in the systems operated in this investigation this rubbing through the strainer feeding procedure was not used yet much higher than 0,13 f_{up} values were obtained, indeed values much higher than Clayton *et al.* (1989) also. Therefore the rubbing through the sieve procedure could not have been the reason for the higher f_{up} in Clayton's systems, and it was accepted that some process feature caused the higher MLVSS mass; the most likely feature being the unaerated mass fraction. Because the anoxic mass fraction of Clayton *et al* (1989) and in this investigation were 35% and 65% respectively and the f_{up} values in the MUCT systems of Clayton *et al* (1989) were lower than that in this investigation, it appears that the f_{up} value increases as the anoxic sludge mass fraction increases. However, because it was found in this investigation, that over loading the anoxic reactor with nitrate cause the f_{up} value to decline to Clayton's value (i.e. approximately 0,20) the link between increasing anoxic mass fraction applies only when the anoxic reactors are under loaded with respect to their denitrification potential. To ameliorate low F/M filament bulking, underloaded anoxic reactors are desired (see below) and therefore nutrient removal systems operated to control low F/M filament bulking can be expected to generate greater masses of sludge at fixed sludge age and mass COD load.

The cause for the increase in f_{up} is unlikely to be additional unbiodegradable particulate COD as the f_{up} term suggests, rather a different phenomenon causes this apparent increase in the f_{up} value of the model. The possible phenomenon being the difference in the yield of the floc-formers and filaments in underloaded anoxic (with respect to nitrate or nitrite) conditions. However further investigations still need to be done in order to determine these phenomena.

3.2.3 COD Removal

The influent COD varied from 800 to 1100 mgCOD/ℓ and the effluent COD varied from 65 to 100 mgCOD/ℓ thereby giving a COD removal greater than 90%. There was no change in COD removal of the system due to the dosing of nitrate to the second anoxic reactor.

3.2.4 Nitrification and estimation of specific growth rate for nitrifiers

Nitrification occurs only in the aerobic zone since nitrifiers are obligate aerobes. With a 20 day sludge age, the maximum design unaerated sludge mass fraction is given by (WRC, 1984):

$$f_{xm} = 1-S_f(b_{nT}+1/Rs) \qquad (3.6)$$

where

S_f = safety factor for nitrification

= 1,25

b_{nT} = specific endogenous mass loss rate for Nitrosomonas

= 0,04 (/d) at 20°C

U_{nmT} = maximum specific growth rate for nitrifiers at T°C (/d)
= $U_{nm20}(1,123)^{(T-20)}$
U_{nm20} = the rate at 20°C
R_s = sludge age (d)

With U_{nm20} = 0,45 /d which is the recommended value for raw sewage, f_{xm}=0,75 for the MUCT systems operated in this investigation. The actual f_{xm} of the systems was 80% making it five percent higher than the calculated design value. However despite this, the average system influent and effluent TKN were 82,4 and 5,12 mgN/ℓ respectively giving a nitrification efficiency greater than 90%. This showed that the specific growth rate for nitrifiers at 20°C was higher than 0,45 /d.

During the investigation the random effluent ammonium concentration measurements were used to calculate the U_{nm20} value. The effluent TKN concentration (which includes the free and saline ammonia) indicated that dosing of nitrate to the second anoxic reactor did not affect the effluent TKN concentrations and therefore also not the effluent ammonium concentrations. The average of the random effluent ammonia concentrations measurements over the experimental period was 2.5 mgN/ℓ.

An estimate of the actual maximum specific growth rate of the nitrifiers at 20°C, U_{nmT20} can be made using the measured effluent ammonia concentration and a rearrangement of the effluent ammonia concentration equation in WRC (1984), viz:

$$U_{nmT20} = \{(K_n + N_{ae})(b_{nT} + 1/R_s)\}/\{(1-f_{xt})N_{ae}\} \qquad (3.7)$$

where

K_n = half saturation constant {mg(NH_3-N)/ℓ}
= 1,0 mgN/ℓat 20°C
N_{ae} = concentration of ammonia surrounding the organisms {mg(NH_3-N)/ℓ}
b_n = specific endogenous mass loss rate for *Nitrosomonas*
= 0,04 /d) at 20°C
f_{xt} = unaerated sludge mass fraction

R_s = sludge age

The average specific growth rate calculated for the system was 0,63 /d which is within the range of 0,20-0,70 /d for municipal wastewaters in South Africa but significantly higher than the recommended design value of 0,45/d (WRC, 1984).

3.2.5 Biological Excess Phosphorus removal

Unlike the COD and N balances mentioned above a phosphorus (P) mass balance can not be easily performed for the system unless the P content of the VSS wasted per day is measured, which was not done in this investigation. In order to compare the P release, uptake and removal behaviour of the MUCT system with the steady state design theory for biological excess phosphorus removal (BEPR) (Wentzel *et al.*, 1990), the average phosphorus concentrations in each of the reactors and effluent for each of the steady state periods were used to calculate the release or uptake in each reactor and the system P removal. The uptake (+ve) or release (-ve) in each reactor is given by

$$\text{P concentration into the reactor} - \text{P concentration out of the reactor} \qquad (3.8)$$

The measured P removal is the difference between the influent and effluent concentrations. Because of the difference between the aerobic and effluent P concentrations, the release or uptake in the settling tank was included. Table 3.5 shows the release, uptake and removal values for the 13 steady state periods.

Table 3.5: P release (-ve) and P uptake (+ve) in the reactors and settling tank of the MUCT1 system and overall system removal.

Per.	Panaer. mgP/ℓ	Panox.1 mgP/ℓ	Panox.2 mgP/ℓ	Paer. mgP/ℓ	Psett. mgP/ℓ	Prem. mgP/ℓ
1	-6,0	-10,5	+3,5	+23,0	+0,5	+10,5
2	-8,0	-23,9	+6,5	+35,5	+0,8	+10,9
3	-16,0	-13,1	+9,0	+30,4	+0,1	+10,4
4	-18,4	-13,2	+7,2	+35,1	+1,0	+11,7
5	-26,3	-14,1	+39,9	+18,9	+0,7	+17,7
6	-31,5	-2,9	+33,7	+14,8	+2,1	+12,0
7	-32,7	-6,9	+37,9	+13,1	+2,0	+13,4
8	-30,2	-8,4	+39,9	+10,1	+2,3	+13,7
9	-17,7	-21,7	+38,5	+11,8	+0,5	+11,4
10	-17,9	-21,4	+21,6	+28,0	+1,6	+11,9
11	-18,5	-15,5	+5,1	+38,3	+1,6	+11,0
12	-17,9	-7,4	+16,1	+17,9	+3,2	+11,9
13	-16,5	-10,1	+19,0	+16,1	+3.8	+12,3

Note
Nitrate dosed to second anoxic during periods 5 to 9.

The data in Table 3.5 show that there was considerable P release and P uptake in the first anoxic and second anoxic reactors respectively. The P release in the first anoxic reactor was higher than 10 mg/ℓ (and higher than the release in the anaerobic reactor for periods 1, 2, 9 and 10) for most of the time except during steady state periods 6, 7, 8 (which form part of the periods when nitrate was dosed to the second anoxic reactor). Because of the very low concentration of nitrate in the first anoxic reactor during periods 1 to 4 and 10 to 13 thus creating virtually anaerobic conditions, P release was stimulated like in the anaerobic reactor. Dosing of nitrate to the second anoxic reactor increased the concentration of nitrate in the first anoxic reactor as well hence the reduction in P release in this reactor during these periods. P uptake in the second anoxic reactor was low (<10 mg/ℓ) during the first 4 periods but increased to 40 mg/ℓ during period 5 when nitrate was dosed to the second anoxic reactor remaining higher than the P uptake in the aerobic reactor until nitrate dosing was stopped in period 10. The presence of excess nitrate which acts as an electron acceptor in the absence of oxygen during periods 5 to 10 stimulated more P uptake in this reactor than in the following aerobic reactor.

To calculate the P removal with the steady state BEPR design theory the readily biodegradable COD concentration is required to be known. This was measured in a separate system set up specifically for this purpose (Ekama *et al.*, 1986). The parameters required as input by the model were obtained from the average values measured for each steady state period as well as the estimated values of f_{us} and f_{up} for these periods. In the interests of brevity, the steady state model equations have not been included in this text and reference should be made to Wentzel *et al.*, (1990). Table 3.6 shows the theoretically calculated and measured P removal values for each steady state period and a graphical representation is shown in Fig. 3.10. Also shown in Table 3.6 is the measured P removal as a % of the calculated value and the theoretically calculated and measured Prelease/Puptake and the Premoval/Prelease ratios.

From Table 3.6 the system removed less phosphorus than expected, an average of 12,20 mg P/ℓ instead of an expected average of 21,34 mgP/ℓ over the whole investigation period. Dosing of nitrate to the second anoxic reactor during periods 5 to 9 did not have any effect on the system phosphorus removal but did affect where the release and uptake took place. That the overall removal was not affected is understandable because in the MUCT system, high concentrations of nitrate in the effluent can be present without interfering with BEPR because the first anoxic reactor effectively protects the anaerobic reactor against nitrate recycle by denitrifying the nitrate recycled via the settling tank underflow. However how the nitrate dosing should affect the release and uptake is not clear: without nitrate dosing the release was principally in the first anoxic reactor, with nitrate dosing this switched to the more usual situation of most of the release taking place in the anaerobic reactor but when the nitrate dose was removed, the system again reverted to the unusual reduced release in the anaerobic reactor and a high release in the first anoxic reactor. This could not

Table 3.6 Theoretically calculated and measured P removal per litre influent for the MUCT1 system. Also shown in this table are the theoretical and measured Prelease/Puptake and Premoval/Prelease ratios.

Period	Theoretical		Measured		Premoval	Premoval	
	Prel. Pupt.	Prem. Prel.	Prel. Pupt.	Prem. Prel.	theor. mgP/l	meas. mgP/l	Pmeas. Ptheor. %
1	0.74	0.36	0.62	0.64	19.21	10.47	54.50
2	0.74	0.35	0.75	0.34	19.28	10.85	56.28
3	0.77	0.3	0.74	0.36	23.46	10.35	44.12
4	0.76	0.31	0.74	0.37	23.45	11.69	49.85
5	0.76	0.31	0.68	0.44	24.53	17.7	72.16
6	0.76	0.32	0.87	0.35	21.68	11.99	55.30
7	0.76	0.32	0.76	0.34	21.32	13.37	62.71
8	0.78	0.22	0.76	0.35	19.27	13.71	71.15
9	0.78	0.22	0.78	0.29	19.63	11.4	58.07
10	0.77	0.23	0.77	0.3	20.43	11.88	58.15
11	0.73	0.38	0.77	0.32	19.44	10.96	56.38
12	0.72	0.39	0.71	0.47	20.25	11.92	58.86
13	0.72	0.38	0.76	0.46	20.74	12.26	59.11

Note:
1. Combined anaerobic + anoxic release
2. Combined anoxic + aerobic uptake

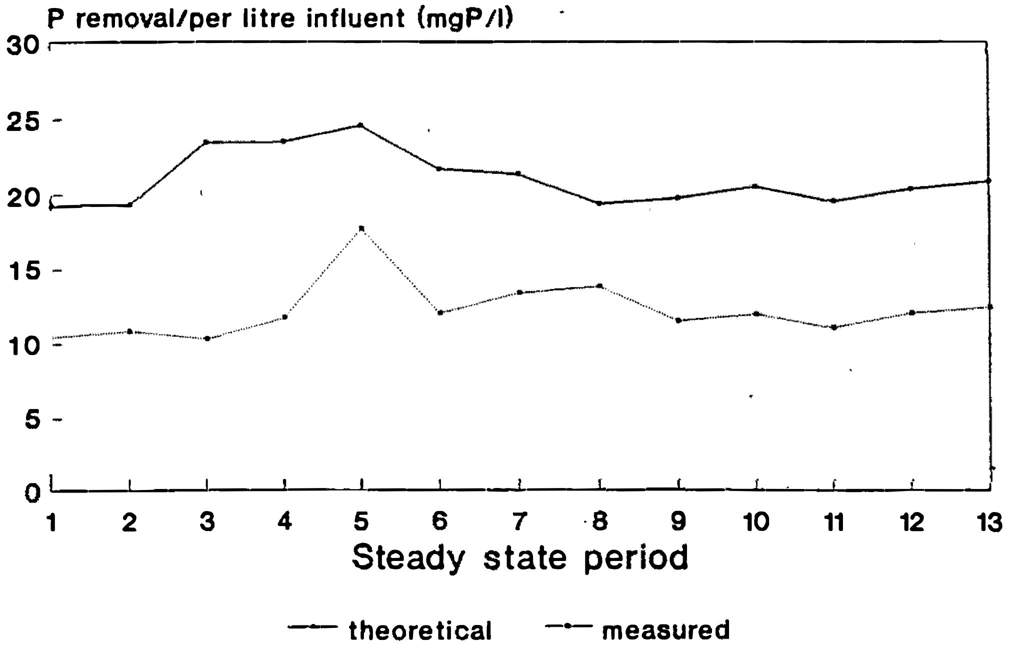


Fig 3.10 The theoretically calculated and measured P removal (per litre influent) for each steady state period for the MUCT1 system.

have happened as a result of RBCOD leakage through the anaerobic reactor because anoxic batch tests (see below) conducted on sludge harvested from the first anoxic reactor did not indicate an initial rapid rate of denitrification with RBCOD.

The values of the theoretical and total measured Prelease/Puptake ratios are close to each other for the steady state periods and the average for the 13 steady state periods is the same with a value of 0,75. The values of the theoretical and measured Premoval/Prelease ratios are also not very different but a higher average value of 0,39 is obtained for the measured values compared with 0,34 for the theoretical values. The closeness of the theoretical and measured ratios show that the system was not limited in P release or P uptake but was releasing, taking up and hence removing less phosphorus than expected as if the RBCOD concentration of the influent was 40% lower than measured.

The main factors which affect P release, P uptake and hence P removal are sludge age and anaerobic mass fraction, influent COD and the nature of influent sewage (raw or settled). The anaerobic mass fraction of the system (f_{xa}=0,15) is the minimum acceptable for design of MUCT systems with a single anaerobic reactor (Wentzel *et al.*, 1990) and the average nitrate concentration in the anaerobic reactor was less than 1 mgNO_3-N/ℓ for most of the investigation period except for periods 9, 10 and 13. These factors could therefore not have caused the low P removal observed in the systems in this investigation. The effect of the aerobic mass fraction on P uptake in the aerobic zone has not yet been investigated. It was thought that the poor P removal performance was due to the very low aerated mass fraction of 20% significantly lower than MUCT systems operated previously in the laboratory. However the low P removal could also not be ascribed to the low aerated mass fraction because from the Prelease/Puptake and Premoval/ Prelease ratios the P uptake was not limited by the low aerated mass fraction. Also 4 other MUCT systems in the laboratory fed with the same wastewater which had a 45% aerated mass fraction, also showed lower than expected P removals and of the same magnitude as the 2 systems in this investigation. Further investigations still have to be done in order to determine why the laboratory systems have shown lower P removals than those predicted by the kinetics.

3.2.6 Denitrification kinetics

The denitrification kinetics in nitrification-denitrification (ND) systems as set out by van Haandel *et al.* (1981) were accepted for describing nitrification-denitrification in nitrogen and biological excess phosphorus removal (NDBEPR) systems as well. However the work by Clayton *et al.* (1989) showed that there is, in fact a difference in the denitrification kinetics in nitrogen removal systems and in NDBEPR systems . The difference lies mainly in the absence of an initial rapid rate (K_1) and a higher second rate (K_2') of denitrification in the primary anoxic reactor, this rate being about 2 times higher in NDBEPR systems than that in N removal systems (K_2). In view of this it was decided to investigate the denitrification kinetics of the MUCT systems and compare these with the results of Clayton *et al.* (1989).

To measure the K_2' denitrification rate, a number of batch tests were conducted on sludge from the second anoxic reactor. The sludge was harvested from the first anoxic and the aerobic reactors and blended in the proportion with their flow rates into the second anoxic reactor via the inter reactor mixed liquor recycles. In cases where the nitrate concentration was low, nitrate was added to make up the concentration to about 30 mgNO_3-N/ℓ which would be adequate to last for a minimum of six hours in the batch test. Nitrate, nitrite, COD and TKN concentrations were measured on samples harvested at intervals from the batch reactor. The batch tests were also conducted with dosed nitrite instead of nitrate so as to determine the nitrite denitrification rate. The results of the batch tests are listed in Appendix C. Typical nitrate and nitrite versus time profiles observed in the batch tests are shown in Figs 3.11 and 3.12. The nitrate and nitrite profiles were evaluated and the denitrification rates calculated as shown below. The rates have been denoted as follows; K_2" is the rate with respect to the VSS and K_2' is the rate with respect to the AVSS.

3.2.6.1 *Separation into first and second rate components*

In ND systems two rates of denitrification were observed in the primary anoxic zone and a third single rate in the secondary anoxic zone. The two rates in the primary anoxic reactor are an initial rapid rate K_1, attributable to the simultaneous utilization of readily biodegradable COD (RBCOD) and adsorbed slowly biodegradable COD

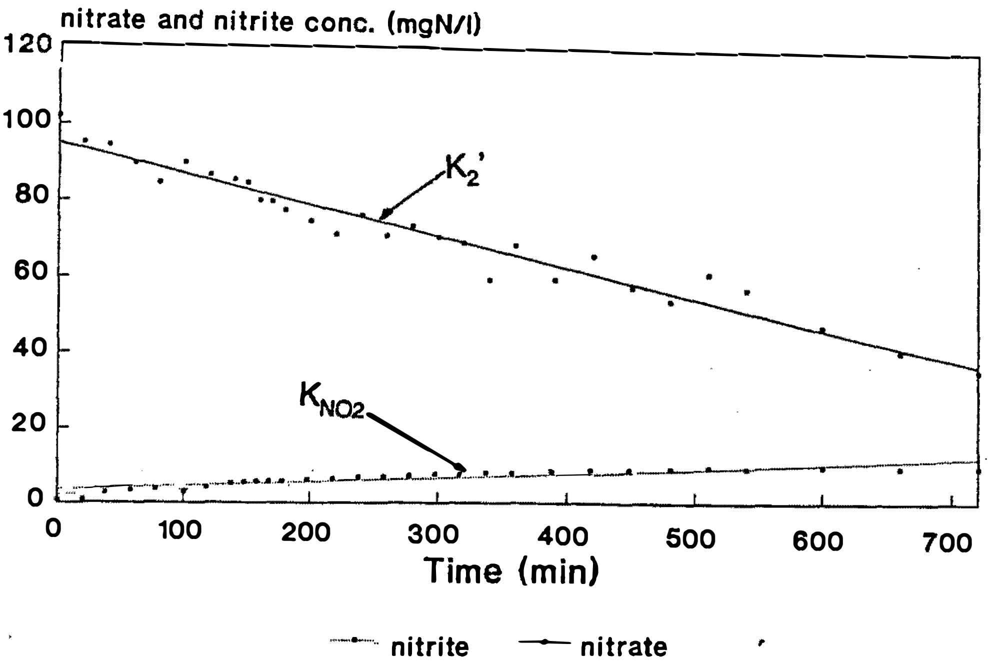


Fig 3.11 Typical nitrate vs time anoxic batch test profile.

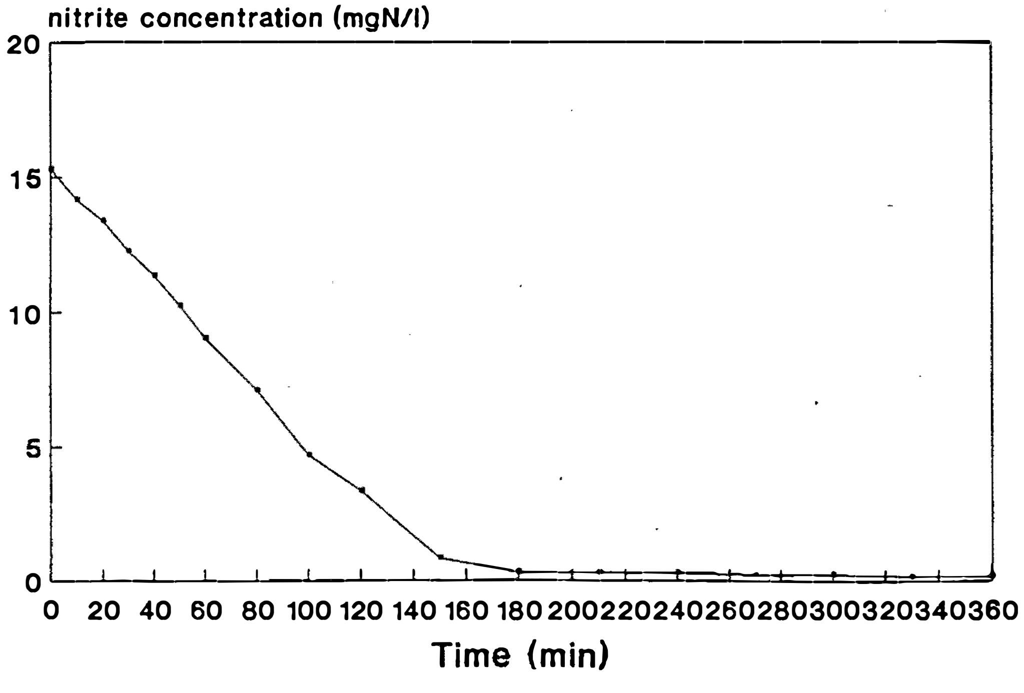


Fig 3.12 Typical nitrite vs time anoxic batch test profile.

(SBCOD) and a second slower rate K_2 attributable to the utilization of adsorbed SBCOD only (van Haandel *et al.*, 1981).

In contrast, in the 18 batch tests conducted in this investigation, only one continuous rate was observed comparable to the 2nd slow rate K_2 in N removal systems. The absence of the first rate K_1 was expected since about 70-90% of the RBCOD in the influent would have been converted to short chain fatty acids (SCFA) in the anaerobic reactor by non-Poly P organisms through the mechanisms of BEPR (Wentzel *et al.*, 1985). A single K_2' denitrification rate was also observed by Clayton *et al.* (1989) in all the 19 batch tests they conducted on the MUCT/UCT systems.

3.2.6.2 *Adjustment for nitrite formation*

When nitrate is denitrified to nitrogen gas, some nitrate is reduced only as far as nitrite and this causes an increase in the concentration of nitrite in the batch test. This increase continues until all the nitrate has been reduced. Thereafter the nitrite is reduced to nitrogen gas and its concentration decreases (see Fig 3.11). The nitrite formation rate measures the quantity of nitrate reduced only to nitrite and the difference between the nitrate disappearance and the nitrite appearance is the denitrification rate of nitrate. Stoichiometrically, when nitrate is reduced to nitrite instead of nitrogen gas, the electron accepting capacity of the nitrate is reduced with only 2/5 of the electrons being available thus:

$$K\ (\text{nitrate to } N_2 \text{ gas}) = K_{NO3} - 3/5.K_{NO2} \qquad (3.9)$$

where

K_{NO2} is the rate of formation of NO_2-N

K_{NO3} is the rate of disappearance of NO_3-N

The slopes of the nitrate profiles were adjusted for nitrite formation thus

$$\left\{\begin{matrix}\text{nitrate conc.}\\ \text{reduction per}\\ \text{unit time}\end{matrix}\right\} = \left\{\begin{matrix}\text{nitrate and nitrite}\\ \text{conc. reduction}\\ \text{per unit time}\end{matrix}\right\} - \frac{3}{5}\left\{\begin{matrix}\text{nitrite conc.}\\ \text{increase per}\\ \text{unit time}\end{matrix}\right\}$$

The nitrite denitrification rate, which takes place after the nitrate has been depleted could not be calculated from these anoxic batch tests with nitrate dosing because the sample frequency to establish this was too large. Separate anoxic batch tests with nitrite dosing were carried out on the MUCT1 system to measure the nitrite denitrification rate (see 3.2.6.5 below).

3.2.6.3 *Adjustment for the active volatile suspended mass (AVSS)*

Stern and Marais (1974) found that the specific denitrification rate expressed in terms of the MLVSS concentration X_v (i.e $mgNO_3$-N/mgVSS.d) decreased as the sludge age increased. They concluded that this was because the activity (i.e the active fraction of the MLVSS) decreased as the sludge age increased. When the denitrification rates were expressed in terms of the active VSS concentration X_a (i.e $mgNO_3$-N/mgAVSS.d), they found the resulting specific rates independent of sludge age.

Despite the variation of the MLVSS and f_{up} in the system throughout the whole investigation period, the above approach was followed and the specific denitrification rates were adjusted with respect to the AVSS.

The active fraction of the MLVSS f_{av} was calculated as shown in Section 3.2.2 above. The active MLVSS concentration is a fraction of the measured MLVSS concentration i.e

$$X_a = f_{av}.X_v \qquad (3.10)$$

The specific denitrification rate K_2'' with respect to the VSS is given by

$$K_2'' = \frac{\{\text{nitrate concentration reduction per unit time (mgN/}(\ell\text{.d)}\}}{X_v \text{ mgVSS}/\ell}$$

and adjusting for the AVSS

$$K_2' = \frac{\{\text{nitrate concentration reduction per unit time, mgN/}(\ell\text{.d)}\}}{X_a \text{ mgAVSS}/\ell} = \frac{K_2''}{f_{av}} \qquad (3.11)$$

The specific nitrate denitrification rates with respect to the VSS and AVSS calculated for each batch test are shown in Table 3.7a. The K rates with respect to the AVSS were determined from the active concentration X_a using the f_{up} value applicable for the steady state period when the batch tests were conducted. Also shown in the same table are the nitrite formation rates with respect to the MLVSS.

3.2.6.4 *Nitrate denitrification rates*

The rates measured during periods when nitrate was dosed to the second anoxic reactor (i.e periods 7 and 9 in Table 3.7a) are lower than those before nitrate was dosed (period 4). The rate decreased as nitrate dosing commenced from 0,42 $mgNO_3$-N/(mgAVSS.d) down to 0,239 (period 7), 0,332 (period 7) and 0,202 $mgNO_3$-N/(mgAVSS.d) (period 9). However after stopping the nitrate dose; the rate did not increase and remained at around 0,25 i.e 0,274 in period 11 and 0,225 $mgNO_3$-N/(mgAVSS.d) in period 13. These results seem to indicate that dosing of nitrate decreases the denitrification rate of the second anoxic reactor. This observation is confirmed by the nitrate concentrations in the second anoxic reactor which increased as the dosing of nitrate progressed (See Fig 3.9 day 130 to 240 and Appendix A for nitrate concentrations data).

The average specific nitrate denitrification rate was 0,305 $mgNO_3$-N/(mgAVSS.d). Clayton *et al.* (1989)[1] measured average rates of 0,185 $mgNO_3$-N/(mgAVSS.d) and 0,240 $mgNO_3$-N/(mgAVSS.d) for batch tests on MUCT/UCT systems and primary anoxic plug flow reactors respectively; combining their two results, they obtained a mean rate of 0,224 $mgNO_3$-N/(mgAVSS.d)

The rate obtained in this investigation is 36% higher than that obtained by Clayton *et al.* (1989) and 3 times higher than the second rate (K_2=0,101 mgN_{O3}-N/(mgAVSS.d) in the primary anoxic reactors of ND systems observed by van Haandel *et al.* (1981). This finding seems to support the hypothesis by Clayton *et al.* (1989) that "Due to a

---

[1] Clayton *et al.* (1989) estimated an average f_{up} value of 0,20 and accepted an f_{av} value of 0,24 for their study.

Table 3.7a Nitrate denitrification rates determined from anoxic batch tests for the MUCT1 system.

Batch No.	Period	Day of batch test	DSVI ml/g	MLVSS mg/l	fup	AVSS mg/l	KNO2 mgNO2-N/ (mgVSS.d)	K2'' mgNO3-N/ (mgVSS.d)	K2' mgNO3-N/ (mgAVSS.d)
1	4	104	86	2934	0.36	406	0.024	0.061	0.441
2	4	113	86	2960	0.36	406	0.009	0.057	0.416
3	7	179	84	3182	0.32	439	0.007	0.033	0.239
4	7	238	105	3034	0.32	439	0.0004	0.048	0.332
5	9	274	165	2860	0.21	525	0.0002	0.037	0.202
6	11	290	103	3213	0.39	387	0.012	0.033	0.274
7	13	317	95	3283	0.38	453	0.008	0.031	0.225

Note:
KNO2 is the nitrite formation rate.

Table 3.7b Nitrite denitrification rates determined during anoxic batch tests for the MUCT1 system.

Batch No.	Period	Day of batch test	DSVI ml/g	MLVSS mg/l	fup	AVSS mg/l	Kno2'' mgNO2-N/ (mgVSS.d)	Kno2' mgNO3-N/ (mgVSS.d)
1	11	270	103	3213	0.39	387	0.026	0.274
2	12	290	87	3253	0.4	402	0.02	0.162
3	13	317	95	3283	0.38	453	0.038	0.276

conditioning or selection effect by the anaerobic reactor, the non-poly P facultative heterotrophs acquire a faster hydrolysis/utilization rate of adsorbed PBCOD, originating from both influent and generated by organism death and lysis." The mechanisms or the conditions which stimulate this increase are still not clear.

3.2.6.5 *Nitrite denitrification rates*

The average nitrite formation rate obtained is 0,060 mgNO_2-N/(mgAVSS.d) which is 5 times lower than the average nitrate denitrification rate.

As mentioned above, the nitrite denitrification rate was obtained in anoxic batch tests with nitrite dosing. Three such tests were done on the MUCT1 system, i.e one during each of the periods 11, 12 and 13. The rates are shown in Table 3.7b. The nitrite denitrification rates were calculated from the nitrite batch test data in the same way as the nitrate denitrification rates from the nitrate batch test data with one exception; no adjustment needs to be made for nitrite formation. Generally the concentration of nitrate during the batch test was so low that the nitrate denitrification rate could not be determined in the nitrite batch tests. Indeed in supplementary anoxic batch tests (Friedrich *et al.*,1992) with high initial nitrate and nitrite concentrations (10-20 mgNO_x/ℓ) it was found that nitrite denitrification does not commence until the nitrate concentration reaches low levels (< 1mgNO_3-N/ℓ): Indeed, while nitrate is present in high concentrations (>2mgNO_3-N/ℓ) nitrite is formed at a slow rate (see Fig 3.11). A mean nitrite denitrification rate of 0,237 mgNO_2-N/(mgAVSS.d) was obtained for the system. The average nitrite denitrification rate is 80% of the average nitrate rate. This nitrite denitrification rate could not be checked with the nitrate batch test data because the nitrite concentration in these tests was too low.

3.2.7 System effluent nitrate concentrations

The system effluent nitrate concentration can be theoretically predicted according to the procedure set out in WRC design manual (1984). The denitrification potential of the anoxic zone is calculated with the aid of the following equation

$$D_{p1} = S_{bi}\{\alpha + K_2 f_{x1} Y h R_s/(1+b_{hT}R_s)\} \qquad (3.12)$$

where

D_{p1} = denitrification potential of the primary anoxic reactor (mgN/ℓinfluent)

S_{bi} = biodegradable COD concentration of the influent (mgCOD/ℓ)

α = fraction of nitrate removed by the initial rapid phase of denitrification

= $f_{bs}(1-f_{cv}Y_h)/2{,}86$

f_{bs} = readily biodegradable fraction of the influent biodegradable COD

f_{cv} = COD to VSS ratio of the volatile sludge mass

= 1,48 mgCOD/mgVSS

Y_h = heterotrophic organism yield coefficient

= 0,45 mgVSS/mgCOD

f_{x1} = primary anoxic sludge mass fraction

R_s = sludge age (d)

b_{hT} = endogenous mass loss rate for heterotrophic organisms at T°C

= $0{,}24(1{,}029)^{(T-20)}$ (/d)

For the secondary anoxic reactor:

$$Dp3 = S_{bi}f_{x3}K_3Y_hR_s/(1+b_{hT}R_s) \qquad (3.13)$$

where

D_{p3} = denitrification potential of the secondary anoxic reactor (mgN/ℓinfluent)

fx3 = anoxic sludge mass fraction of the secondary anoxic reactor.

Equation 3.12 above is used to calculate the denitrification potential for the MUCT system since the anoxic zone is all in the form of a primary anoxic zone subdivided into two reactors. The effluent nitrate concentration is calculated according to the procedure and equations given out in WRC (1984). The effluent nitrate concentration can also be predicted using the new denitrification kinetics for NDBEPR systems proposed by Clayton *et al.* (1989) and the denitrification rates measured during batch tests. The denitrification potential of the primary anoxic reactor is similar to that given for ND systems except that there is no RBCOD denitrification and the denitrification rate K_2 is replaced by the rate measured during batch tests K_2'. Hence the equation reduces to

$$D_{p1} = S_{bi}\{Y_h R_s/(1+b_{hT}R_s)\}f_{x1}K_2' \qquad (3.14)$$

The effluent nitrate concentration is then calculated according to the procedure detailed in WRC (1984).

Table 3.8 gives the measured effluent nitrate concentrations and those predicted by the two denitrification design methods given above for each of the steady state periods. The following points are noted from Table 3.8:

(a) **Periods 1 to 4 and periods 11 to 13:**

The effluent nitrate concentrations predicted by the two methods are the same and they are slightly lower than the measured values except for period 2. No nitrate was dosed to the second anoxic reactor during these periods and the TKN/COD ratio was <0,10. This resulted in the nitrate load on the anoxic reactor being less than the reactor denitrification potential. Under these conditions the effluent nitrate concentration is governed by the recycle ratio and not the denitrification kinetics (See WRC,1984) and therefore no reliable check can be made on the respective kinetic methods. Both kinetic methods underestimate the effluent nitrate concentrations by up to 3% (relative to the influent TKN).

(b) **Periods 5 to 9**

When nitrate was dosed to the second anoxic reactor thereby effectively increasing the TKN/COD ratio to between 0,13 and 0,17 the denitrification potential (D_{pp}) by the ND kinetics is less than the nitrate load on the anoxic reactor. In this case the effluent nitrate concentration is governed by the denitrification kinetics of the reactor (See WRC, 1984). The effluent nitrate

Table 3.8 Theoretical and experimental denitrification behaviour for the MUCT1 system.

Period	TKN Infl. mgN/l	 Efl. mgN/l	TKN/COD ratio mgN/mgCOD	Dpp1 mgN/l	Dpp2 mgN/l	Nc mgN/l	Nitrate load mgN/l	Theoretical NO3e1 mgN/l	 NO3e2 mgN/l	Measured NO3e mgN/l	% error 1	% error 2
1	81.4	2.91	0.082	82	193	49.2	38.7	9.84	9.84	11.7	2.3	2.3
2	97.9	5.21	0.099	82	193	62.9	52.8	12.58	12.58	9.47	-3.2	-3.2
3	69	3.98	0.075	83	167	36.4	31.6	7.28	7.28	8.13	1.2	1.2
4	76.8	4.89	0.083	80	161	41.3	35.5	8.26	8.26	8.53	0.4	0.4
5	62.4	2.77	0.13	91	195	101	97	12.45	20.2	8.27	-6.7	-19.1
6	96.1	5.9	0.168	88	198	133	123	47.45	26.6	17.9	-30.7	-9.1
7	79.8	5.91	0.163	81	174	117	110	38.45	23.4	18.9	-24.5	-5.6
8	66.7	5.85	0.163	77	167	109	104	34.45	21.8	21.4	-19.6	-0.6
9	91.2	6.49	0.172	91	208	133	123	44.45	26.6	21.5	-25.2	-5.6
10	88.9	5.89	0.094	82	181	54.8	46.3	10.96	10.96	13.7	3.1	3.1
11	67.7	4.86	0.073	69	153	30.9	27.2	6.18	6.18	7.58	2.1	2.1
12	87.2	5.28	0.089	71	159	47.7	40.6	9.54	9.54	10.9	1.6	1.6
13	106.3	6.59	0.101	78	180	64.1	53.7	12.80	12.82	14.8	1.9	1.9

Note:

1. Denotes values calculated using the ND kinetics.
2. Denotes values calculated using the NDBEPR kinetics.
3. %error=(error in NO3e/Nti)

concentrations estimated are higher than the measured values (during periods 8, 9 and 10 no RBCOD measurements were taken so the Dpp values were based on the average RBCOD fraction of the sewage).

The D_{pp} predicted by the NDBEPR kinetics is higher than the nitrate load hence the effluent nitrate prediction is once again governed by the recycle ratios and not the denitrification kinetics. The effluent nitrate concentrations predicted by the NDBEPR kinetics are (i) lower than for ND kinetics and (ii) higher than the measured value but closer to it (except for period 5).

For TKN/COD ratios greater than 0,10 the ND kinetics overestimate the effluent nitrate concentrations (which now depend on the kinetics) by as much as 30% and the error in overestimation is reduced to 10% when using the NDBEPR kinetics. The NDBEPR kinetics show that the anoxic reactor is under loaded throughout the investigation period hence the effluent nitrate prediction depended on the recycle ratios and not the kinetics. However by showing that the anoxic reactor is indeed under loaded thereby giving better estimations of effluent nitrate concentrations at high TKN/COD ratios, the NDBEPR design method is more accurate than the ND design method. Clayton *et al.* (1989) also found out that the NDBEPR kinetics gave more accurate effluent nitrate predictions at higher TKN/COD ratios than ND kinetics. This is because the NDBEPR kinetics with a single faster K_2' rate gives a better denitrification potential estimate for large anoxic mass fractions compared with the ND kinetics with an initial fast rate followed by a second slower rate (see Fig 3.13).

3.2.8 DSVI and low F/M filament bulking

The experimental work in this investigation was designed to test the effect of a large anoxic mass fraction (65%) and the concentration of nitrate and nitrite in the anoxic reactor prior to the aerobic reactor, on the low F/M filament bulking in MUCT systems. This is as a follow up to investigations by Casey *et al.* (1990, 1991, 1992a,b,c); Warburton *et al.* (1991); Ketley *et al.* (1991) and Hulsman *et al* (1992) (see Chapter 2 above) which showed that in intermittently aerated nitrogen removal systems at low

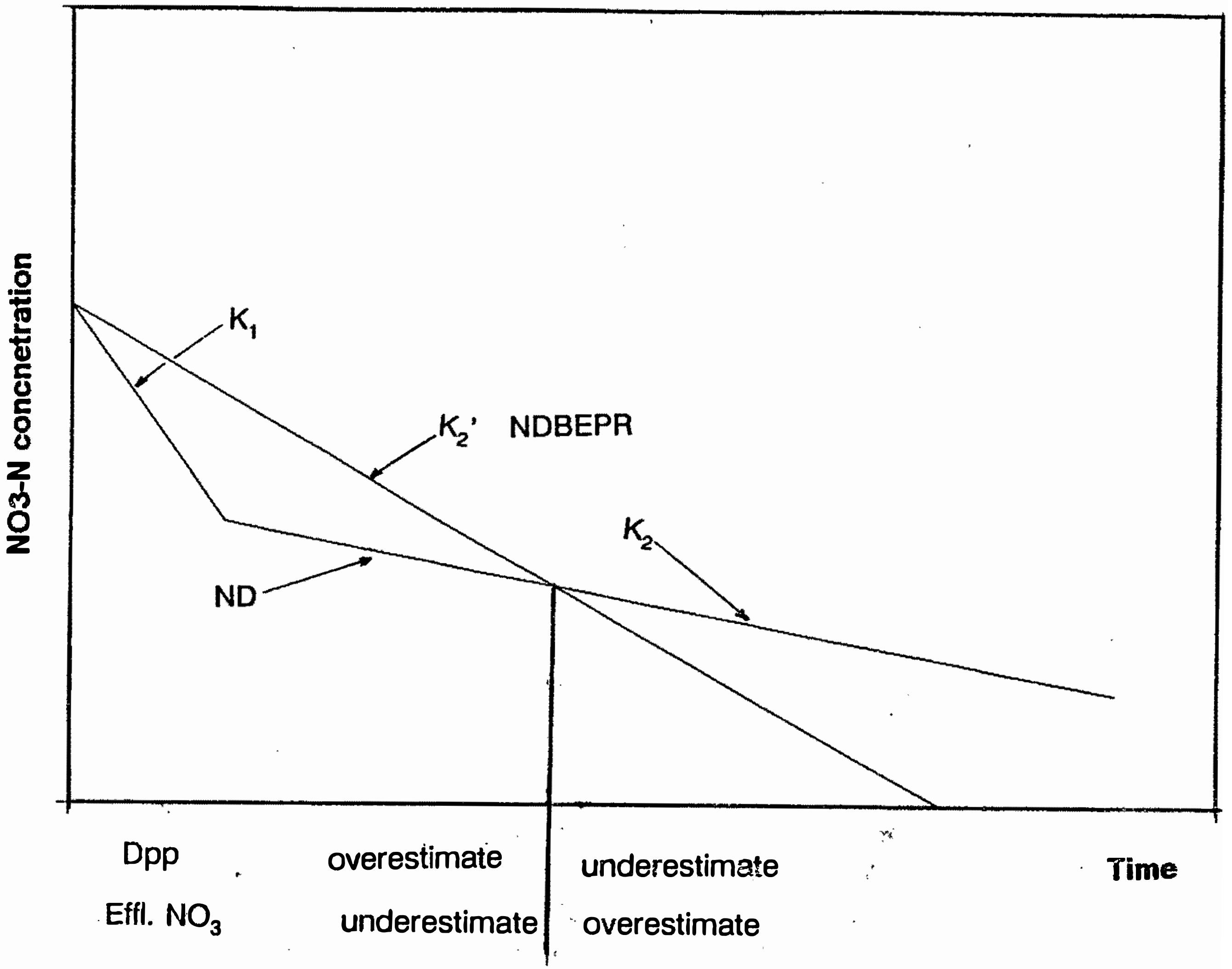


Fig 3.13 The denitrification rates K_1 and K_2 for ND kinetics and K_2' for NDBEPR kinetics in the primary anoxic reactor of the MUCT system.

(0-25%) and very high (90-100%) anoxic mass fractions, low F/M bulking was ameliorated. Also in MUCT systems with low (<20%) and high (approximately 40%) the DSVI and hence bulking by low F/M filaments was low and high respectively. It was also observed that periods of poor settleability (high DSVI) were associated with periods of high concentrations of nitrate and nitrite in the anoxic zone prior to the aerobic zone.

In this investigation, the system DSVI was measured on a daily basis and filament identifications were done about once every 3 to 4 weeks (more regularly in the later half of the investigation period than in the first half). The DSVI is shown plotted in Fig 3.9 together with the nitrate and nitrite concentrations in the second anoxic reactor which are believed to affect the proliferation of low F/M filaments and hence the DSVI. Also shown on the same Fig 3.9 are the results of the filament identifications. The effect of nitrate and nitrite concentrations in the second anoxic reactor on DSVI and low F/M filaments is discussed in detail below.

3.2.8.1 *Effect of low nitrate and nitrite concentrations in the second anoxic reactor: Day 0-128*

The system started off with a bulking sludge with a DSVI of 164 mℓ/g. The sludge was obtained from two other MUCT systems in the laboratory and contained 0092 as the dominant filament; 021N, *M.parvicella* and *H.hydrossis* as the secondary filaments and 0041, 1851 and 0961 as the incidental filaments. From the start of the investigation the DSVI slowly decreased reaching a value of 71 mℓ/g on day 128. The nitrate and nitrite concentrations in the second anoxic reactor during this period (1-128) averaged 0,47 $mgNO_3$-N/ℓ and 0,18 $mgNO_2$-N/ℓ respectively. Therefore practically there was no nitrate or nitrite in the second anoxic reactor (see also Section 3.2.7 above which shows that during this period the nitrate load on the anoxic zone was 50% of its denitrification potential). Two filament identifications were conducted during this period on day 61 (DSVI = 105) and day 119 (DSVI = 82). From Fig 3.9 it can be seen that there was no difference in filament types and relative amounts on these days. The dominant filament was 0092 with 021N as the secondary filament. The other filaments present were *M.parvicella*, 0041 and *H.hydrossis*. Apart from 021N which is associated with septic sewage, the other filaments are typical of those causing bulking in full scale nutrient removal plants. The presence of 021N was found to be a laboratory artefact caused by the sewage turning septic due to cold room malfunction and improper cleaning of the transport container. The relative amount of filaments concluded from the microscopic examinations did not at times reflect the relative filament quantities as suggested by the measured DSVI. This is because overall filament abundance is a qualitative assessment of the number of filaments in the microscopic sample whereas the DSVI is a measure of the sludge settleability which depends not only on the amount of filaments present but also on the shape and size of the filaments. Therefore the high reported filament abundances of a particular filament or filaments need not necessarily imply a sludge with high DSVI.

Based on previous work on the effect of nitrate on low F/M filament bulking (Casey *et al.*,1990, 1991; Ketley *et al.*, 1991; Warburton *et al.*, 1991; Hulsman *et al.*, 1992) it was concluded at this stage that the absence of nitrate and/or nitrite in the second anoxic reactor (due to the large anoxic mass fraction) ameliorated low F/M filament bulking and decreased the DSVI from 164 mℓ/g to 71 mℓ/g in 128 days.

3.2.8.2 *Effect of nitrate dose on second anoxic reactor:Day 129-240*

In order to determine the quantity of nitrate to be dosed to the second anoxic reactor, two anoxic batch tests were conducted on day 104 and 113 (see Table 3.7a) from which the denitrification rate was calculated. With the rate known, the denitrification potential of the second anoxic reactor was determined. Knowing the denitrification potential of the second anoxic reactor, it was decided to impose a nitrate load on the second anoxic reactor which was equal to its denitrification potential. The nitrate dose to achieve this was calculated at 720 mgNO_3-N/d and dosing started on day 129.

Initially the DSVI continued to decrease down to 66 mℓ/g on day 137 and thereafter started to increase reaching 176 mℓ/g 99 days later on day 236. The nitrate and nitrite concentrations increased to between 2 - 11 mgNO_3-N/ℓ and 1,5 - 3 mg NO_2-N/ℓ respectively. The nitrate concentration in the second anoxic reactor increased with time as dosing progressed (see Table 3.8 with effluent nitrate concentration averages for the steady state periods) which seemed to indicate that the denitrification potential was not as high as initially estimated before dosing commenced and decreased as the DSVI increased. The batch tests did show this decrease as already discussed in section 3.2.6 above. Three filament identifications were conducted during the nitrate dosing period on day 181, 202 and 237. The dominant filament was 0914 on day 181 with 0092 as the secondary filament. The incidental filaments present were *M.parvicella*, 0041, *H.hydrossis* and *flexibacter*. The relative amount was common. On day 202 the dominant filament was 0092 with *M.parvicella* as the secondary filament. *H.hydrossis*, 0041 and 0803 were the incidental filaments present. The relative amount was abundant. On day 237, the dominant filament was 0092 with 0041 as secondary and the incidental filaments present were 0803, *M.parvicella* and 021N. The relative amount was common. As before nitrate dosing, the relative amounts of filaments concluded from the microscopic examination did not reflect the relative filament quantities as suggested by the measured DSVI on these three occasions. It was concluded at this stage that the presence of excess nitrate (concentrations >2mg NO_3-N/ℓ) and/or nitrite (concentrations >1,5 mgNO_2-N/ℓ) induced bulking in a non bulking sludge increasing the DSVI from 66 mℓ/g to 176 mℓ/g in 111 days.

During the dosing period there was a decrease in the MLSS and MLVSS concentrations of the system; the average dropped from 3900 mgTSS/ℓ and 3116 mgVSS/ℓ respectively in period 5 when dosing commenced to 2873 mgTSS/ℓ and 2350 mgVSS/ℓ respectively in period 9 the last period prior to stopping nitrate dosing. Initially it was thought that this decrease in solids concentrations was caused by accumulation of solids in a foam layer on the second anoxic reactor due to nitrogen bubble formation. However this problem was rectified by moving the stirrers to the surface of the reactor so that they would break up the sludge foam layer, but to prevent any oxygen entrainment from the air space above the mixed liquor, the reactor was completely sealed. Nevertheless the decline in solids concentrations continued. Because decreases in MLSS and MLVSS concentrations with nitrate or nitrite dosing to the anoxic reactors or ammonia dosing to the influent have also been observed with other systems in the laboratory (Lakay *et al.*, 1991) it was concluded that these changes form part of the conditions favouring bulking.

3.2.8.3 *Effect of removal of nitrate dose from the second anoxic reactor:Day 240-340*

On day 239 the nitrate dose was stopped. After the removal of the nitrate dose, the DSVI started to decrease reaching 91 mℓ/g 70 days later on day 309. The nitrate and nitrite concentrations in the second anoxic reactor decreased to averages of 0,66 $mgNO_3$-N/ℓ and 0,14 $mgNO_2$-N/ℓ respectively. From day 310 to day 337 the DSVI increased slightly up to 105 mℓ/g. Also from day 310 the influent TKN of the sewage increased to values between 110 to 128 mgN/ℓ (the mean influent TKN prior to this was less than 100 mgN/ℓ) resulting in a slight increase in the nitrate concentrations in the second anoxic reactor to values between 0,5 and 2 $mgNO_3$-N/ℓ. There was not much change in the nitrite concentration in the second anoxic reactor except on a few days when values between 0,5 and 0,9 mg NO_2-N/l were recorded.

The MLSS and MLVSS concentrations increased from mean values of 2873 mgTSS/ℓ and 2350 mgVSS/ℓ respectively in period 9, the last period before dosing was stopped to values of 3748 mgTSS/ℓ and 3083 mgVSS/ℓ respectively during period 10 the first period after the removal of the nitrate dose. This behaviour confirmed that the decrease in MLVSS and MLSS observed earlier during nitrate dosing was stimulated by the nitrate dose in that removal of the nitrate dose caused the solids concentration to again increase. Two filament identifications were conducted during this stage on day 270 (DSVI = 129 mℓ/g) and day 308 (DSVI = 91 mℓ/g). The dominant filament was 0092 on both occasions with 021N as the secondary filament. The other filaments present were *M.parvicella*, 0041, 0675, *H.hydrossis* and *Thiothrix sp.*.

The results of this final stage confirmed the findings in the initial stage that the absence of nitrate and/or nitrite in the second anoxic zone ameliorated bulking caused by low F/M filaments.

3.3 EXPERIMENTAL RESULTS: MUCT2

Since the presence of excess nitrate (which ensures the presence of excess nitrite through denitrification) in the second anoxic reactor was shown to induce low F/M filament bulking in the MUCT1 system, the MUCT2 system was set up to investigate the effect of excess nitrite in the second anoxic reactor maintaining a low concentration of nitrate. This would show whether the effect of nitrate on low F/M filament bulking in the MUCT1 system was due to nitrate only or also from nitrite formed by denitrification of nitrate.

The MUCT2 system was run from day 171 to day 340 and nitrite was dosed to the 2nd anoxic reactor on day 291. Unlike for MUCT1 where the nitrate dose was withdrawn to restore the initial conditions, for MUCT2 the investigation was stopped before withdrawing the nitrite dose from the second anoxic reactor. The operational changes made to MUCT2 are set out in Table 3.9. The same parameters as for MUCT1 were measured to monitor the performance of the system. The results of these parameters are graphically shown in Figs 3.14 to 3.21 and the data are given in Appendix A. The results have been analyzed in the same way as for MUCT1 in terms of mass balances and kinetic evaluation.

Table 3.9: Operational changes made to the MUCT2 system.

Day	Change	Reason
171	Set up system with design parameters shown in Table 3.1 above.	
291	Dose 900 mgNO_2-N to 2nd anoxic reactor.	To ensure presence of excess nitrite in the 2nd anoxic reactor so as to observe the effect on DSVI.
340	Terminate operation	Investigation complete.

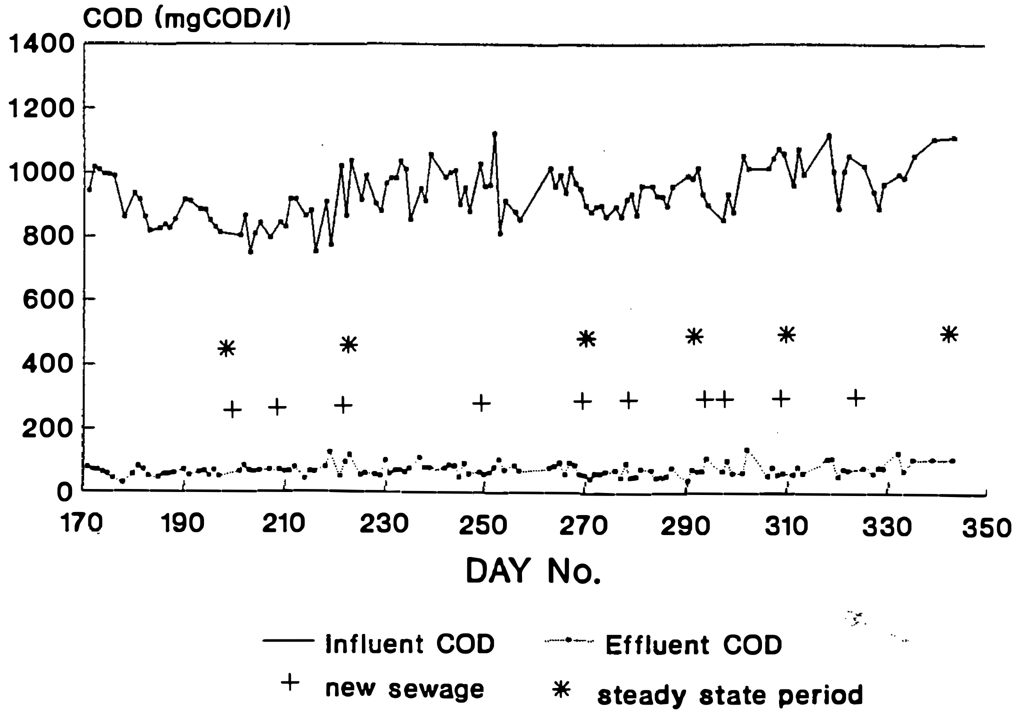


Fig 3.14 The daily influent and effluent COD concentrations for the MUCT2 system.

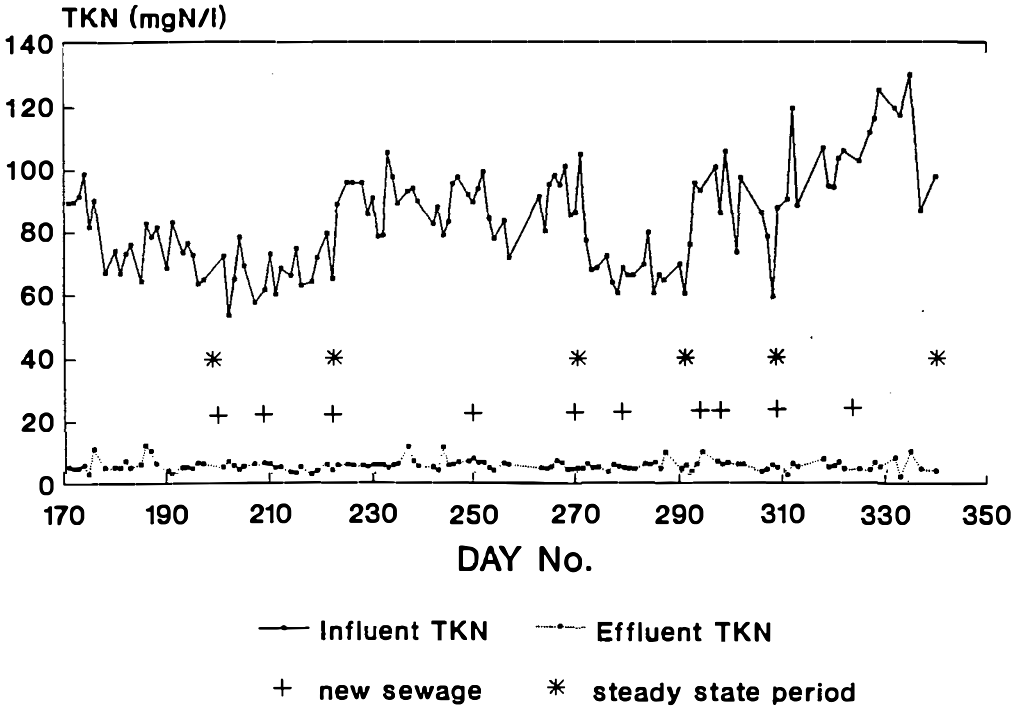


Fig 3.15 The daily influent and effluent TKN concentrations for the MUCT2 system.

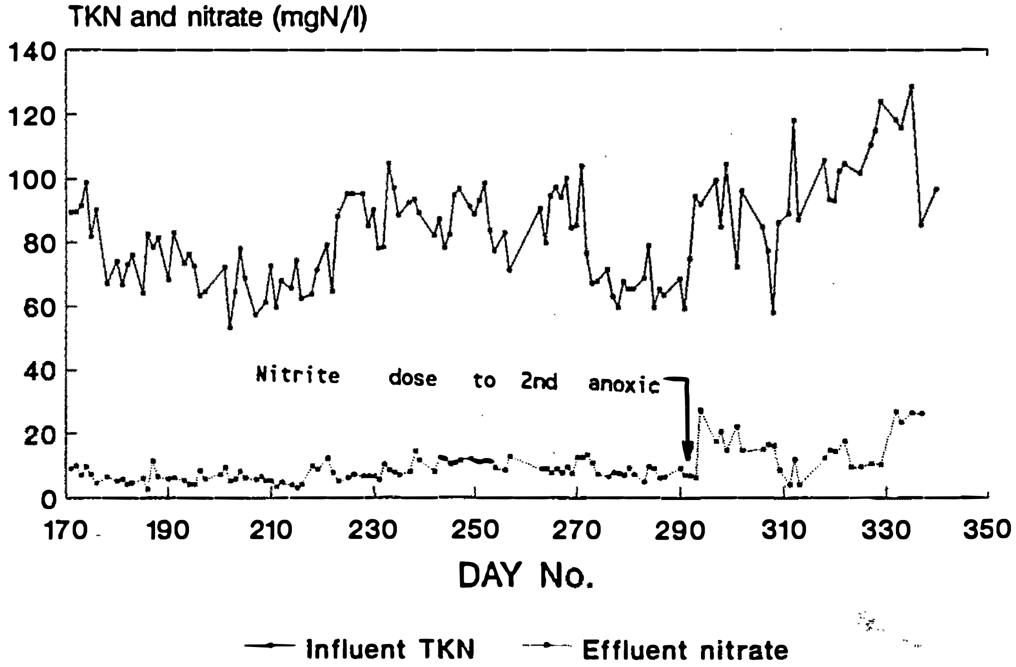


Fig 3.16 The daily influent TKN and effluent nitrate concentrations for the MUCT2 system.

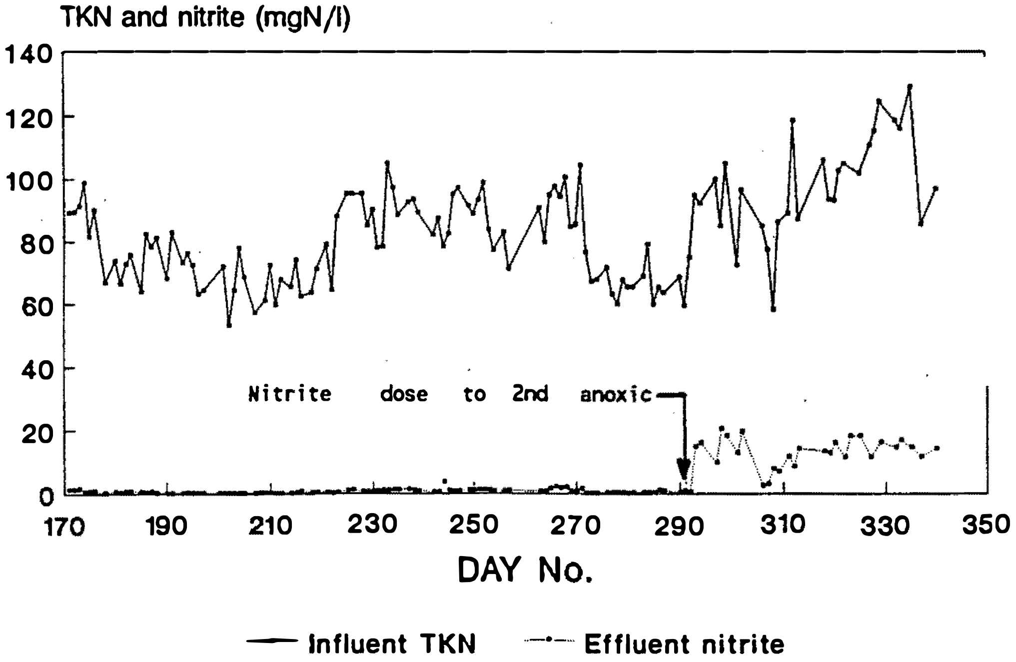


Fig 3.17 The daily influent TKN and effluent nitrite concentrations for the MUCT2 system.

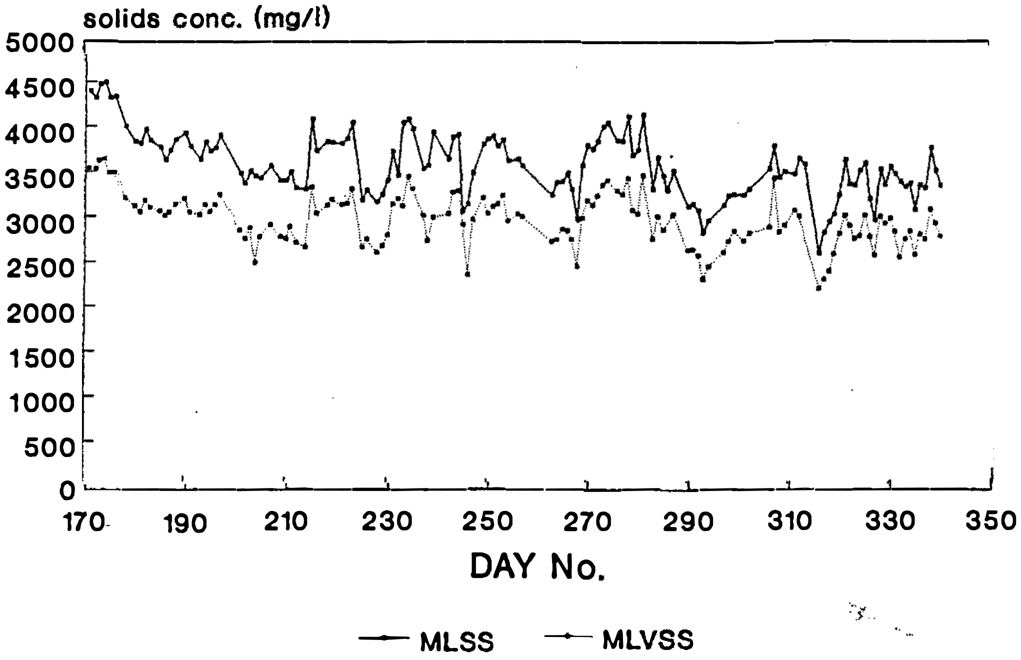


Fig 3.18 The daily MLSS and MLVSS concentrations for the MUCT2 system.

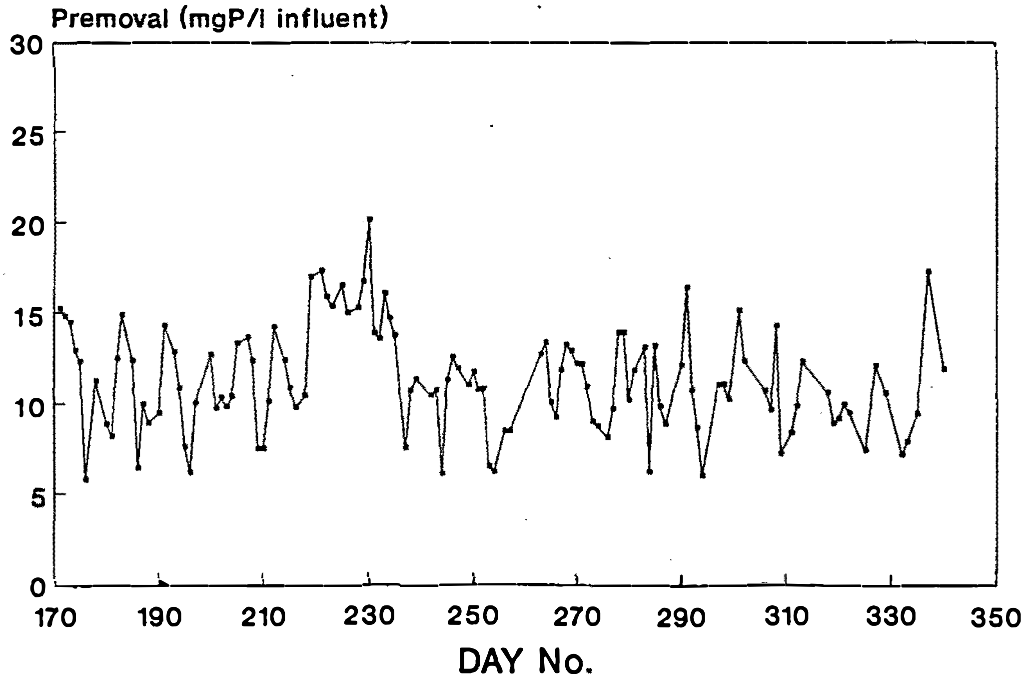


Fig 3.19 The daily P removal (per litre influent) for the MUCT2 system.

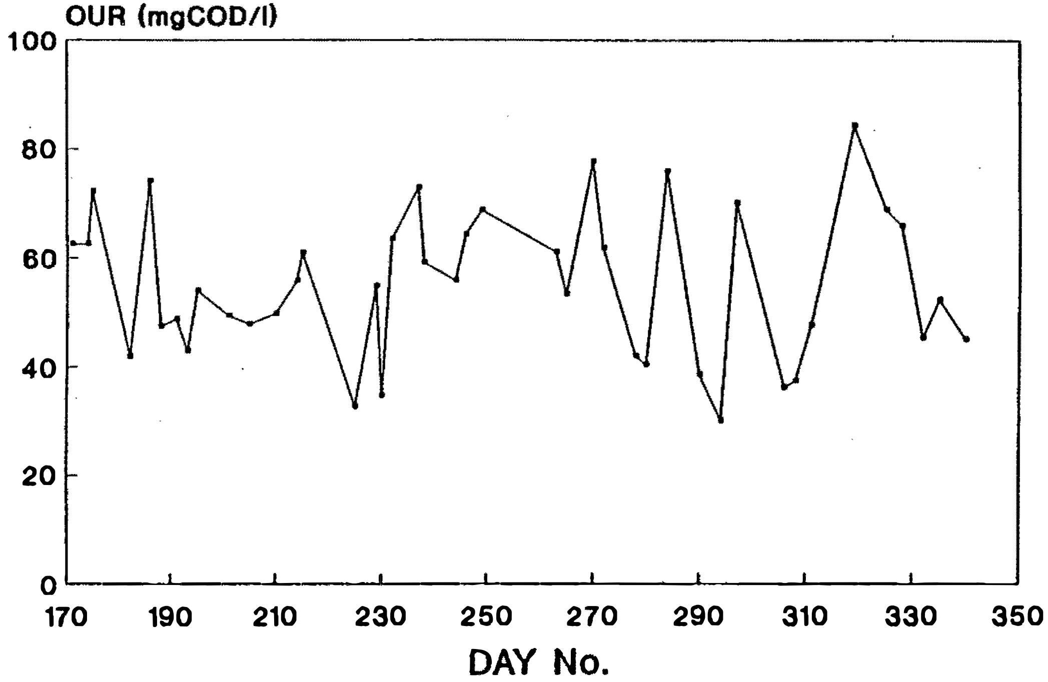
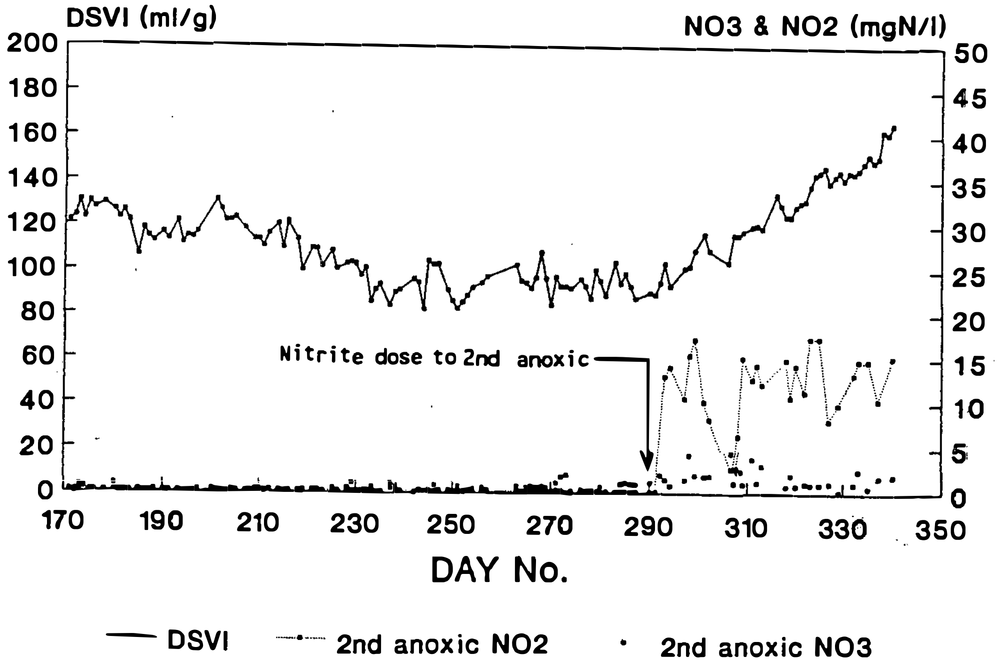


Fig 3.20 The oxygen utilization rate (OUR) measured in the aerobic reactor of the MUCT2 system.



Day No.	DSVI	Dominant Filament	Secondary Filament	Other Filaments Present	Relative Amount of Filaments	Remarks
181	122	0092	021N	M parvicella 0041 H.hydrossis	Common	Little bridging between flocs
202	127	0092	0041	021N H.hydrossis	V.common	Little bridging
237	94	0092	0041	H.hydrossis M.parvicella	Common	Bead like chains
270	84	0092	H.hydrossis	M.parvicella 0041;021N	Common to very common	Bridging present
308	116	0092	021N/0675	M.parvicella	Very common to abundant	Bridging-common

Fig 3.21 Sludge settleability in DSVI for the MUCT2 system. Also shown in this figure are the filament identifications done every three to four weeks.

3.3.1 Mass balances

Table 3.10 shows the COD and N mass balances obtained over the 6 steady state periods identified.

Table 3.10: N and COD mass balances for the MUCT2 system.

Period	From Day	To Day	Nitrogen %	COD %
1	171	196	88	117
2	197	220	94	112
3	221	269	96	101
4	270	290	108	103
5	291	308	108	93
6	309	340	102	114
Weighted	Average		98	107

The N mass balances vary between 88 and 108% with a weighted average of 98% which is less than the average for MUCT1 of 105%. Like the N mass balances for MUCT1 which tended to be somewhat above 100%, three of the steady state periods for MUCT2 also have average N balances above 100%. The N mass balances obtained for the MUCT2 are within acceptable limits which shows that the data obtained are reliable.

The COD mass balances obtained range between 93 and 117% with a weighted average of 107% which is 1% higher than the weighted average of 106% for MUCT1. The COD mass balances obtained for MUCT2 are good and the system also displayed higher than usual MLVSS concentrations confirming that good COD mass balances are obtained in MUCT systems with higher than usual MLVSS concentrations.

3.3.2 Estimation of the values of the soluble and particulate unbiodegradable COD fractions of the sewage and the active fraction of the VSS

The MLVSS concentration for MUCT2 were also higher than those expected with the WRC (1984) recommended value of f_{up} =0,13. The average MLVSS concentration for the 6 steady state periods was 3035 mgVSS/ℓ (which compares favourably with that obtained for the MUCT1 of 2996 mgVSS/ℓ). The MLVSS concentration decreased from a period 1 to 4 average before nitrite was dosed to the second anoxic reactor of about 3100 mgVSS/ℓ to a period 5 and 6 average when nitrite was dosed to the second anoxic reactor of about 2800 mgVSS/ℓ (Table 3.11).

The f_{us} and f_{up} values for MUCT2 were estimated for each steady state period in the same manner as outlined before for the MUCT1 system. The f_{us} and f_{up} values are shown together with the MLVSS concentrations in Table 3.11 below.

Table 3.11: Values of the unbiodegrable particulate COD fraction estimated for each steady state period for MUCT2.

Period	Day From	Day To	X_v	f_{us}	f_{up}^2	f_{up}^3
1	171	196	3359	0,061	0,42	0,46
2	197	220	2946	0,081	0,39	0,42
3	221	269	3014	0,076	0,34	0,35
4	270	290	3167	0,068	0,39	0,40
5	291	308	2862	0,079	0,29	0,29
6	309	340	2860	0,083	0,26	0,25

Note:
1. Nitrite dosed to 2nd anoxic reactor.
2. f_{up} calculated with WRC (1984) model.
3. f_{up} calculated with Wentzel *et al.* (1990) model.

The variation of f_{up} follows the same trend as the MLVSS concentration with the average value decreasing from 0,39 in period 4 (before nitrite dosing) to 0,26 in period 6 (nitrite dosing). The average f_{up} and f_{us} values for MUCT2 over the whole investigation are 0,35 and 0,075 respectively which are of the same order as the average f_{up} =0,32 and f_{us} =0,073 obtained for MUCT1. The f_{up} and f_{us} values for each steady state period were used to calculate the active fraction and the denitrification rate for that period (see Section 3.3.6 below).

3.3.3 COD Removal

The average influent and effluent COD concentrations varied from 850 to 1050 mgCOD/ℓ and 56 to 86 mgCOD/ℓ thereby giving a COD removal greater than 90% similar to MUCT1. Dosing of nitrite to the second anoxic reactor did not have any effect on the COD removal performance.

3.3.4 Nitrification

The average influent and effluent TKN were 82,6 mgN/ℓ and 5,4 mgN/ℓ respectively showing that the system had a nitrification efficiency higher than 90% like MUCT1. For MUCT2 no random effluent ammonia concentrations were measured so the maximum specific growth rate for nitrifiers at 20°C, U_{nm20} could not be estimated. However the rate can be assumed to be equal to the one estimated for MUCT1 of 0,63 /d since the influent TKN concentration was the same for both systems and the effluent TKN concentration obtained was approximately the same (5 to 6 mgN/ℓ).

3.3.5 Biological Excess Phosphorus Removal

Table 3.12 below shows the P release and P uptake in all the reactors including the settling tank.

Table 3.12 P release (-ve) and P uptake (+ve) in the reactors and settling tank for MUCT2.

Period	Panaer. mgP/ℓ	Panox.1 mgP/ℓ	Panox.2 mgP/ℓ	Paer. mgP/ℓ	Psett. mgP/ℓ	Prem. mgP/ℓ
1	-23,9	-19,6	+9,2	+44,9	+0,91	+11,5
2	-19,8	-17,4	+11,5	+36,2	+1,33	+11,8
3	-18,8	-15,1	+6,2	+38,7	+1,06	+12,1
4	-17,4	-11,0	+8,9	+30,0	+0,68	+11,2
5	-19,6	-2,9	+19,2	+12,6	+1,26	+10,6
6	-16,0	+1,1	+12,1	+12,6	+0,69	+10,5

Similar to MUCT1, the data shows considerable P release in the 1st anoxic reactor for the first 4 periods before nitrite was dosed to the second anoxic reactor. In period 5 when nitrite dosing commenced, the P release in the 1st anoxic reactor dropped from 11 mgP/ℓ (period 4) to 3 mgP/ℓ. In period 6 instead of releasing P in the 1st anoxic reactor , there was a slight uptake of 1,10 mgP/ℓ. There was considerable P uptake in the 2nd anoxic reactor which was less than that in the aerobic reactor except during period 5 when nitrite dosing commenced. The P release and P uptake pattern is similar to that observed in MUCT1 with nitrate dosing. The values of the releases and uptakes are also closely the same in the two systems.

The theoretically calculated (using BEPR kinetics, see Section 3.2.5 above) and measured P removals, P release/P uptake and P removal/P release ratios are shown in Table 3.13. Fig 3.22 shows a plot of the theoretical and measured P removal.

The measured P removal is less than the expected P removal throughout the investigation period; the average measured value of 11,3 mgP/ℓ being 42% less than the average theoretical value of 19,6 mgP/ℓ. The theoretical and measured Prelease/Puptake ratios are almost the same with averages of 0,75 and 0,72 respectively for the 6 steady state periods. The average measured Premoval/Prelease ratio of 0,41 is slightly higher than the theoretical value of 0,34. This data for MUCT2 shows the same pattern of behaviour as that observed in MUCT1 and the values of the release, uptake, removal and the ratios compare well with those obtained for MUCT1. Dosing of nitrite to the 2nd anoxic reactor of MUCT2 seems to have had the same effect as dosing of nitrate to the 2nd anoxic reactor of MUCT1 on the BEPR performance of the systems.

3.3.6 Denitrification Kinetics

The nitrate and nitrite denitrification rates were determined by anoxic batch tests in the same manner as outlined in Section 3.2.6 above. Eight batch tests were conducted on MUCT2, 4 with nitrate dosing and the other 4 with nitrite dosing. The time when the batch tests were conducted in this investigation is shown in Tables 3.14a and 3.14b. It should be noted that in these tests, as also in the earlier tests on MUCT1, the nitrite concentration in the nitrate denitrification batch tests were low (<2 $mgNO_2$-N/ℓ) and the nitrate concentration in the nitrite denitrification batch tests were low (<1 $mgNO_3$-

Table 3.13 Theoretically calculated and measured P removal per litre influent for the MUCT2 system. Also shown in this table are the theoretical and measured Prelease/Puptake and Premoval/Prelease ratios.

Period	Theoretical		Measured		Premoval	Premoval	
	Prel. Pupt.	Prem. Prel.	Prel. Pupt.	Prem. Prel.	theor. mgP/l	meas. mgP/l	Pmeas. Ptheor. %
1	0.75	0.34	0.79	0.26	22.05	11.5	52
2	0.74	0.34	0.76	0.32	18.85	11.8	63
3	0.75	0.34	0.74	0.36	19.86	12.1	61
4	0.74	0.36	0.72	0.39	19.51	11.2	57
5	0.75	0.34	0.68	0.47	18.76	10.6	57
6	0.74	0.34	0.61	0.66	18.45	10.5	57
Mean	0.75	0.34	0.72	0.41	19.6	11.3	57

Note:

1. Combined anaerobic + anoxic release
2. Combined anoxic + aerobic uptake

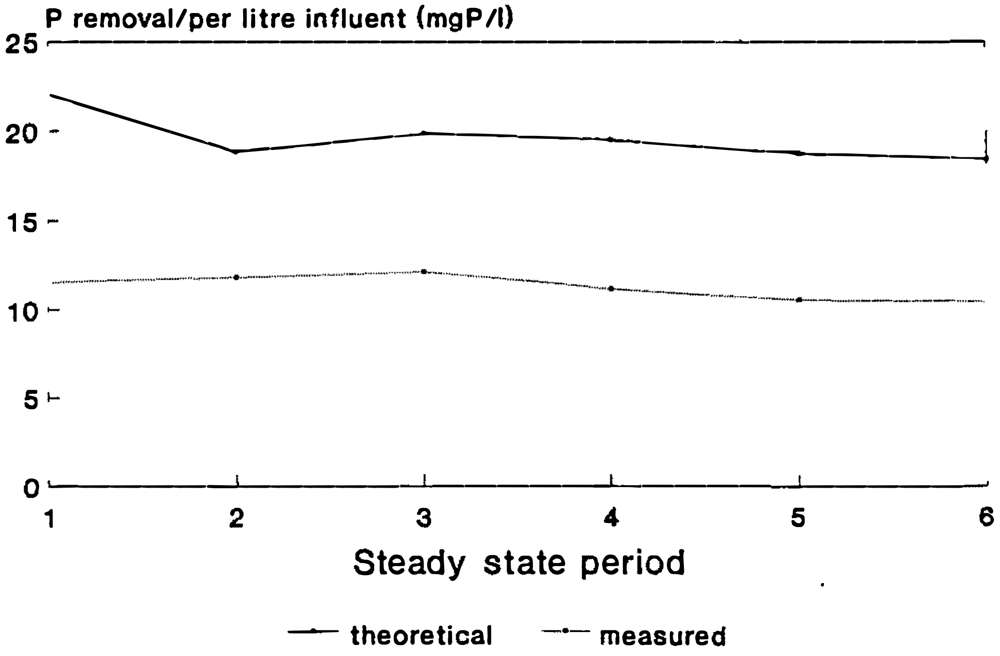


Fig 3.22 The theoretically calculated and measured P removal (per litre influent) for each steady state period for the MUCT1 system.

N/ℓ). Consequently the effect of high nitrite and nitrate concentrations on the nitrate and nitrite denitrification rates could not be established from these tests. In supplementary batch tests (not reported in this thesis, see Friedrich *et al.*, 1992) examining the effect of high nitrite and nitrate concentrations on the nitrate and nitrite denitrification rates, it was found that significant nitrite denitrification did not commence until the nitrate concentration reached low values (<1 mgNO_3-N/ℓ) and confirmed the observations of Stern and Marais (1974), Clayton *et al.* (1989) and this investigation that while significant nitrate denitrification is taking place (nitrate >1 mgNO_3-N/ℓ), the nitrite concentration is increasing at a slow rate i.e. 0,060 mgNO_2-N/(mgAVSS.d) (see 3.2.6 above).

3.3.6.1 *Nitrate denitrification rates*

The nitrate denitrification rates are shown in Table 3.14a. Dosing of nitrite to the second anoxic reactor (periods 5 and 6) decreased the specific nitrate denitrification rate K_2' from 0,420 mgNO_3-N/(mgAVSS.d) determined in period 3 before nitrite dosing to 0,276 mgNO_3-N/(mgAVSS.d) in period 5. The two nitrate denitrification rates determined later in period 6 as nitrite dosing continued were also lower than the 0,420 mgNO_3-N/(mgAVSS.d) rate determined in period 3. The decrease in K_2' with nitrite dosing to the second anoxic reactor is similar to that observed when nitrate was dosed to the second anoxic reactor of MUCT1 (see section 3.2.6 above).

The average value of the four K_2' obtained for MUCT2 over the investigation period is 0,286 mgNO_3-N/(mgAVSS.d) which is about 6% lower than that for MUCT1 (see section 3.2.6 above) of 0,305 mgNO_3-N/(mgAVSS.d) for nitrate dosing. Combining these two rates gives an average value of 0,296 mgNO_3-N/(mgAVSS.d) for the two systems in this investigation. This average value of K_2' for the two systems in this investigation is 32% higher than the value obtained by Clayton *et al.* (1989) (K_2'=0,224 mgNO_3-N/(mgAVSS.d) and 3 times higher than the 2nd rate of denitrification (K_2=0,101 mgNO_3-N/(mgAVSS.d)) in primary anoxic reactors of ND systems (van Haandel *et al.*, 1981).

Table 3.14a Nitrate denitrification rates determined from anoxic batch tests for the MUCT2 system.

Batch No.	Period	Day of batch test	DSVI ml/g	MLVSS mg/l	fup	AVSS mg/l	Kno2 mgNO2-N/ (mgVSS.d)	K2'' mgNO3-N/ (mgVSS.d)	K2' mgNO3-N/l (mgAVSS.d)
1	3	258	125	3106	0.34	432	0.001	0.058	0.42
2	5	299	107	2892	0.29	502	0.007	0.048	0.276
3	6	313	113	2840	0.26	529	0.005	0.033	0.176
4	6	340	163	3031	0.26	529	0.005	0.048	0.272

Note:
KNO2 is the nitrite formation rate.

Table 3.14b Nitrite denitrification rates determined during anoxic batch tests for the MUCT2 system.

Batch No.	Period	Day of batch test	DSVI ml/g	MLVSS mg/l	fup	AVSS mg/l	Kno2'' mgNO2-N/ (mgVSS.d)	Kno2' mgNO3-N/ (mgVSS.d)
1	4	285	98	2962	0.39	387	0.048	0.372
2	5	299	107	2892	0.29	502	0.027	0.157
3	6	313	113	2840	0.26	528	0.045	0.242
4	6	340	163	3031	0.26	529	0.045	0.256

3.3.6.2 *Nitrite denitrification rates*

Table 3.14b shows the nitrite denitrification rates. The rate determined before dosing of nitrite to the 2nd anoxic reactor in period 4 is 0,372 mgNO_2-N/(mgAVSS.d). This is higher than the other three rates determined later when nitrite dosing had started in periods 5 and 6. This shows that the nitrite denitrification rate, like the nitrate denitrification rate, decreased when nitrite was dosed to the 2nd anoxic reactor. The average of the 4 nitrite denitrification rates measured over the investigation period is 0,257 mgNO_2-N/(mgAVSS.d) which is 8% higher than the nitrite rate determined for MUCT1 of 0,237 mgNO_2-N/(mgAVSS.d). Combining these two rates gives an average nitrite denitrification rate of 0,247 mgNO_2-N/(mgAVSS.d) for the two systems operated in this investigation.

3.3.7 System effluent nitrate concentration

The measured effluent nitrate concentration and those predicted by the ND and NDBEPR kinetics as outlined for the MUCT1 system in Section 3.2.7 above are shown in Table 3.15.

3.3.7.1 *Periods 1 to 4 (no nitrite dose)*

The TKN/COD ratio was <0,10 and the denitrification potentials predicted by both the ND and NDBEPR kinetics are greater than the nitrate load on the anoxic zone. Therefore the effluent nitrate concentration is governed by the recycle ratio and not the denitrification kinetics and therefore both methods predict the same value of the effluent nitrate concentration. The error in predicting the effluent nitrate concentration is small varying between 0,4 and 3% relative to the influent TKN.

3.3.7.2 *Periods 5 and 6 (nitrite dosing)*

In the MUCT2 system it was found that some of the nitrite in the outflow of the second anoxic reactor was nitrified to nitrate because the outflow of the second anoxic reactor contained high nitrite and low nitrate but the outflow of the aerobic reactor contained high nitrate and low nitrite. Also, due to the dosing of nitrite, high concentrations of nitrite were denitrified in the anoxic reactor. These changes were taken into account in the COD mass balance calculations. Although the nitrification and denitrification of

Table 3.15 Theoretical and experimental denitrification behaviour for the MUCT2 system.

Period	TKN Infl. mgN/l	TKN Efl. mgN/l	TKN/COD ratio mgN/mgCOD	Dpp mgN/l	Dpp mgN/l	Nc mgN/l	Nitrate load mgN/l	Theoretical Ne1 mgN/l	Theoretical Ne2 mgN/l	Measured Ne mgN/l	% error 1	% error 2
1	80.3	5.9	0.087	72	138	40.8	35.1	8.16	8.16	6.3	-2.3	-2.3
2	66.7	4.78	0.079	66	129	32.5	28.4	6.5	6.5	6.74	0.4	0.4
3	89.2	5.79	0.094	76	161	53.3	45.1	10.66	10.66	10.04	-0.7	-0.7
4	66.9	5.32	0.073	69	144	29.9	26.4	5.98	5.98	8	3.0	3.0
5	175.6	5.17	0.179	81	178	142.1	116.1	63.548	28.42	25.62	-21.6	-1.6
6	196.4	5.61	0.189	88	197	162.2	132.2	76.648	32.44	29.45	-24.0	-1.5

Note:
1. Denotes values calculated using the ND kinetics
2. Denotes values calculated using NDBEPR kinetic
3. % error = (error in NO e/Nti)

high concentrations of nitrite could be taken account in the COD balance, the denitrification and nitrification of high concentrations of nitrite could not be taken into account in the kinetic evaluation of the MUCT2 system because the established design denitrification theories accept that nitrite is formed only in negligibly low concentrations. To overcome this problem, the system perfomance was evaluated on the assumption that nitrate plus nitrite was equivalent to nitrate.

Therefore in order to check the denitrification kinetics of MUCT2 during nitrite dosing, it was assumed that the nitrite dose was in effect nitrate and the ND and NDBEPR kinetics applied as in the case for MUCT1 (see section 3.2.7 above). The average nitrate denitrification rate K_2' established in the batch tests of this investigation for MUCT2 (i.e 0,286 mgNO_3-N/(mgAVSS.d)) was used in applying the NDBEPR kinetics instead of the nitrite denitrification rate.

The TKN/COD ratio is effectively increased to averages of 0,18 and 0,19 in periods 5 and 6 respectively due to the dosing of nitrite. The D_{pp} calculated using the ND kinetics is less than the nitrate load on the anoxic reactor thus the effluent nitrate concentration is governed by the denitrification kinetics of the anoxic reactor. The estimated effluent nitrate concentration is higher than the measured value of nitrate and nitrite and the error in overestimation is 21,6% and 24% (relative to the influent TKN) in periods 5 and 6 respectively. The D_{pp} predicted by the NDBEPR kinetics is greater than the nitrate load on the anoxic reactor. The effluent nitrate is, like before nitrite dosing, governed by the recycle ratios. The error in overestimation of the effluent nitrate concentration using the NDBEPR kinetics is very small; 1,6% and 1,5% in periods 5 and 6 respectively.

Similar to the MUCT1 above, there is no merit between the ND and NDBEPR kinetics for TKN/COD ratios<0,10 since the effluent nitrate predictions are the same. At high TKN/COD ratios the NDBEPR kinetics give better effluent nitrate predictions than ND kinetics.

3.3.8 DSVI and low F/M filament bulking

The experimental investigation on MUCT2 was designed to test the effect of a large anoxic mass fraction (65%) and low and high nitrite concentrations in the 2nd anoxic reactor prior to the aerobic zone. This was done because previous work, as mentioned in Section 3.2.8 above, had indicated that periods of poor settleability were associated with high concentrations of both nitrate and nitrite in the anoxic reactor prior to aeration. Also from the behaviour of MUCT1 above, high concentrations of nitrate resulted in high concentrations of nitrite so that it was not possible to establish whether the nitrate or nitrite had an effect on low F/M filament bulking.

The DSVI measured on a daily basis together with the concentration of nitrate and nitrite in the 2nd anoxic reactor are shown graphically in Fig 3.21. The results of the filament identifications conducted during the investigation period are also shown in Fig 3.21.

3.3.8.1 *Effect of low nitrate and nitrite concentrations in the 2nd anoxic reactor. Day 171-290*

The system was started up with a non-bulking sludge which had a DSVI of about 131 mℓ/g. The sludge was harvested from MUCT1 and 4 other MUCT systems in the laboratory. The filament content of the MUCT1 sludge is given in Fig 3.9 for day 165 and for the other 4 systems the dominant filaments were also all of the low F/M type i.e. 0092, 0914 and *M.parvicella.* After start up the DSVI slowly decreased reaching a value of 90 mℓ/g, 118 days later on day 289. Four filament identifications were conducted during this time on days 181, 202, 237, and 270 (see Fig 3.21). The dominant filament was 0092 on all 4 occasions with 021N, 0041 and *H.hydrossis* being the secondary filaments. *M.parvicella* was also present. These filaments are associated with low F/M bulking in full scale nutrient removal plants.

The nitrate and nitrite concentrations in the 2nd anoxic reactor were very low varying between 0,2 to 0,7 mgNO_3-N/ℓ and 0,1-0,2 mgNO_2-N/ℓ respectively (see Fig 3.21). Like in the first part of the MUCT1 operation with no nitrate dosing (see section 3.2.8 above) the absence of nitrate and nitrite in the second anoxic reactor caused the DSVI of the sludge to decrease to below 100 mℓ/g; in this case for MUCT2 from 131 mℓ/g to 90 mℓ/g in 118 days.

3.3.8.2 *Effect of high concentrations of nitrite in the 2nd anoxic reactor*

On day 291, 900 mgNO_2-N/d was dosed to the 2nd anoxic reactor. This dosing rate was based on the nitrite batch test denitrification rate (see Table 3.14b on day 258) and was calculated to be sufficient together with the nitrate formed from the influent TKN, to load the 2nd anoxic reactor to its denitrification potential. In this calculation it was accepted that the nitrite dose in effect was nitrate. On dosing nitrite, the DSVI initially increased sharply over 11 days from 90mℓ/g on day 290 to 116 mℓ/g on day 301. Thereafter the DSVI increased slowly reaching 174 mℓ/g 35 days later on day 340. One filament identification was done during this stage on day 308 which showed the presence of the low F/M filaments as before. The dominant filament was 0092 with 021N and 0675 present as the secondary filaments.

The nitrite concentration in the 2nd anoxic reactor varied between 10 and 20 mgNO_2-N/ℓ (Fig 3.21). Dosing of nitrite apparently caused the nitrate concentration in the 2nd anoxic reactor to increase slightly from <0,7 mgNO_3-N/ℓ to between 0,5 and 3 mgNO_3-N/ℓ. This increase in nitrate concentration with nitrite dosing is surprising and can only be due to (1) the nitrate denitrification rate being significantly reduced with nitrite dosing or (2) an analytical artefact arising from the auto-analyser nitrate and nitrite method in the presence of high nitrite, which requires less dilution than similar concentrations of nitrate. With regard to the former reason, the nitrate and nitrite batch tests of this investigation were done at low (<1 mgNO_x-N/ℓ) nitrite and nitrate concentrations respectively. In supplementary anoxic batch tests on sludge harvested from the MUCT systems (see Friedrich *et al*., 1992) in which initial nitrate and nitrite concentrations were both high (10-20 mgNO_x-N/ℓ), it was found that (1) while nitrate was present (>1 mgNO_3-N/ℓ) and being denitrified, the nitrite concentration slowly increased and (2) only when the nitrate concentration reached low values (<1 mgNO_3-N/ℓ), did nitrite denitrification commence. These results are in conformity with those observed by Stern and Marais (1974), Clayton *et al*. (1989) and in this investigation, albeit that the nitrite concentrations were low (<5 mgNO_2-N/ℓ).

From the foregoing discussion, it can be concluded that (1) significant nitrite denitrification can only take place once the nitrate concentration has reached low levels (<1 mgNO_3-N/ℓ) and (2) the nitrate denitrification rate can be expected to continue at the measured rate (i.e. $>0{,}276$ mgNO_3-N/(mgAVSS.d)) in the presence of high nitrite concentrations. Consequently the higher nitrate concentration with nitrite dosing is not possible because for all the TKN/COD ratios fed to the system during the nitrite dosing period (including steady state period 6 when the influent TKN/COD ratio increased to 0,11), no TKN/COD ratio was high enough to increase the nitrate load on the second anoxic reactor to above the denitrification potential.

It is accepted therefore that the increase in the nitrate concentration is a consequence of the analytical procedure. The auto-analyser measures nitrite only and any nitrate present is first converted to nitrite. In order to determine the nitrate concentration two tests were run; one to determine nitrite only and the other to determine both the nitrate (converted to nitrite) and nitrite. The nitrate concentration was then determined by subtracting the nitrite measurement from the combined nitrate and nitrite measurement. During nitrite dosing to MUCT2 the nitrite concentration in the second anoxic reactor was very high and samples had to be diluted up to 50 times in order to obtain a reading on the auto-analyser. In contrast, the nitrate concentrations only needed to be diluted 20 times due to the additional dilution by the nitrate to nitrite conversion reagents. The procedure with high nitrites therefore may have introduced inaccuracies in the measurements which could have resulted in the apparent small increase in the nitrate concentration in the second anoxic reactor.

As a result, the increased nitrate concentration with nitrite dosing is accepted as an analytical artefact and the increase in DSVI is as a consequence of the increased nitrite concentration only. Because the nitrite concentration in MUCT2 was greater than that in MUCT1, it appears that the higher the nitrite concentration entering the aerobic reactor, the faster the increase in DSVI. In conclusion the effect of higher concentrations of nitrite in the second anoxic reactor (MUCT2) increased the DSVI (inducing low F/M bulking) from 90 mℓ/g to 174 mℓ/g in 55 days which is faster than the effect of lower concentrations of nitrite (from denitrification of nitrate; MUCT1) where the DSVI increased from 66 to 176 mℓ/g in 111 days.

The conclusions from this investigation are presented and discussed in Chapter 4.

CHAPTER FOUR

CONCLUSIONS

4.1 OBJECTIVES OF THE INVESTIGATION

Filamentous bulking is the major problem causing poor sludge settleability in activated sludge systems. Two surveys, by Blackbeard *et al.* (1986, 1988), one on 96 principally nitrogen removal systems but also including (26) nutrient (N&P) removal systems and the other on 33 nutrient removal systems, showed that filamentous bulking is a significant problem in biological N and N&P removal plants. Six filamentous organisms were identified as the major causes of bulking namely 0092, *M.parvicella*, 0675, 0041, 0914 and 1851. These filaments are classified as low F/M filaments (Jenkins *et al.*, 1984; Blackbeard *et al.*,1988) due to their tendency to proliferate in long sludge age systems.

In a 4 year research programme at UCT, Gabb *et al.* (1989) investigated the promoted specific control procedure for low F/M filaments and concluded *inter alia* that the selector effect did not control low F/M filament bulking. This finding prompted a comprehensive follow-up research programme into the causes and control of low F/M filament bulking in N and N&P removal plants. Work by Casey *et al.* (1990, 1991), Warburton *et al.* (1991), Ketley *et al.* (1991), and Hulsman *et al.*, (1992), which formed part of this programme, confirmed and found that in single reactor fully aerobic and fully anoxic systems, low F/M filament proliferation was ameliorated, but that in intermittent aeration N removal systems with large anoxic mass fractions (60-70%), low F/M filament bulking was promoted. Also in MUCT N&P removal systems with low (<20%) and high (approximately 40%) anoxic mass fractions, they found that low F/M filament bulking was ameliorated and promoted respectively. In these experiments it was observed that the periods of poor settleability were associated with high concentrations of nitrate and nitrite in the anoxic zone immediately before the aerobic zone.

The research in this thesis also forms part of the follow-up research programme mentioned above and focuses mainly on the effects on low F/M filament bulking of the magnitude of the anoxic mass fraction in N&P removal (MUCT) systems and the nitrate and nitrite concentrations in the anoxic zone immediately before the aerobic zone . Because the anoxic mass fraction governs the degree of denitrification that can be achieved and is therefore linked to the nitrate and nitrite concentrations in the system and also fully anoxic systems did not bulk, it was decided to set up a MUCT system with a very large anoxic mass fraction.

Two MUCT nutrient removal systems MUCT1 and MUCT2 were set up, each with 15% anaerobic, 65% anoxic and 20% aerobic mass fractions. Both systems were operated identically at the same operating parameters such as sludge age (20 days), influent feed (10 ℓ at 1000 mg COD/ℓ) and recycle ratios. The only difference between the two systems was that in MUCT1 nitrate was dosed into the second anoxic reactor for a period of time whereas in MUCT2 nitrite was dosed into the second anoxic reactor for a period of time. This enabled the effect of the large anoxic mass fraction and nitrate and nitrite concentrations on low F/M filament bulking to be examined.

The MUCT1 system was run for 340 days and received dosed nitrate from day 129 to 240. The MUCT2 system was run for 169 days from day 171 to day 340 and received dosed nitrite from day 290 to 340. The results of the two MUCT system performance and 18 ancillary batch tests on sludge harvested from the systems were evaluated in Chapter 3 and the conclusions from this evaluation are now given below.

4.2 MUCT SYSTEM:- MASS BALANCES AND KINETIC EVALUATION

4.2.1 Good N and COD mass balances were obtained in the two MUCT systems operated in this investigation, i.e weighted averages of 105% and 106% for N and COD mass balances respectively for MUCT1 and 93% and 107% for N and COD mass balances respectively for MUCT2. Clayton *et al.* (1989) also obtained good N and COD mass balances on MUCT nutrient removal systems. However, N removal systems operated by Casey *et al.* (1990, 1991, 1992c), Ketley *et al.* (1991), Warburton *et al.* (1991) and Hulsman *et al.* (1992) have been found to yield good N balances (>95%) but very poor COD balances (70 to 80%). The problem is compounded because in examining these investigations, it appears that for the same wastewater, the nutrient removal systems produce more sludge per mass COD treated than N removal systems. This manifests in a higher unbiodegradable COD fraction f_{up} than the N removal systems when evaluating the VSS production rate in terms of the biological excess phosphorus removal steady state design model (Wentzel *et al.* 1990)- (see 4.2.2 below).

4.2.2 Unbiodegradable particulate COD fractions (f_{up}) higher than 0,20 estimated by Clayton *et al.*, (1989) on MUCT systems were obtained, i.e values ranging between 0,22 and 0,38 with average values of 0,32 and 0,35 for MUCT1 and MUCT2 respectively. Dosing of nitrate to MUCT1 and nitrite to MUCT2 caused the f_{up} values to decline from 0,38 to 0,22. Cessation of dosing nitrate caused the f_{up} value to increase to around 0,38 again (the influence of cessation of nitrite dosing was not tested). N removal systems receiving the same sewage (Warburton *et al.*, 1991; Ketley *et al.*, 1991) reported lower f_{up} values between 0,10 and 0,15. These increases and decreases on f_{up} values result from corresponding increases and decreases in the MLVSS concentration in the system while the daily influent COD mass load remained constant. The sludge settleability DSVI, and correspondingly the low F/M filamentous organism population, were also connected to those changes - increasing as the VSS concentration decreased and vice versa.

4.2.3 The P removal was only 60% of that expected (approximately 12 mgP/ℓ instead of 20 mgP/ℓ) for both the MUCT1 and MUCT2 systems. This was not due to the low aerated mass fraction of 20% as initially suspected: This same problem was found also with 4 other MUCT systems with 45% aerated, 40% anoxic and 15% anaerobic mass fractions operated in the laboratory at the time under the same conditions and receiving the same wastewater.

4.3 BATCH TESTS:- DENITRIFICATION RATES

4.3.1 A single nitrate denitrification rate was observed in the second anoxic reactor (of the primary anoxic zone) of the MUCT systems with an average value of K_2'= 0,296 mg NO_3-N/(mgAVSS.d). This rate is 24% higher than the rate observed by Clayton *et al.* (1989) on MUCT/UCT systems i.e. K_2' = 0,224 mg NO_3-N/(mgAVSS.d) and about 3 times higher than the second rate of denitrification K_2=0,101 mgNO_3-N/(mgAVSS.d) observed in ND systems (van Haandel *et al.*, 1981). Dosing of nitrate to the 2nd anoxic reactor of MUCT1 decreased the value of K_2' by about 40% from 0,43 to 0,25 mgNO_3-N/(mgAVSS.d). After withdrawal of the nitrate dose, the rate remained at the low value and did not increase back to the original value. Dosing of nitrite to the 2nd anoxic reactor of MUCT2 had the same 40% depressing effect on the K_2' nitrate denitrification rate from 0,43 to 0,24 mgNO_3-N/(mgAVSS.d).

4.3.2 A single nitrite denitrification rate was observed in the second anoxic reactor (of the primary anoxic zone) with an average value of 0,247 mgNO_2-N/(mgAVSS.d) i.e. about 83% of the nitrate denitrification rate. The nitrite denitrification rate was also decreased by 40% from 0,37 to 0,22 mgNO_2-N/(mgAVSS.d) with nitrite dosing to the second anoxic reactor of MUCT2.

4.3.3 In the above batch tests, the nitrate and nitrite denitrification rates were measured in the presence of low concentrations of nitrite and nitrate respectively (< 2 mgNO_x-N/ℓ). From these tests, as well as those of Clayton *et al.* (1989) it appeared that nitrite denitrification commenced only once the nitrate was depleted. Indeed, the nitrite concentration increased very slowly while nitrate was present. Consequently the effect of high concentration of nitrite on the nitrate denitrification rate and vice versa could not be established. In additional tests (Friedrich *et al.*, 1992) this effect was examined. The same result as at low nitrite was found:

While nitrate was present, nitrite, even at relatively high concentration (10-20 mgNO_3-N/ℓ), would not be denitrified; in fact the nitrite concentration increased at a very slow rate i.e. 0,060 mgNO_2-N/(mgAVSS.d). Only when the nitrate was depleted did nitrite denitrification commence.

4.4 DSVI AND LOW F/M FILAMENT BULKING

The DSVI and filament identifications were used to monitor the settleability and filamentous organism behaviour. The effect of the large anoxic mass fraction and the nitrate and nitrite concentrations in the 2nd anoxic reactor were investigated. The following conclusions were drawn from the observations made:

4.4.1 With no nitrate or nitrite dosing to the 2nd anoxic reactor of MUCT1 and MUCT2 respectively, the DSVI decreased from 176 to 80 mℓ/g in 128 days for MUCT1 and from 131 to 90 mℓ/g in 118 days for MUCT2. The nitrite and nitrate concentrations in the 2nd anoxic reactor were very low ($<$ 0,2 mgNO_2-N/ℓ and $<$ 1,0 mgNO_3-N/ℓ respectively). The dominant filaments identified were 0092, 0914 and *M.parvicella* which are 3 of the six filaments associated with low F/M filament bulking in N&P removal plants. Filaments 0041, 021N and *H.hydrossis* were also present in the sludge.

4.4.2 Dosing of 720 mgNO_3-N/d of nitrate (equivalent to 72 mgNO_3-N/ℓ influent and effectively doubling that mass of nitrate and nitrite to be denitrified i.e. equivalent TKN/COD ratio ≈ 0,16 mgN/mgCOD) into the 2nd anoxic reactor of the MUCT1 system increased the DSVI from 80 to 176 mℓ/g (bulking) in 111 days. The nitrite and nitrate concentrations in the outflow of the second anoxic reactor increased from $<$ 0,2 mgNO_2-N/ℓand $<$ 1,0 mgNO_3-N/ℓ respectively to between 1 to 2 mgNO_2-N/ℓ and 2 to 10 mgNO_3-N/ℓ respectively. The dominant filaments were 0092 and 0914 with *M.parvicella*, 0041, 021N 0803 and *H.hydrossis* present as secondary or incidental filaments in the sludge.

4.4.3 Dosing of 900 $mgNO_2$-N/d (equivalent to 90 $mgNO_2$-N/ℓ influent and effectively doubling that mass of nitrate and nitrite to be denitrified i.e. equivalent TKN/COD ratio ≈ 0,18 mgN/mgCOD) into the 2nd anoxic reactor of MUCT2 increased the DSVI from 90 to 174 mℓ/g (bulking) in 55 days. The nitrite and nitrate concentrations in the outflow of the second anoxic reactor increased from < 0,2 $mgNO_2$-N/ℓ and < 1 $mgNO_3$-N/ℓ to between 10 to 20 $mgNO_2$-N/ℓ and 1 to 3 $mgNO_3$-N/ℓ respectively. From 4.3.3 above, the increase in nitrate concentration with nitrite dosing is an analytical artefact because significant nitrite denitrification only takes place when the nitrate concentration is low (< 1 $mgNO_3$-N/ℓ). The same low F/M filaments identified as dominant before nitrite dosing were also identified as dominant during the dosing period i.e. 0092 and 0914. The same secondary and incidental filaments before dosing i.e. 021N, 0803, 0041, *H.hydrossis* and 0675 were present also after dosing only the respective relative abundance changed. The presence of 021N which is associated with septic sewage was identified as a laboratory artefact arising either from the sewage turning septic in the storage tanks due to cold room malfunction or failure to clean the sewage tanks and transport container properly.

4.4.4 Withdrawal of the nitrate dose from the 2nd anoxic reactor of the MUCT1 system which caused a decrease in nitrite and nitrate concentrations in the outflow of the second anoxic reactor from between 1 to 2 $mgNO_2$-N/ℓ and between 2 to 10 $mgNO_3$-N/ℓ respectively to < 0,2 $mgNO_2$-N/ℓ and < 1 $mgNO_3$-N/ℓ respectively, resulted in a decrease of the DSVI from 176 to 90 mℓ/g in 70 days and similarly very low concentrations of nitrate and nitrite observed during the stage before nitrate dosing were observed again. The same low F/M filaments as before were identified, only their abundance declined. This confirms that the effects observed during nitrate dosing were indeed caused by the nitrate dosing and not some unidentified artefact. Restoration of the pre-nitrite dosing conditions following removal of the nitrite dose was not tested on MUCT2.

4.4.5 From the above results although both nitrate and nitrite dosing caused low F/M filament bulking, it appears that the nitrite concentration in the outflow of the anoxic reactor prior to the aerobic reactor is the principal cause: Dosing nitrate in such quantity that complete nitrate denitrification is not possible causes the nitrite concentration entering the aerobic reactor to increase; dosing nitrite in such quantities that complete nitrite denitrification is not possible also causes the nitrite concentration entering the aerobic reactor to increase (see 4.3.3 above).

4.4.6 From 4.4.2 to 4.3.5 above it appears that it is not the anoxic mass fraction *per se* which affects the proliferation of low F/M filaments but the concentration of nitrite in the anoxic zone prior to the aerobic zone. These results provide strong support for the low F/M filament bulking hypothesis of Casey *et al.* (1992a,b) (see Chapter 2, Section 2.8.7): If the anoxic mass fraction is sufficiently large and the a-recycle ratio sufficiently low that complete denitrification of nitrate and nitrite occurs in the anoxic zone prior to aeration, then the floc formers will not be inhibited by NO in their aerobic oxygen uptake and low F/M filament bulking is ameliorated. On the other hand even if the anoxic mass fraction is large but the denitrification of nitrate and nitrite is not complete in the anoxic zone due to either high influent TKN or a-recycle ratio, resulting in nitrate and/or nitrite concentrations in the outflow of the anoxic reactor to the aerobic reactor, then the floc formers will be inhibited in their aerobic oxygen uptake by internally accumulated NO and low F/M filaments, which do not accumulate the NO will proliferate. It appeared that the higher the concentrations of nitrate and/or nitrite in the outflow of the anoxic reactor to the aerobic reactor the faster the proliferation of low F/M filaments.

4.4.7 With the aid of the denitrification rates of nitrate and nitrite determined in this investigation, supported by similar nitrate denitrification rates measured earlier by Clayton *et al.* (1989), it is possible to design the anoxic reactors of the nutrient removal system i.e. anoxic mass fraction and mixed liquor recycle ratio, in such a way as to considerably reduce the risk of low F/M filament bulking, by ensuring that the stream entering the aerobic reactor from the anoxic reactor contains very little nitrate and nitrite i.e. $< 0{,}5$ $mgNO_3$-N/ℓ and $< 0{,}2$ $mgNO_2$-N/ℓ respectively.

REFERENCES

Arkley M J and Marais GvR (1981). The effect of the anoxic zone on sludge settleability in the activated sludge process. Res.Rept. W38, Dept of Civ Eng., Univ. of Cape Town.

Bailey D A and Thomas E V (1975). Removal of inorganic nitrogen from sewage effluents by biological denitrification. Wat.Pollut.Control, 74, 497.

Barnes D and Goronszy M C (1980). Continuous intermittent wastewater systems for municipal and industrial effluents. Public Health Engineer, 8, 20.

Blackbeard J R, Ekama G A and Marais GvR (1986). A survey of filamentous bulking and foaming in activated sludge plants in South Africa. Wat.Pollut.Control, 85, 90-100.

Blackbeard J R, Gabb D M D, Ekama G A and Marais GvR (1988). Identification of filamentous organisms in nutrient removal activated sludge plants in South Africa. Water SA, 14, 29-34.

Carr G J and Ferguson S J (1990). Nitric oxide formed by nitrite reductase of *Paracoccus denitrificans* is sufficiently stable to inhibit cytochrome oxidase activity and is reduced by its reductase under aerobic conditions. Biochim. Biophys. Acta, 1017, 57-62.

Casey T G, Hulsman A C, Ketley D A, Ekama G A and Marais GvR (1990). Development of a defined artificial substrate for investigation of filamentous bulking and activated sludge process kinetics. Progress Report to the Water Research Commission, Dept. Civil Eng., Univ. of Cape Town.

Casey T G, Warburton C A, Ketley D A, Hulsman A, Lakay M T, Ekama G A, Wentzel M C and Marais GvR (1991). Development of specific control strategies for ameliorating low F/M filament bulking in long sludge age nutrient removal activated sludge systems. Executive summary report to the Water Research Commission, Dept. Civil Eng., Univ. of Cape Town.

Casey T G, Wentzel M C, Loewenthal R E, Ekama G A and Marais GvR (1992a). A hypothesis for the cause of low F/M filament bulking in nutrient removal activated sludge systems. Water Research, 26, (6), 867-869.

Casey T G, Ekama G A, Wentzel M C and Marais GvR (1992b). Causes and control of low F/M filamentous bulking in nutrient removal activated sludge systems.Two-day workshop on prevention and control of bulking activated sludge. Perugia, Italy, 22-23 June, 1992.

Casey T G, Lakay M T, Ekama G A, Wentzel M C and Marais GvR (1992c). Studies on low F/M filament bulking control in N and N & P removal systems. Progress report to the Water Research Commission, Dept. Civil Eng., Univ. of Cape Town.

Chiesa S C and Irvine R L (1982). Growth and control of filamentous microbes in activated sludge - An integrated hypothesis. Presented at 55th Annual WPCF Conference, St. Louis, Mo.

Chiesa S C and Irvine R L (1985). Growth and control of filamentous microbes in activated sludge: an intergrated hypothesis. Water Research, 19, 471-479.

Chudoba J, Ottova V and Madera V (1973a). Control of activated sludge filamentous bulking. I Effect of hydraulic regime or degree of mixing in an aeration tank. Water Research, 7, 1163.

Chudoba J, Grau P and Ottova V (1973b). Control of activated sludge filamentous bulking. II Selection of micro-organisms by means of a selector. Water Research, 7, 1389-1406.

Chudoba J, Blaha J and Madera V (1974). Control of activated sludge filamentous bulking. III Effect of sludge loading. Water Research, 8, 231.

Clayton J A, Ekama G A, Wentzel M C and Marais GvR (1989). Denitrification kinetics in biological nitrogen and phosphorus removal activated sludge systems. Res.Rep. W63, Dept. Civil Eng., Univ. of Cape Town.

Cooper P F, Drew E A, Bailey D A and Thomas E V (1977). Recent advances in sewage effluent denitrification Part I. Wat.Pollut.Control, 76, 287.

Cooper P F and Boon A G (1983). Scale-up of biological wastewater treatment process - practical experiences in the U.K. Scale-up of Water and wastewater Treatment Processes. Eds. Schmidtke N W and Smith D W. Butterworth Publishers.

Daigger G T, Robbins M H and Marshall B R (1985). The design of a selector to control low F/M filamentous bulking. Journal WPCF, 57, 220-226.

Eikelboom D H (1982). Biosorption and prevention of bulking sludge by means of high floc loading. Chapter 6 in Bulking of activated sludge: Preventative and remedial methods. Eds: Chambers B and Tomlinson E J, Ellis Horwood Ltd., Chichester, England, 90-104.

Ekama G A and Marais GvR (1986a). Sludge settleability and secondary settling tank design procedures. Wat.Pollut.Control, 85,(1), 101-103.

Ekama G A and Marais GvR (1986b). Implications of the IAWPRC hydrolysis hypothesis on low F/M bulking. Wat.Sci.Tech, 18, 11-19.

Ekama G A, Dold P L and Marais GvR (1986). Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. Wat.Sci.Tech., 18, 91-114.

Friedrich M, Wentzel M C, Ekama G A and Marais GvR (1992). Denitrification kinetics with nitrate and nitrite as electron acceptor. Internal report. Dept. Civil Eng., Univ. of Cape Town.

Gabb D M D, Ekama G A, Marais GvR (1988). Interim report to Water Research Commission. Dept. Civil Eng., Univ. of Cape Town.

Gabb D M D, Still D A, Ekama G A, Jenkins D, Wentzel M C and Marais GvR (1989a). Development and full scale evaluation of preventative and remedial methods for control of activated sludge bulking. Report No 165/1/89, Water Research Commission, P O Box 824, Pretoria, 001.

Gabb D M D, Ekama G A, Jenkins D and Marais GvR (1989b). The incidence of *Sphaerotilus natans* in laboratory scale activated sludge systems. Wat.Sci.Tech, 21, 29-41.

Gabb D M D, Ekama G A, Jenkins D and Marais GvR (1991). The selector effect on filamentous bulking in long sludge age activated sludge systems. Wat.Sci.Tech., 23, 867-877.

Goronszy M C (1979). Intermittent operation of the extended aeration process for small systems. J.Wat.Poll.Contr.Fed, 51, 274.

Goronszy M C and Barnes D (1979). Continuous single vessel activated sludge treatment of dairy wastes. Proc. 87th Ameri. Inst. Chem. Eng, Boston, MA.

Grau P, Chudoba J and Dohanyos M (1982). Theory and practice of accumulation-regeneration approach to the control of activated sludge filamentous bulking. Chapter 7 in Bulking of Activated Sludge: Preventative and Remedial Methods. Eds. Chambers B and Tomlinson E J, Ellis Horwood Ltd., Chichester, England, 111-122.

Hao O J, Richard M G and Jenkins D (1983). The half saturation coefficient for dissolved oxygen: a dynamic model for its determination and its effect in dual species competition. Biotechnol. and Bioeng, 25, 403-416.

Heide B A and Pasveer A (1974). Oxidation Ditch: Prevention and control of filamentous sludge. H_2O, 7, 373.

Houtmeyers J (1978). Relations between substrate feeding pattern and development of filamentous bacteria in activated sludge processes. Agricultura, (Belgium), 26.

Houtmeyers J, van den Eynde E, Poffe R and Verachtert H (1980). Relations between substrate feeding pattern and in activated sludge processes. I: Influence of process parameters. European J.Appl.Microbiol.Biotechnol, 9(63).

Hulsman A, Casey T G, Ekama G A, Wentzel M C and Marais GvR (1992). The effect of type, size, posistion and recycle ratio of the anoxic zone on low F/M filament bulking in nitrogen removal activated sludge systems. Res. Rep. W73, Dept. Civil Eng., Univ. of Cape town.

Jenkins D, Parker D S, van Niekerk A M, Shao Y J and Lee S E (1983). Relationship between bench scale and prototype activated sludge systems. In Scale-up of water and wastewater treatment processes. Eds: Schmidtke N W and Smith D W, Butterworth Publishers, 307.

Jenkins D, Richard M G and Daigger G T (1984). Manual on the causes and control of activated sludge bulking and foaming. Published by Water Research Commission, P O Box 824, Pretoria, 0001.

Ketley D A, Casey T G, Ekama G A, Wentzel M C and Marais GvR (1991). The effect of fully anoxic conditions and frequency of exposure to anoxic and aerobic conditions on the growth of low F/M filaments in nitrogen removal systems. Res. Rep. W68, Dept. Civil Eng., Univ. of Cape Town.

Krul J M (1976). Dissimilatory nitrate and nitrite reduction under aerobic conditions by an aerobically and anaerobically grown *Alcaligenes sp.* and by activated sludge. J. Appl.Bact., 40, 245-260.

Krul J M and Veeningen R (1977). The synthesis of the dissimilatory nitrate reductase under aerobic conditions in a number of denitrifying bacteria, isolated from aerobic conditions in a number of denitrifying bacteria, isolated from activated sludge and drinking water. Water Research, 11, 39-43.

Kučera I, Kozák L and Dadák V (1987). Aerobic dissimilatory reduction of nitrite by cells of *Paracoccus denitrificans*: the role of nitric oxide. Biochim. Biophys. Acta, 894, 120-126.

Lakay M T, Wentzel M C, Ekama G A and Marais GvR (1988). Bulking control with chlorination in a nutrient removal activated sludge system. Water SA, 14, 35-42.

Lakay M T, Casey T G, Ekama G A and Marais GvR (1991). Bulking in N and N&P removal systems. Personal communication. Dept. Civil Eng., Univ. of Cape Town.

Lau A O, Strom P F and Jenkins D (1984). Growth kinetics of *Sphaerotilus natans* and a floc-former in pure and dual continuous culture. Journal WPCF, 56, 41-51.

Lee S E, Koopman B, Bode H and Jenkins D (1983). Evaluation of alternative sludge settleability indices. Water Ressearch, 17, 1421-1426.

Lee S E, Koopman B L, Jenkins D and Lewis R F (1982). The effect of aeration basin configuration on activated sludge bulking at low organic loading. Wat.Sci.Tech, 14, 407-427.

Mulder E G and Deinema M H (1981). The sheathed bacteria, Chapter 27 in: The prokaryotes - a handbook of habitats, isolation and identification of bacteria. Eds: Starr M P, Stolb H, Trüper G H, Balows A, Schlegel H G, Springer-Verlag, Berlin, Heidelberg.

Palm J C, Jenkins D and Parker D S (1980). Relationship between organic loading, dissolved oxygen concentration and sludge settleability in the completely mixed activated sludge process. Journal WPCF, 52, 2484-2506.

Payne W J (1973). Reduction of nitrogenous oxides by microorganisms. Bacteriol.Rev., 37, 409-452.

Pichinoty F and D'Ornano L (1961). Influence des conditions de culture sur la formation de la nitrtae réductase *d'Aerobacter aerogenes*. Biochim. Biophys. Acta. 48, 218-220.

Price T (1982). Use of anoxic zones to improve activated sludge settleability. Supplementary contribution (iii), in Bulking of activated sludge, preventative and remedial methods. Eds. B Chambers and E J Tomlinson, Ellis Horwood Ltd., Chichester, England, 259-260.

Rensink J H, Donker H J G W and Ijwema T S J (1982). The influence of feed pattern on sludge bulking. Chapter 9 in Bulking of activated sludge: preventative and remedial methods. Eds: Chambers B and Tomlinson E J, Ellis Horwood Ltd., Chichester, England, 147-163.

Richard M G, Jenkins D, Hao O and Shimizu G (1981). The isolation and characterization of filamentous micro-organisms from activated sludge bulking. Progress Report No. 81-2, SERL, Univ of California, Berkeley.

Robertson L A and Kuenen J G (1984). Aerobic denitrification: a controversy revived. Arch. Microbiol., 139, 351-354.

Shao Y J (1986). The mechanism and design of anoxic selectors for the control of low F/M filamentous bulking. PhD Thesis, Univ. of California, Berkeley, CA.

Showe M K and De Moss J A (1968). Localization and regulation of synthesis of nitrate reductase in *Escherichia coli*. J.Bacteriol., 95, 1305-1313.

Slijkhuis H (1983). The physiology of the filamentous bacterium *Microthrix parvicella*. PhD thesis, Agricultural College of Wageningen, Holland.

Stern L B and Marais GvR (1974). Sewage as the electron donorin biological denitrification. Res.Rep. W7, Dept of Civil Eng., Univ. of Cape Town.

Still D, Blackbeard J R, Ekama G A and Marais GvR (1986). The effect of feeding patterns on sludge growth rate and sludge settleability. Res.Rep. No. W55, Dept. Civil Eng., Univ. of Cape Town.

Strom P F and Jenkins D (1984). Identification and significance of filamentous organisms in activated sludge. Journal WPCF, 56, 52.

Tomlinson E J and Chambers B (1979). Methods for prevention of bulking in activated sludge. Wat.Pollut.Control, 78, 524.

van den Eynde E J, Houtmeyers J and Verachtert H (1982a). Relation between substrate feeding pattern and development of filamentous bacteria in activated sludge. Chapter 8 in: Bulking of activated sludge: preventative and remedial methods, Eds: B Chambers and E Tomlinson, Ellis Horwood Ltd., Chichester, 128-142.

van den Eynde E J, de Vries L and Verachtert H (1982b). Relationship between substrate feeding pattern and development of filamentous bacteria in activated sludge processes. III Application with industrial wastewaters. European J.Appl.Microbiol.Biotechnol., 15, 246.

van Haandel A C, Ekama G A and Marais GvR (1981). The activated sludge process Part 3 - single sludge denitrification. Water Research, 15, 1135-1152.

van Leeuwen J (1988). Bulking control with ozonation in a nutrient removal activated sludge system. Water SA, 14, 119-124.

van Leeuwen J and Pretorius W A (1988). Sludge bulking control with ozone. Journal IWEM, 2, 223-227.

van Niekerk A M (1985). Competitive growth of flocculant and filamentous microorganisms in activated sludge systems. PhD dissertation, Dept. Civil Eng., Univ. of California, Berkeley, CA.

van Niekerk A M, Jenkins D and Richard M G (1987). The competitive growth of *Zoogloea Ramigera* and Type 021N in activated sludge and pure culture - a model for low F/M bulking. Presented at IWPC biennial conference, Port Elizabeth, May 1987.

Verachtert H, van den Eynde E, Poffe R and Houtmeyers J (1980). Relations between substrate feeding pattern and development of filamentous bacteria in activated sludge processes. II Influence of substrate present in the influent. European J.Appl.Microbiol.Biotechnol, 9, 137-149.

Wagner F (1982). Study of the causes and prevention of sludge bulking in Germany. Chapter 2 in Bulking of activated sludge, preventative and remedial methods. Eds: Chambers B and Tomlinson E J, Ellis Horwood Ltd., Chichester, England, 29-40.

Wanner J, Chudoba J, Kucman K and Proske L (1987a). Control of activated sludge filamentous bulking - VIII. Effect of anoxic conditions. Water Research, 21, 1447-1451.

Wanner J, Kucman K, Ottova V and Grau P (1987b). Effect of anaerobic conditions on activated sludge filamentous bulking in laboratory systems. Water Research, 21, 1541-1546.

Wanner J, Kucman K, and Grau P (1988). Activated sludge process combined with biofilm cultivation. Water Research, 22, 207-216.

Warburton C A, Lakay M T, Casey T G, Ekama G A, Wentzel M C and Marais GvR (1991). The effect of sludge age and aerobic mass fraction on low F/M filament bulking in intermittent aeration nitrogen removal systems. Res.Rep. W65, Dept. Civil Eng., Univ. of Cape Town.

Wentzel M C, Dold P L, Ekama G A and Marais GvR (1985). Kinetics of biological phosphorus release. Wat.Sci.Tech, 17, 57-71.

Wentzel M C, Ekama G A, Dold P L and Marais GvR (1990). Biological excess phosphorus removal - steady state design. Water SA, 16(1), 29-48.

WRC (1984). Theory, design and operation of nutrient removal activated sludge processes. Published by the Water Research Commission, P O Box 824, Pretoria 001, South Africa, ISBN 0908356 137.

Wu Y C , Hsieh H N Carey D F and Ou K C (1984). Control of activated sludge bulking. J.Env.Eng, ASCE, 110, 472.

APPENDIX A

Experimental data measured for the MUCT1 and MUCT2 systems.

A.2

Experimental data measured for the MUCT1 system.
COD, TKN, solids and phosphorus concentrations,
OUR and DSVI.

													PHOSPHORUS						
DATE	DAY	Infl. COD mg/l	Effl. COD mg/l	Sbsi mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Sett ml/l	Sett Vol. ml	DSVI ml/g	OUR	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem. mgP/l
10/08/91	1	1152	68		73.9	3	3357	2972	165	300	164	40	20.3	22.9	21.5	14.7	12.1	12.0	8.3
12/08/91	4	1024	120		70.0	2	3564	3196	165	300	154		19.8	22.7	20.9	15.3	13.8	13.9	5.9
14/08/91	5	992	60	108	69.8	1.5	3578	3001	170	300	158	47	21.6	22.9	20.8	14.0	9.1	9.8	11.8
15/08/91	6	906	41	168	76.2	2.5	4179	3861	178	300	142		21.9	22.9	20.8	14.2	12.1	13.5	8.3
16/08/91	7	1056	65.3	159	75.5	3	3404	3070	155	300	152	40							
17/08/91	8	958	62.5		74.8	0.77	3775	2950	169	300	149		21.9	22.6	21.2	14.2	6.9	9.0	12.8
18/08/91	9	954	64.5		87.9	0.7	3523	3022	170	300	161	46	21.2	23.6	21.2	11.8	6.3	7.6	13.6
19/08/91	10	939	58.5	128	76.7	0.91	3554	2934	160	300	150		21.2	23.3	20.5	12.5	8.0	7.6	13.6
20/08/91	11	1028	75.6	160	78.7	1.05	3477	2914	160	300	153	42	18.5	19.9	17.7	12.2	5.1	5.7	12.9
21/08/91	12	1000	78.6		79.2	0.7	3406	2892	160	300	157		18.0	22.1	18.8	10.8	7.7	5.7	12.3
22/08/91	13	1097	56.4	221	89.6	3.2	3589	2834	160	300	149	45	16.0	21.7	18.7	13.8	8.3	7.2	8.8
23/08/91	14	1004	48.6	221	85.3	3.5	3432	2834	160	300	155		16.8	22.6	22.0	14.6	7.7	6.3	10.5
24/08/91	15	935	76.6		90.9	6.44	3312	2808	156	300	157	43	17.5	22.3	21.8	13.0	9.3	7.9	9.6
25/08/91	16	984	54.4		87.9	4.15	3652	2838	160	300	146		16.1	24.6	24.3	15.3	8.2	8.2	7.9
26/08/91	17	984	54.4		87.9	4.15	3358	2838	145	300	144	44	16.1	22.1	20.9	14.1	8.5	8.2	7.9
27/08/91	18	952	51	108	82.7	3.47	3436	2913	145	300	141		15.6	21.9	22.4	13.2	7.8	6.7	8.9
28/08/91	19	971	67.3	148	82.3	3.15	3276	2725	140	300	142		15.9	22.0	22.4	13.8	6.7	6.2	9.7
29/08/91	20	922	71.4	128	81.8	4.06	3328	2774	140	300	140	48	16.0	24.3	22.3	16.8	7.2	6.2	9.8
30/08/91	21	993	75.5		80.9	5.46	3077	2513	130	300	141		16.3	21.9	22.3	15.4	8.0	6.5	9.8
31/08/91	22	948	63.6		95.5	4.48	3206	2633	130	300	135	48	18.3	20.0	20.0	17.1	7.6	6.7	11.6
1/09/91	23	948	63.6		95.5	4.48	3206	2633	130	300	135		18.3	20.0	20.0	17.1	7.6	6.7	11.6
2/09/91	24	1042	63.7	124	95.5	2.94	3216	2694	130	300	135	41	18.6	23.2	19.7	14.8	7.0	6.4	12.2
3/09/91	25	1024	68.3	176	75.5	6.86	3155	2610	126	300	133		16.4	23.0	22.2	17.0	8.6	6.9	9.5
4/09/91	26	938	65.3		84.7	7.14	3204	2649	125	300	130	46	17.0	23.6	24.8	19.0	8.6	7.2	9.8
5/09/91																			
6/09/91	28	987	80.6	219	91.8	9.1	2961	2558	109	300	123		15.5	24.7	20.8	10.1	5.9	7.3	8.2
9/09/91	31	975	60.2	164	98.8	3.78	3225	2726	129	300	133	36	16.6	25.3	27.3	9.3	6.2	5.6	11.0
10/09/91	32	1028	63.2	172	92.7	3.4	3302	2728	126	300	127		16.1	26.1	29.8	14.2	6.7	5.0	11.1
11/09/91	33	1004	63.2	128	86.0	3.08	3438	2872	130	300	126	65	16.1	25.9	30.0	13.4	9.2	6.7	9.5
12/09/91	34	969	70.4	156	93.5	3.78	3571	2989	137	300	128		17.2	25.9	26.2	11.3	5.5	6.1	11.1
13/09/91	35	1024	56.1	140	94.1	3.75	3319	2768	130	300	131	51	17.5	26.8	28.2	10.8	3.2	4.4	13.1
14/09/91	36	943	67.3		96.3	7.25	3702	3136	140	300	126		16.0	29.4	29.7	9.8	4.9	8.1	7.8
15/09/91	37	943	67.3		96.3	7.25	3702	3136	140	300	126		16.0	29.4	29.7	9.8	4.9	8.1	7.8
16/09/91	38	1024	67.3		93.5	3.78	3691	3144	141	300	127	52	16.8	27.7	28.8	10.4	5.0	7.4	9.4
17/09/91	39	994	76.5	137	95.2	2.94	3826	3200	135	300	118		14.9	24.6	28.9	18.0	6.6	5.7	9.1
18/09/91	40	1055	76.5		94.4	2.94	3781	3185	130	300	115	58	16.9	28.9	33.5	14.0	4.6	5.7	11.2
19/09/91	41	987	73.4		89.9	4.48	3708	3094	133	300	120		17.8	2.0	32.7	13.6	4.0	3.7	14.1
20/09/91	42	991	67.3		96.0	3.79	3780	3118	145	300	128	57	16.1	31.3	29.1	11.6	4.2	4.0	12.1
22/09/91	44	938	81.6		89.6	4.2	2827	2371	110	300	130		16.7	22.1	24.9	14.7	13.0	4.0	12.7
23/09/91	45	959	93.8		98.6	5.46	3553	3005	126	300	118	55	16.2	32.0	30.6	11.9	3.7	3.7	12.5
24/09/91	46	890	49.9		99.7	4.69	3881	3216	129	300	111		15.7	25.5	28.3	12.8	3.4	3.4	12.3
25/09/91	47	1102	70.7		117	3.36	3842	3212	130	300	113	54	17.0	27.5	27.5	12.5	8.5	6.2	10.8
26/09/91	48	1023	77		103	6.23	4290	3625	155	300	120		17.7	24.8	29.2	25.1	14.5	12.3	5.5
27/09/91	49	1111	91.5		122	12.3	3697	3102	130	300	117	50	17.5	29.2	33.8	23.5	8.2	13.4	4.1
29/09/91	51	1073	54.1		125	6.44	3860	3052	130	300	112		17.7	28.5	24.5	10.3	3.7	2.0	15.7
30/09/91	52	1073	54.1		125	6.44	3860	3052	130	300	112		17.7	28.5	24.5	10.3	3.7	2.0	15.7

													PHOSPHORUS						
DATE	DAY	Infl. COD mg/l	Effl. COD mg/l	Sbsi mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Sett ml/l	Sett Vol. ml	DSVI ml/g	OUR	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem. mgP/l
1/10/91	53	990	83.2		96.6	4.55	3920	3240	130	300	111	50	17.4	32.5	23.7	9.7	6.0	3.7	13.7
2/10/91	54	886	54.9		93.5	5.04	3852	3248	131	300	113	47	16.0	31.1	26.5	8.6	3.7	3.7	12.3
3/10/91	55	890	63		102	6.44	3739	3086	120	300	107		15.0	28.1	28.1	11.4	5.0	4.7	10.3
4/10/91	56	927	65		73.9	3.15	3657	3070	122	300	111	52	15.6	29.2	26.1	9.4	5.8	4.7	10.8
6/10/91	58	879	75.2		56.8	5.53	3523	2926	117	300	111		13.7	25.4	23.4	11.7	4.5	7.0	6.7
7/10/91	59	879	75.2	269	56.8	5.53	3523	2926	115	300	109	33	13.7	25.4	23.4	11.7	4.5	7.0	6.7
8/10/91	60	958	50.2		62.7	4.97	3774	3138	130	300	115	40	14.2	26.2	24.3	12.3	4.5	4.2	10.0
9/10/91	61	884	30.8		61.6	3.92	3825	3179	121	300	105	39	13.4	27.1	25.7	13.9	7.8	5.9	7.5
10/10/91	62	961	69.9		77.3	2.66	3806	3137	125	300	109		13.8	25.1	24.3	13.5	7.2	6.9	6.9
11/10/91	63	923	39.1		76.2	2.8	3684	3113	123	300	111	21	14.9	27.6	25.4	13.3	6.4	6.1	8.8
12/10/91	64	896	67.8		65.0	1.4	3824	3145	125	300	109		15.1	26.6	26.1	11.3	4.7	4.7	10.4
14/10/91	66	810	88.4		63.3	3.22	3405	2996	130	300	127	34	16.0	29.0	27.2	12.1	5.3	5.3	10.7
15/10/91	67	904	44.5		81.8	3.5	3882	3228	123	300	106	24	17.2	27.2	27.5	14.0	4.3	2.6	14.6
16/10/91	68	892	15.3		85.7	4.13	3644	2990	122	300	112	27	17.2	29.2	28.1	12.6	5.7	4.6	12.6
17/10/91	69	802	63.1		48.4	6.79	3871	3137	128	300	110		14.6	27.6	27.3	15.2	3.0	3.3	11.3
18/10/91	70	998	97.8	240	73.6	4.62	3964	3214	139	300	117	24	12.4	25.1	24.8	13.5	4.1	3.9	8.5
20/10/91	71	1002	65.2	234	78.4	5.46	3948	3088	130	300	110		15.6	25.4	21.7	11.5	5.2	4.0	11.5
21/10/91	73	908	87		73.9	3.92	3747	3131	149	350	114		15.0	26.8	24.2	12.7	3.8	3.2	11.8
22/10/91	74	931	63.1		73.4	8.82	3149	2700	110	300	116	25	15.6	27.7	19.3	8.1	4.9	7.8	7.8
23/10/91	75	1044	79.2		74.5	4.41	3353	2732	125	300	124	34	14.9	28.5	22.5	8.5	3.9	3.7	11.3
24/10/91	76	1049	71.1		82.6	4.48	3246	2715	115	300	118	58	15.5	30.1	25.1	9.3	5.1	3.9	11.6
25/10/91	77	975	69.1		73.4	6.09	3400	2806	128	300	125	33	15.8	29.0	24.5	9.6	3.1	4.8	11.0
27/10/91	79	864	69.1		56.6	3.08	3282	2657	112	300	114		15.5	27.8	23.5	9.7	2.9	2.6	12.9
28/10/91	80	836	91.4		62.7	2.38	3288	2500	105	300	106		14.6	28.6	23.2	8.0	5.7	5.9	8.7
29/10/91	81	829	67.8		67.8	1.75	3003	2463	102	310	110	36	14.0	28.3	21.8	7.2	4.9	4.9	9.2
30/10/91	82	950	71.7		73.4	3.64	3052	2517	100	310	106	24	16.8	27.5	21.6	7.9	4.2	4.4	12.4
31/10/91	83	983	81.9		79.2	2.98	3018	2562	100	300	110		17.1	30.6	25.0	8.7	5.3	5.3	11.9
1/11/91	84	872	77.8	204	73.4	2.94	3025	2527	100	300	110	44	17.4	32.5	27.8	11.2	5.9	5.6	11.8
3/11/91	86	967	107		61.6	0.98	3102	2452	103	350	95		16.7	27.3	22.1	9.0	6.6	5.2	11.5
4/11/91	87	918	86		62.7	2.24	3122	2530	100	300	107	46	16.4	31.4	25.4	9.3	5.5	5.5	10.9
5/11/91	88	844	81.9		71.4	4.55	3313	2691	100	300	101	45	16.4	34.4	31.1	13.9	8.7	8.2	8.2
6/11/91	89	888	61.4	257	63.3	4.62	3444	2781	100	300	97	42	19.4	27.1	24.1	15.4	7.4	7.4	12.1
7/11/91	90	840	57.3	221	70.0	4.9	3269	2682	100	300	102	30	16.7	32.8	30.8	14.7	6.0	6.4	10.4
8/11/91	91	900	95.1	221	76.2	5.04	3688	3100	110	300	99		14.8	26.2	24.2	8.8	5.1	4.6	10.3
9/11/91	92	836	62		62.4	4.97	3680	3000	105	300	95		14.2	27.0	21.1	7.4	3.4	3.1	11.1
11/11/91	94	910	39.3		72.2	5.6	3700	3050	120	300	108	45	15.4	17.6	25.0	10.0	4.5	3.1	12.2
12/11/91	95	811	70.3	316	65.2	4.83	3580	2940	191	500	107		13.5	27.9	20.7	7.5	3.7	3.7	9.8
13/11/91	96	902	72.4	257	75.9	3.85	3655	2962	180	500	98	40	16.4	33.1	27.6	10.9	4.0	3.7	12.7
14/11/91	97	968	64.1	251	73.9	4.34	3800	2950	180	500	95		15.5	32.8	28.2	11.1	3.7	3.7	11.8
15/11/91	98	995	64.1	239	81.8	3.5	3876	2985	190	500	98	66	16.5	25.9	23.0	11.2	4.3	3.5	13.1
16/11/91	99	842	55.8	234	71.7	4.55	3985	3152	198	500	99		15.5	30.8	25.0	9.5	4.6	4.0	11.5
18/11/91	101	846	63.1		75.3	4.16	3900	3102	175	500	90	25	15.5	28.2	25.0	9.2	2.0	2.3	13.2
19/11/91	102	802	62		68.3	5.32	3960	3177	170	500	86								
25/11/91	108	964	68.2	298	69.4	4.48	3490	2872	165	500	95	50	15.2	30.7	27.8	12.6	5.2	3.2	12.0
26/11/91	109	977	91	287	83.2	4.2	3485	2810	160	500	92	46	14.6	31.3	25.8	10.3	7.5	4.6	10.0
27/11/91	110	994	49.6		77.8	2.1	3484	2828	150	500	86	31	14.9	33.9	26.1	8.9	4.3	3.7	11.2
28/11/91	111	927	60	269	76.7	5.88	3612	2923											
29/11/91	112	972	68.7	213	76.7	5.88	3612	2923	159	500	88		14.8	28.7	30.2	13.3	5.8	6.4	8.4
30/11/91	113	978	70.7		81.2	6.72	3705	3011	159	500	86	56	17.7	36.5	24.9	13.3	4.9	5.2	12.5

DATE	DAY	Infl. COD mg/l	Effl. COD mg/l	Sbsi mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Sett ml/l	Sett Vol. ml	DSVI ml/g	OUR	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem. mgP/l
2/12/91	115	921	48.5	173	71.7	1.12	3769	3043	152	500	81		15.4	35.7	33.6	15.4	5.5	5.5	9.9
3/12/91	116	954	64.6	191	81.5	7	4178	3408	170	500	81	50	16.8	33.7	25.7	8.3	4.4	3.6	13.3
4/12/91	117	1059	62.6	191	84.0	5.6	4029	3245	165	500	82	57	17.1	32.9	22.9	8.3	3.3	3.3	13.8
5/12/91	118	881	74.7	198	95.6	6.65	3650	3019	150	500	82	56	13.3	26.5	30.9	25.1	3.5	2.5	10.8
6/12/91	119	921	74.7	215	79.5	6.97	3765	3065	150	500	80	52	16.9	28.7	20.5	5.7	4.6	4.9	12.0
7/12/91	120	917	76.8		77.6	4.34	3556	2940	150	500	84		15.6	24.8	28.1	23.2	2.7	2.7	12.8
9/12/91	122	901	72.7	161	93.0	6.02	3402	2808	120	500	71	45	18.6	34.4	26.2	14.7	9.3	7.9	10.6
10/12/91	123	922	58.6		72.0	4.34	3621	2912	131	500	72	48	17.7	31.0	22.6	9.5	3.5	3.3	14.4
11/12/91	124	1067	84.8	205	68.9	2.8	3863	3124	140	500	72	51	19.6	31.8	25.3	9.8	3.5	1.4	18.2
12/12/91	125	1111	74.7	209	41.4	0	3929	3165	145	500	74	52	19.6	32.9	28.8	9.2	1.6	2.2	17.4
13/12/91	126	1028	110	233	39.1	0.49	2976	2424	110	500	74	66	19.3	28.3	29.1	8.4	2.5	1.6	17.7
14/12/91	127	1015	69.3		38.8	1.47	4258	3370	155	500	73	66	21.2	34.8	32.6	15.2	2.7	1.6	19.6
16/12/91	129	1081	118		39.8	2.8	3602	2883	108	500	60	60	20.5	36.6	33.3	9.4	5.8	3.3	17.2
17/12/91	130	1138	84.6	144	52.2	0	3776	2997	125	500	66	45	21.1	39.9	30.8	6.7	4.2	4.2	16.9
18/12/91	131	995	77.5	209	56.9	0	3988	3166	133	500	67		23.6	41.6	32.2	5.5	3.3	3.3	20.2
19/12/91	132	995	69.3	251	60.9	0	3951	3156	130	500	66	53	18.5	38.8	27.1	3.9	2.1	2.1	16.4
20/12/91	133	1040	93.8	281	86.9	5.18	3671	2949	125	500	68	58	18.7	41.6	35.1	6.0	2.6	1.8	16.9
21/12/91	134	1032	71.4		84.0	6.02	4032	3242	140	500	69		19.8	40.3	33.8	4.4	1.8	1.8	18.0
23/12/91	136	995	65.2	244	79.8	6.72	3922	3162	130	500	66		18.0	38.0	27.1	3.9	2.3	1.6	16.4
27/12/91	140	956	83.6	227	96.3	6.51	3692	2923	125	500	68		16.5	37.6	30.2	9.6	6.0	6.0	10.4
28/12/91	141	1032	73.4		101	5.88	3072	2489	110	500	72	44	18.4	43.1	31.6	14.3	9.3	8.0	10.4
29/12/91	142	1032	61.2		101	3.01	3365	2694	115	500	68		17.9	36.3	25.8	8.0	6.6	5.5	12.4
30/12/91	143	1036	53		95.2	5.04	3196	2582	119	500	74	38	18.1	45.3	37.8	13.7	6.3	4.1	14.0
31/12/91	145	1036	65.2		95.2	6.02	3530	2849	122	500	69		20.4	38.3	25.8	9.2	5.4	4.4	16.0
2/01/92	144	971	59.1		95.5	6.44	3897	3166	140	500	72	30	16.3	37.0	26.6	11.2	8.4	6.0	10.3
3/01/92	148	948	83.6	229	93.8	7	3786	3064	135	500	71		14.7	37.8	27.2	10.1	6.8	6.0	8.7
4/01/92	149	995	89.1	159	96.7	5.88	3966	3182	140	500	71	36	17.3	35.6	21.2	7.0	6.4	6.4	10.9
6/01/92	151	1106	75.8	163	100	6.93	4052	3230	145	500	72		18.7	32.0	13.6	6.1	5.6	6.1	12.5
7/01/92	152	922	47.1		85.7	6.3	4130	3260	155	500	75	39	18.9	33.1	20.3	8.1	6.7	4.7	14.2
8/01/92	153	977	66.6	209	83.4	5.32	3956	3114	145	500	73		16.9	37.0	27.6	10.9	8.1	6.4	10.5
9/01/92	154	1102	61.4		80.4	6.3	3918	3084	150	500	77		16.7	37.5	26.8	7.1	5.6	5.8	10.8
10/01/92	155	1118	70.7		86.5	6.02	3566	2874	140	500	79	40	16.4	37.5	34.7	8.8	6.2	5.1	11.3
11/01/92	156	995	63.5		85.7	7.14	3838	3060	150	500	78		18.5	35.1	35.1	9.9	7.9	6.9	11.5
14/01/92	159	971	73.7	199	74.0	8.26	4386	3542	180	500	82	42	20.3	40.2	30.9	6.7	6.5	6.7	13.6
15/01/92	160	943	73.7	209	71.1	6.02	3990	3206	167	500	84		16.4	36.3	31.2	9.2	5.8	4.4	12.0
16/01/92	161	988	63.5		73.9	4.1	4516	3603	170	500	75	47	17.8	41.3	29.4	9.0	5.8	4.9	12.9
20/01/92	165	893	61.4		87.9	4	3819	3077	165	500	86		18.8	35.8	25.3	8.8	6.5	6.5	12.2
22/01/92	166	934	69.6	209	78.1	5.25	3640	2967	170	500	93	45	18.8	44.7	37.3	12.5	8.3	7.7	11.1
23/01/92	167	1028	75.8	221	89.0	6.9	3775	3042	170	500	90		19.9	46.1	32.1	9.1	7.4	6.8	13.1
24/01/92	168	938	79.9	215	83.4	6.02	3679	2966	168	500	91		19.1	41.8	28.7	8.4	6.3	6.3	12.8
25/01/92	169	938	79.9		83.4	6.02	3716	3012	165	500	89		20.3	43.9	31.4	8.4	7.2	6.6	13.7
27/01/92	171	942	57.3	128	103	4.62	3564	2894	170	500	95	38	20.9	48.4	29.3	8.7	5.4	5.4	15.5
28/01/92	172	1016	76.8		89.5	4.83	3742	3060	165	500	88		23.7	50.0	38.2	9.6	8.9	4.9	18.8
29/01/92	173	1008	73.7		91.3	6.3	4088	3280	175	500	86		24.4	55.0	42.8	15.5	9.9	6.9	17.5
30/01/92	174	995	94.2		98.6	6.27	3816	3066	170	500	89	48	19.9	48.3	29.7	7.3	6.6	6.6	13.2
31/01/92	175	992	57.3		81.8	5.6	3602	2914	175	500	97		21.5	47.0	34.4	9.6	7.3	6.0	15.6
01/02/92	176	989	57.7		90.2	10.1	3678	2953	180	500	98		16.6	45.4	37.1	9.9	7.4	4.5	12.2
3/02/92	178	861	43.3		66.9	6.16	3402	2710	179	500	105	36	18.5	46.4	35.8	6.1	4.8	4.8	13.7
4/02/92	179						3556	2846			ERR								
7/02/92	182	861	59.7		72.8	6.16	3430	2703	165	500	96	35	20.6	45.8	39.3	9.8	5.9	5.9	14.7
8/02/92	183	816	82.4		75.9	4.62	3429	2715	170	500	99		23.4	43.8	38.9	10.5	6.9	4.6	18.8
10/02/92	185	824	49.4		64.1	6.16	3374	2683	170	500	101		21.3	44.8	32.0	10.5	6.3	5.6	15.7
11/02/92	186	836	51.5		82.6	5.25	3253	2598	170	500	105	40	18.1	41.8	30.7	9.9	5.6	5.3	12.9
12/02/92	187	826	58.7		78.4	6.79	3388	2688	171	500	101		18.7	40.3	28.9	9.1	8.2	5.6	13.2
13/02/92	188	853	45.3		81.2	5.39	3297	2612	175	500	106	37	17.0	39.6	25.4	5.9	7.3	6.1	10.9
14/02/92	189	913	65.5		68.3	5.88	3172	2506	170	500	107		15.9	26.5	16.2	9.2	6.1	6.1	9.8
15/02/92	190	909	92.2		82.9	5.88	3220	2534	170	500	106		20.3	41.2	37.9	19.4	9.3	7.5	12.8
17/02/92	192	885	71.7		73.4	5.25	3200	2566	173	500	108	31	19.4	37.9	30.2	9.6	7.5	5.7	13.7
18/02/92	193	881	75.8		76.2	5.25	3262	2626	175	500	107		17.6	42.5	31.1	9.4	5.6	5.0	12.6
19/02/92	194	848	49.2		72.5	5.88	3484	2818	180	500	103	40	17.3	41.7	28.7	5.6	5.3	4.7	12.6
20/02/92	195	828	45.1		63.3	5.88	3160	2572	179	500	113		17.4	34.5	32.1	7.4	4.1	3.0	14.4
21/02/92	196	811	53.2		64.5	5.53	3068	2484	180	500	117		16.5	43.3	39.5	5.3	3.2	3.0	13.6
25/02/92	200	800	86		72.0	6.3	3440	2796	200	500	116	62	18.6	33.4	47.3	14.2	9.5	9.2	9.5
26/02/92	201	863	81.4		53.2	6.72	3030	2426	150	400	124		18.9	41.3	44.6	10.9	7.4	7.4	11.5
27/02/92	202	745	71.3		64.4	5.6	3174	2556	160	400	126		17.6	38.7	39.0	8.6	5.7	4.8	12.8
28/02/92	203	806	52.9		77.8	4.55	3124	2506	160	400	128		17.0	39.6	34.2	8.3	6.0	3.3	13.7
29/02/92	204	839	81.4		68.6	7.28	2990	2354	160	400	134	46	18.2	39.4	34.9	7.0	3.0	2.1	16.1

													PHOSPHORUS						
DATE	DAY	Infl. COD mg/l	Effl. COD mg/l	Sbsi mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Sett ml/l	Sett Vol. ml	DSVI ml/g	OUR	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem. mgP/l
2/03/92	206	794	67.2		57.1	5.04	3068	2442	160	400	130	38	17.9	47.3	27.6	4.9	2.7	2.1	15.8
3/03/92	207	843	77.4		61	6.44	3490	2432	180	400	129		18.3	38.6	33.0	7.4	5.6	2.1	16.2
4/03/92	208	827	69.2		72.5	3.55	3110	2446	165	400	133	35	18.6	44.5	29.8	6.2	5.3	2.1	16.5
5/03/92	209	916	102		59.6	5.46	3082	2454	170	400	138		17.8	38.5	21.4	7.5	3.6	3.0	14.8
6/03/92	210	916	102	249	59.6	5.46	3082	2454	170	400	138		16.6	37.9	23.2	8.7	6.6	3.6	13.0
7/03/92	211	916	67.2		67.8	9.1	3046	2406	165	400	135		16.5	42.1	22.2	3.8	3.5	3.2	13.3
9/03/92	213	863	44.8	164	65.5	5.18	2986	2330	180	400	151	40	18.1	39.3	22.2	5.1	3.8	3.8	14.3
10/03/92	214	880	73.3	156	74.2	4.25	3110	2454	170	400	137	40	17.7	36.9	27.0	5.0	4.0	3.4	14.3
11/03/92	215	749	36.6	237	62.4	4.97	3158	2472	175	400	139		16.8	39.7	23.9	5.9	5.0	3.7	13.0
12/03/92	216	910	36.6	204	71.4	4.55	2691	2130	170	400	158	31	14.0	27.7	22.2	4.1	3.7	2.6	11.3
13/03/92	217	906	108	200	63.6	7	2914	2298	170	400	146		12.9	30.3	25.7	5.0	3.5	3.1	9.8
14/03/92	218	770	48.1		71.1	6.86	3264	2648	120	300	123		19.1	40.5	30.6	5.1	3.1	3.4	15.7
16/03/92	220	1018	60.1	204	79	7	2908	2312	165	400	142		19.7	42.2	29.3	6.5	5.7	4.4	15.3
18/03/92	222	1034	68.1	225	87.9	4.45	2612	2112	141	400	135		19.0	35.2	26.6	11.3	9.8	10.7	8.3
19/03/92	223	914	72.1	212	95.2	14.3	2544	2068	151	400	148		18.7	34.9	30.0	11.0	9.5	11.0	7.7
20/03/92	224	914	72.1		95.2	14.3	2544	2068	151	400	148	56	18.7	34.9	30.0	11.0	9.5	11.0	7.7
21/03/92	225	988	69.1	229	95.2	6.44	2768	2356	120	300	145		19.3	34.3	30.6	10.1	10.1	10.1	9.2
23/03/92	227	900	53.1	204	95.2	3.64	2386	1910	149	400	156		18.4	47.8	38.0	13.2	8.6	8.3	10.1
24/03/92	228	878	66.1	219	85.1	4.4	2802	2280	182	400	162	35	18.6	32.0	25.4	9.3	9.3	9.6	9.0
25/03/92	229	964	52.4	200	90.2	5.53	2756	2270	185	400	168	52	23.3	32.6	27.3	11.5	10.2	6.5	16.8
26/03/92	230	980	80.6	172	77.8	4.97	3024	2558	140	300	154		18.1	33.2	29.3	9.7	7.0	7.9	10.3
27/03/92	231	980	123	172	78.4	4.06	2838	2350	185	400	163	40	18.4	33.5	32.9	12.7	9.4	7.6	10.9
28/03/92	232	1032	109		105	4.34	3076	2604	180	400	146		21.5	32.6	28.6	11.1	8.4	5.7	15.8
29/03/92	233	1008	60.5	184	96.9	4.9	3240	2744	155	300	159		21.5	40.7	38.6	11.8	9.8	9.8	11.8
30/03/92	234	851	70.6	197	88.5	5.74	3358	2766	165	300	164		21.5	42.4	37.4	8.8	7.7	9.1	12.5
1/04/92	236	948	50.4	136	92.4	6.72	3030	2518	160	300	176	49	20.8	46.9	41.9	12.6	6.9	6.9	13.9
2/04/92	237	911	88.7		93.5	7.07	3244	2416	161	300	165	51	22.1	43.2	37.5	12.9	7.9	6.0	16.1
3/04/92	238			168															
6/04/92	241	1000	64.5	214	87.4	4.41	3678	3062	160	300	145		21.9	36.6	37.9	19.7	10.8	10.5	11.4
7/04/92	242	839	56.4	194	79	5.25	3508	2440	160	300	152	52	19.1	40.3	36.0	19.7	11.1	8.3	10.8
8/04/92	243	1008	64.5	194	78.4	5.11	4072	3414	151	300	124	47	19.6	42.1	36.2	20.6	8.6	7.7	12.0
9/04/92	244	901	55.5	219	82.6	6.02	3108	2858	152	300	163		19.3	39.6	36.8	19.3	9.5	7.7	11.7
10/04/92	245	954	128	154	94.9	6.72	3598	2966	150	300	139	48	18.7	34.4	29.5	14.7	8.3	4.6	14.1
11/04/92	246	880	65.8		96.9	3.78	3688	3098	152	300	137		19.0	34.4	30.7	12.9	5.5	4.9	14.1
13/04/92	248	1028	78.1		91.3	5.88	3746	3100	152	300	135	48	19.6	38.1	33.2	15.4	9.5	6.5	13.2
14/04/92	249	958	49.3		88.8	7.07	3736	3100	150	300	134		21.3	40.0	40.0	19.3	10.5	7.5	13.8
15/04/92	250	962	49.3	159	93.2	5.81	3690	3016	150	300	136	62	20.6	39.3	38.0	19.7	11.1	7.9	12.8
16/04/92	251	1123	53.5	219	98.6	6.09	3992	3198	150	300	125		21.0	38.4	37.8	17.7	10.8	8.9	12.2
17/04/92	252	810	72	139	83.7	6.37	3862	3192	151	300	130		18.1	34.1	30.5	17.7	9.9	7.9	10.2
18/04/92	253	913	69.9		77.3	6.72	3790	3102	150	300	132		17.4	35.1	32.2	16.1	8.9	7.9	9.5
20/04/92	255	880	82.2	129	82.9	6.3	4042	3320	150	300	124	48	18.4	35.1	31.2	15.1	8.2	7.2	11.2
21/04/92	256	855	61.7		71.1	5.18	3882	3124	145	300	125		17.7	31.5	30.9	18.4	10.2	7.6	10.2
23/04/92	258	950	76.1	192	79	5.04	3760	3022	150	300	133		21.0	35.5	29.2	12.5	8.9	7.2	13.8
24/04/92	259	914	85.3		77.3	6.65	3804	3156	148	300	130	58	21.3	35.5	32.5	16.4	10.2	7.9	13.5
25/04/92	260	950	63		82.9	5.88	3716	3100	155	300	139		21.3	36.4	34.5	16.7	10.5	8.2	13.1
27/04/92	262	1016	110	209	90.7	5.6	3852	3172	150	300	130	54	21.3	38.1	32.8	17.7	11.5	8.5	12.8
28/04/92	263	959	79.2	164	79.8	5.32	3880	3206	150	300	129		22.7	38.7	34.5	17.4	9.2	8.9	13.8
29/04/92	264	992	65	159	94.6	4.48	3962	3292	142	300	119	71	20.7	37.8	33.8	16.4	12.2	9.2	11.5
30/04/92	265	939	61	229	97.4	5.46	4052	3440	160	300	132		18.7	34.2	30.5	14.9	9.3	9.3	9.3

													PHOSPHORUS						
DATE	DAY	Infl. COD mg/l	Effl. COD mg/l	Sbsi mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Sett ml/l	Sett Vol. ml	DSVI ml/g	OUR	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem. mgP/l
1/5/92	266	1016	56.9		94.4	3.85	3640	2994	140	300	128		20.6	37.0	32.2	15.8	8.9	8.6	12.0
2/05/92	267	967	102	214	100	4.76	3276	2610	160	300	163		21.9	35.3	31.2	14.1	9.6	7.5	14.4
4/05/92	269	951	61	209	84.6	3.64	3518	2916	130	300	123	66	21.9	35.3	29.8	14.7	9.3	7.9	14.1
5/05/92	270	898	81.3	169	85.4	7.42	3654	3014	140	300	128		20.2	31.9	31.5	14.4	11.0	10.3	9.9
6/05/92	271	878	61	155	104	5.46	3948	3250	140	300	118	46	18.3	33.2	30.6	14.5	9.2	7.3	11.1
7/05/92	272	894	67.1	137	76.7	6.58	3484	2922	135	300	129		18.0	32.8	30.0	16.4	11.1	9.2	8.8
8/05/92	273	898	104		67.2	5.04	3950	3282	141	300	119		18.0	32.2	27.8	17.1	10.7	8.5	9.5
9/05/92	274	862	65		67.8	4.06	4128	3430	142	300	115		18.8	36.3	30.6	19.1	11.1	9.6	9.2
11/05/92	276			184															
14/05/92	279	935	48.8	129	67.8	4.55	3714	3096	130	300	117	68	21.1	36.9	39.4	22.2	12.3	10.2	10.9
15/05/92	280	935	48.8		67.8	4.55	3714	3096	130	300	117	59	19.1	32.0	30.1	16.5	9.1	6.5	12.6
16/05/92	281	935	48.8		67.8	4.55	3714	3096	130	300	117		18.8	36.2	31.4	16.5	10.0	8.1	10.7
18/05/92	283	959	69.1	129	68.9	4.34	3690	3074	122	300	110		19.7	33.0	30.7	15.9	8.1	8.4	11.3
19/05/92	284	927	40.6	119	79.2	4.55	3998	3314	135	300	113	78	20.1	26.4	23.3	11.2	9.9	8.0	12.1
20/05/92	285	925	74	144	59.9	4.9	3898	3232	130	300	111		23.6	33.4	31.5	15.9	12.7	8.3	15.3
21/05/92	286	896	41.1	136	65.5	4.83	3932	3184	165	400	105		19.7	32.0	28.5	14.9	11.6	9.1	10.7
22/05/92	287	958	63.7		63.6	5.18	3472	3000	151	400	109		21.3	33.3	30.7	17.8	10.7	9.1	12.3
25/05/92	290	991	76.1	112	68.6	5.18	3596	3064	170	400	118	66	22.5	40.1	32.7	15.8	10.6	7.7	14.8
26/05/92	291	983	61.4		59.4	4.34	3766	3188	180	400	119		25.0	36.6	31.0	16.2	10.2	9.5	15.5
27/05/92	292			159															
01/06/92	297	853	42.8	139	99.7	7	4028	3402	170	400	106	40	18.3	29.5	24.8	10.3	8.6	7.1	11.2
02/06/92	298	934	100	209	85.1	4.9	4060	2844	170	400	105		19.0	32.3	23.7	12.1	8.1	9.5	9.5
03/06/92	299	877	77.5	163	105	6.02	4006	3492	171	400	107		19.3	34.0	25.4	13.0	9.2	8.9	10.4
04/06/92	300	910	79.6		104	5.74	3942		160	400	101		19.6	29.4	27.4	14.4	9.5	8.4	11.3
05/06/92	301	1053	89.8	161	72.5	6.02	4070	3480	169	400	104		24.2	33.6	24.2	11.4	10.8	8.6	15.6
06/06/92	302	1012	93.8	119	85.1	5.6	4050	3470	170	400	105		23.3	38.3	32.5	18.1	13.3	10.0	13.3
10/06/92	306	1012	61.2	149	96.3	5.46	4362	3656	151	400	87	86	22.5	37.2	40.3	22.5	13.3	10.6	11.9
11/06/92	307	1044	57.1		77.6	2.45	3870	3512	155	400	100		20.3	30.3	25.9	13.9	10.8	8.8	11.5
12/06/92	308	1073	49		58.2	4.48	3610	3254	160	400	111	87	22.9	36.7	26.9	13.9	9.1	7.8	15.1
13/06/92	309	1057	79.6		86.2	5.18	4142	3454	150	400	91		21.9	29.8	24.9	12.7	13.0	11.0	10.9
15/06/92	311	959	51		89	5.18	4272	3606	155	400	91		19.3	34.7	28.4	14.2	11.5	8.8	10.5
16/06/92	312	1073	95.9	189	118	5.6	4274	3558	155	400	91	65	19.8	31.1	24.5	12.2	12.5	10.8	9.1
17/06/92	313	992	68	203	87.1	12.7	3766	3228	141	400	94		18.6	25.4	20.8	11.3	10.3	10.5	8.1
19/06/92	315	960	94	185	103	7.98	3688	3096	140	400	95	45	17.9	29.6	23.5	10.8	7.6	6.9	11.0
22/06/92	318	1116	76	164	106	4.9	3938	3256	150	400	95		20.1	29.8	29.3	13.0	8.3	5.9	14.2
23/06/92	319	1004	66	154	93.5	7.84	4038	3448	150	400	93	55	18.9	39.4	28.8	13.6	9.3	7.8	11.1
24/06/92	320			149									18.9	28.8	25.2	10.6	8.6	6.1	12.9
26/06/92	322	1052	64	155	105	5.88	4258	3682	161	400	95	67	18.0	30.8	26.1	11.0	8.6	7.3	10.7
29/06/92	325	1020	44	133	102	3.92	4598	3856	170	400	92		18.5	31.4	25.6	11.2	9.4	5.0	13.5
01/07/92	327	940	48		111	4.48	4502	3882	170	400	94		18.0	30.3	27.7	11.8	7.3	5.8	12.3
03/07/92	328	964	80		124	5.04	4502	3886	192	400	107	55	18.1	30.4	25.7	10.1	7.6	4.4	13.7
06/07/92	331	996	102		118	7.84	4208	3530	171	400	102		17.4	31.9	23.8	9.8	6.6	4.2	13.2
07/07/92	332	985	51.8		116	4.76	4056	3390	169	400	104		17.5	29.1	25.8	11.1	7.6	7.1	10.4
09/07/92	334	1054	60.5		129	12.7	4288	3562	180	400	105	46	20.0	29.1	24.5	12.1	10.6	8.6	11.4
13/07/92	338	1106	54		85.4	5.6	4500	3500	189	400	105		25.6	33.4	29.6	14.5	8.9	8.6	17.0
14/07/92	339	1028	67		99.4	5.18	4128	3424	175	400	106	50	21.8	36.3	31.5	14.0	8.9	7.5	14.3
15/07/92	340	1110	75.6		96.6	4.34	4158	3490	170	400	102		21.8	33.4	33.1	18.8	12.1	8.3	13.5

Experimental data measured for the MUCT system
Nitrate and nitrite concentrations.

		NITRATE & NITRITE					NITRITES					NITRATES				
DATE	DAY	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
10/08/91	1	0.33	0.46	0.66	17.0	11.7	0.06	0.07	0.13	2.37	3.39	0.26	0.39	0.53	14.6	8.3
12/08/91	4	0.33	0.42	0.66	17.0	11.7	0.06	0.07	0.13	2.37	3.39	0.26	0.35	0.53	14.6	8.3
14/08/91	5	0.15	0.23	0.60	14.1	12.2	0.08	0.10	0.22	2.56	2.86	0.07	0.13	0.38	11.5	9.3
15/08/91	6	0.59	0.44	0.24	12.6	12.6	0.07	0.11	0.08	2.41	2.41	0.52	0.34	0.16	10.2	10.2
16/08/91	7	0.64	0.24	0.12	8.1	11.2	0.55	0.14	0.10	1.85	1.60	0.09	0.10	0.02	6.3	9.6
17/08/91	8	0.94	0.37	0.76	11.7	12.0	0.39	0.11	0.08	2.37	2.81	0.56	0.26	0.68	9.4	9.2
18/08/91	9	1.15	2.02	1.53	15.2	12.5	0.03	0.52	0.60	2.70	3.05	1.12	1.50	0.94	12.5	9.5
19/08/91	10	1.38	0.41	0.55	12.0	13.8	0.04	0.02	0.04	0.91	1.50	1.33	0.39	0.52	11.1	12.3
20/08/91	11	0.83	0.30	0.52	12.6	13.9	0.05	0.05	0.00	0.88	1.25	0.78	0.25	0.52	11.8	12.7
21/08/91	12	0.88	0.24	0.85	12.6	13.7	0.03	0.03	0.05	0.75	0.56	0.85	0.21	0.81	11.9	13.2
22/08/91	13	1.63	0.47	1.50	11.1	13.4	0.34	0.00	0.02	0.54	0.89	1.29	0.47	1.48	10.6	12.5
23/08/91	14	0.72	0.40	0.50	10.8	12.5	0.10	0.05	0.01	0.30	0.40	0.63	0.36	0.49	10.5	12.1
24/08/91	15	0.68	0.96	0.74	13.1	10.2	0.05	0.12	0.15	1.32	2.24	0.63	0.84	0.59	11.8	8.0
25/08/91	16	1.01	1.33	0.36	11.0	11.3	0.22	0.00	0.01	0.70	0.67	0.79	1.33	0.35	10.3	10.6
26/08/91	17	0.86	0.85	1.02	15.7	14.0	0.05	0.02	0.03	1.59	2.69	0.82	0.83	0.99	14.2	11.3
27/08/91	18	0.57	1.00	0.68	11.1	16.2	0.02	0.03	0.06	1.09	2.39	0.55	0.97	0.62	10.0	13.8
28/08/91	19	0.38	0.58	0.57	15.3	12.8	0.29	0.22	0.08	0.50	1.62	0.09	0.36	0.49	14.8	11.2
29/08/91	20	0.71	0.46	0.39	17.0	15.2	0.29	0.11	0.07	0.94	1.66	0.43	0.35	0.32	16.0	13.6
30/08/91	21	0.15	0.25	1.18	16.0	13.7	0.04	0.05	0.07	0.52	1.54	0.11	0.20	1.11	15.4	12.2
31/08/91	22	0.21	0.45	0.96	17.2	17.8	0.06	0.09	0.13	1.95	1.34	0.14	0.36	0.83	15.2	16.5
1/09/91	23	0.21	0.45	0.96	17.2	17.8	0.06	0.09	0.13	1.95	1.34	0.14	0.36	0.83	15.2	16.5
2/09/91	24	0.10	0.41	1.33	19.4	18.2	0.05	0.09	0.26	2.03	1.64	0.06	0.32	1.07	17.4	16.6
3/09/91	25	1.05	0.17	1.50	20.8	16.7	0.06	0.10	0.57	1.87	1.91	0.99	0.07	0.93	18.9	14.8
4/09/91	26	0.54	0.44	1.70	17.5	17.5	0.08	0.13	0.55	2.85	3.69	0.45	0.31	1.15	14.7	13.8
5/09/91																
6/09/91	28	3.10	0.51	0.21	14.3	15.8	0.35	0.08	0.07	1.97	2.22	2.75	0.43	0.15	12.3	13.6
9/09/91	31	0.43	0.29	1.22	14.7	13.5	0.05	0.07	0.27	2.33	2.76	0.38	0.22	0.95	12.3	10.7
10/09/91	32	1.07	0.32	0.27	13.4	14.8	0.14	0.08	0.05	2.93	2.95	0.93	0.24	0.22	10.4	11.8
11/09/91	33	0.36	0.36	1.13	15.9	14.1	0.07	0.08	0.23	2.88	2.87	0.29	0.28	0.91	13.1	11.2
12/09/91	34	0.24	0.14	0.68	15.3	12.8	0.05	0.05	0.28	2.74	2.71	0.19	0.09	0.40	12.5	10.1
13/09/91	35	1.63	0.46	0.64	15.3	14.5	0.13	0.12	0.19	2.56	2.99	1.50	0.35	0.45	12.7	11.5
14/09/91	36	0.33	0.46	0.66	17.0	11.7	0.06	0.07	0.13	2.37	2.39	0.26	0.39	0.53	14.6	9.3
15/09/91	37	0.33	0.42	0.66	17.0	11.7	0.06	0.07	0.13	2.37	2.39	0.26	0.35	0.53	14.6	9.3
16/09/91	38	0.15	0.23	0.60	14.1	12.2	0.08	0.10	0.22	2.56	2.86	0.07	0.13	0.38	11.5	9.3
17/09/91	39	0.59	0.44	0.24	12.6	12.6	0.07	0.11	0.08	2.41	2.41	0.52	0.34	0.16	10.2	10.2
18/09/91	40	0.64	0.24	0.12	12.5	11.2	0.55	0.14	0.10	2.85	2.20	0.09	0.10	0.02	9.7	9.0
19/09/91	41	0.94	0.37	0.76	11.7	12.0	0.39	0.11	0.08	2.37	2.81	0.56	0.26	0.68	9.4	9.2
20/09/91	42	1.15	2.02	1.53	15.2	12.5	0.03	0.52	0.60	2.70	3.05	1.12	1.50	0.94	12.5	9.5
22/09/91	44	1.38	1.40	0.47	13.1	12.1	0.75	0.47	0.24	2.53	2.35	0.63	0.93	0.23	10.6	9.8
23/09/91	45	0.48	0.36	1.39	11.8	13.1	0.13	0.15	0.28	2.34	2.49	0.35	0.21	1.11	9.4	10.6
24/09/91	46	0.32	0.48	0.64	9.0	12.1	0.12	0.15	0.15	2.60	2.63	0.21	0.33	0.49	6.4	9.5
25/09/91	47	2.20	0.60	1.09	10.9	11.8	0.78	0.28	0.63	2.38	2.13	1.42	0.33	0.46	8.5	9.7
26/09/91	48	0.42	0.35	0.98	9.0	12.6	0.19	0.21	0.89	1.19	2.73	0.23	0.14	0.10	7.8	9.9
27/09/91	49	2.83	0.89	0.52	10.3	12.6	1.55	0.36	0.22	2.03	2.61	1.28	0.54	0.30	8.3	10.0
29/09/91	51	1.67	0.66	1.32	10.5	12.0	0.38	0.26	0.46	3.10	2.90	1.28	0.40	0.86	7.4	9.1
30/09/91	52	1.67	0.66	1.32	10.5	12.0	0.38	0.26	0.46	3.10	2.90	1.28	0.40	0.86	7.4	9.1

DATE	DAY	NITRATE & NITRITE					NITRITES					NITRATES				
		Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
1/10/91	53	1.11	1.38	2.07	15.2	14.8	0.39	0.40	0.56	2.68	2.15	0.72	0.98	1.51	12.5	12.7
2/10/91	54	0.49	1.18	1.31	14.2	14.7	0.31	0.18	0.16	1.40	2.30	0.18	1.00	1.15	12.8	12.4
3/10/91	55	1.03	0.58	0.47	10.8	12.4	0.33	0.13	0.13	1.16	2.25	0.70	0.45	0.34	9.6	10.1
4/10/91	56	0.31	0.54	0.65	15.4	13.4	0.07	0.09	0.26	2.63	1.67	0.24	0.45	0.39	12.8	11.7
6/10/91	58	0.51	0.57	0.60	7.2	7.0	0.03	0.03	0.04	0.55	0.33	0.48	0.55	0.56	6.7	6.7
7/10/91	59	0.51	0.57	0.60	7.2	7.0	0.03	0.03	0.04	0.55	0.33	0.48	0.55	0.56	6.7	6.7
8/10/91	60	0.52	0.40	0.36	8.9	9.1	0.10	0.05	0.07	0.69	0.27	0.43	0.35	0.29	8.2	8.8
9/10/91	61	0.48	0.38	0.65	8.1	10.1	0.10	0.07	0.06	1.38	0.38	0.39	0.31	0.59	6.7	9.7
10/10/91	62	0.23	0.90	0.28	8.6	8.2	0.12	0.07	0.04	1.14	0.34	0.10	0.82	0.25	7.5	7.8
11/10/91	63	0.85	0.32	0.41	6.3	6.5	0.05	0.04	0.02	1.20	0.36	0.81	0.29	0.39	5.1	6.1
12/10/91	64	0.43	0.58	0.78	6.7	6.8	0.32	0.17	0.14	1.05	0.35	0.12	0.42	0.63	5.7	6.5
14/10/91	66	0.85	0.95	0.44	6.3	6.4	0.08	0.09	0.06	0.37	0.48	0.77	0.86	0.38	5.9	5.9
15/10/91	67	0.37	0.53	0.40	6.6	6.6	0.19	0.10	0.08	1.28	0.94	0.18	0.42	0.32	5.4	5.7
16/10/91	68	0.41	1.00	0.30	8.0	7.4	0.29	0.18	0.06	1.08	0.91	0.12	0.83	0.24	6.9	6.5
17/10/91	69	1.20	0.40	0.29	6.9	7.2	0.06	0.06	0.06	0.53	1.08	1.13	0.34	0.22	6.4	6.1
18/10/91	70	0.51	0.65	0.40	7.6	8.8	0.20	0.10	0.08	1.50	0.44	0.31	0.55	0.32	6.1	8.3
20/10/91	71	0.42	0.33	0.76	11.1	11.7	0.20	0.06	0.18	1.40	1.20	0.21	0.27	0.58	9.7	10.5
21/10/91	73	0.77	0.21	0.26	8.7	8.0	0.10	0.06	0.06	1.03	1.33	0.67	0.16	0.20	7.7	6.6
22/10/91	74	0.55	0.39	0.83	10.1	10.4	0.09	0.11	0.12	0.62	0.70	0.45	0.28	0.72	9.4	9.7
23/10/91	75	1.60	0.66	0.44	6.4	6.6	0.07	0.09	0.10	1.24	0.38	1.52	0.57	0.34	5.1	6.2
24/10/91	76	0.40	0.32	0.44	7.4	8.8	0.05	0.06	0.12	0.65	0.43	0.36	0.25	0.33	6.7	8.4
25/10/91	77	0.71	0.51	0.61	6.9	5.7	0.17	0.17	0.16	0.35	0.76	0.54	0.34	0.45	6.6	4.9
27/10/91	79	0.63	0.74	1.02	9.0	7.7	0.14	0.13	0.24	1.05	0.42	0.49	0.61	0.78	7.9	7.3
28/10/91	80	0.54	0.41	0.90	9.8	8.7	0.21	0.09	0.17	0.75	0.32	0.33	0.32	0.73	9.0	8.4
29/10/91	81	0.41	0.44	1.25	13.0	9.5	0.12	0.22	0.86	1.07	0.79	0.29	0.22	0.39	11.9	8.7
30/10/91	82	0.92	0.46	0.14	6.1	7.4	0.37	0.13	0.09	0.86	0.58	0.55	0.33	0.05	5.3	6.8
31/10/91	83	0.45	0.32	0.60	8.2	9.2	0.07	0.08	0.15	1.44	1.92	0.38	0.24	0.45	6.8	7.3
1/11/91	84	0.63	0.66	0.86	12.4	12.8	0.17	0.12	0.11	1.83	1.36	0.45	0.54	0.75	10.6	11.4
3/11/91	86	0.92	0.89	1.36	11.9	11.9	0.12	0.13	0.21	1.52	1.65	0.80	0.76	1.15	10.4	10.3
4/11/91	87	0.37	0.33	0.98	10.6	11.1	0.12	0.11	0.35	1.46	1.35	0.25	0.22	0.63	9.2	9.8
5/11/91	88	0.38	0.44	0.75	11.0	10.6	0.13	0.13	0.25	1.65	1.70	0.26	0.31	0.50	9.4	8.9
6/11/91	89	0.94	0.28	0.23	6.5	7.4	0.11	0.09	0.10	1.21	1.15	0.83	0.19	0.13	5.3	6.3
7/11/91	90	1.09	0.36	0.26	5.5	5.5	0.26	0.15	0.15	1.64	1.41	0.83	0.21	0.11	3.9	4.1
8/11/91	91	0.90	0.67	0.69	11.4	9.4	0.10	0.17	0.19	1.29	1.22	0.80	0.50	0.51	10.1	8.2
9/11/91	92	1.26	0.30	0.62	11.7	8.8	0.13	0.10	0.16	1.04	0.96	1.12	0.20	0.46	10.7	7.8
11/11/91	94	1.00	0.51	1.24	10.2	13.3	0.14	0.21	0.66	2.69	1.48	0.85	0.30	0.58	7.5	11.8
12/11/91	95	0.60	0.76	0.28	9.1	9.4	0.36	0.52	0.18	1.10	0.62	0.24	0.24	0.10	8.0	8.8
13/11/91	96	0.30	0.35	0.55	9.8	10.0	0.13	0.22	0.24	0.56	0.53	0.17	0.13	0.32	9.2	9.4
14/11/91	97	0.71	0.50	0.43	8.5	9.4	0.10	0.10	0.14	0.85	0.62	0.61	0.40	0.29	7.6	8.8
15/11/91	98	0.38	0.39	1.11	7.7	6.7	0.07	0.06	0.14	0.73	0.50	0.31	0.33	0.97	6.9	6.2
16/11/91	99	0.29	0.32	0.68	7.7	7.2	0.04	0.04	0.06	0.44	0.78	0.25	0.28	0.62	7.2	6.4
18/11/91	101	0.83	0.36	0.68	8.1	7.0	0.12	0.05	0.07	0.41	0.57	0.71	0.31	0.62	7.7	6.5
19/11/91	102															
25/11/91	108	0.84	0.52	0.35	9.1	10.0	0.50	0.30	0.25	1.24	1.15	0.34	0.23	0.09	7.8	8.8
26/11/91	109	1.14	0.61	0.26	11.0	11.4	0.86	0.41	0.22	1.73	1.22	0.27	0.20	0.04	9.3	10.2
27/11/91	110	0.41	0.35	0.66	9.6	8.3	0.15	0.18	0.38	1.77	1.43	0.26	0.16	0.29	7.8	6.9
28/11/91	111															
29/11/91	112	1.10	1.03	0.31	9.0	8.9	0.85	0.36	0.21	1.30	1.18	0.25	0.67	0.10	7.7	7.7
30/11/91	113	0.44	0.63	0.39	11.1	12.6	0.17	0.22	0.21	1.34	0.85	0.28	0.41	0.18	9.8	11.7

A.10

		NITRATE & NITRITE					NITRITES					NITRATES				
DATE	DAY	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
2/03/92	206	0.44	0.19	10.97	23.4	20.8	0.25	0.10	2.18	1.03	1.03	0.19	0.09	8.80	22.4	19.7
3/03/92	207	1.04	0.42	11.85	20.2	20.2	0.21	0.21	3.48	0.96	1.16	0.83	0.21	8.37	19.2	19.0
4/03/92	208	0.58	0.53	8.04	18.1	18.1	0.22	0.14	2.25	1.50	0.75	0.35	0.39	5.79	16.6	17.4
5/03/92	209	0.29	0.73	9.36	17.8	18.7	0.28	0.31	2.21	0.76	0.87	0.01	0.42	7.15	17.1	17.9
6/03/92	210	0.30	0.22	8.82	28.9	27.8	0.16	0.18	2.89	1.80	1.05	0.14	0.04	5.93	27.1	26.8
7/03/92	211	0.88	0.91	8.29	27.5	33.7	0.45	0.30	3.14	1.30	1.62	0.43	0.61	5.15	26.2	32.0
9/03/92	213	0.40	1.55	8.07	30.1	27.8	0.12	0.33	2.92	0.63	0.73	0.28	1.22	5.15	29.5	27.1
10/03/92	214	0.45	1.55	8.65	30.3	30.1	0.11	0.26	2.04	1.19	0.68	0.34	1.29	6.61	29.1	29.4
11/03/92	215	0.39	1.16	7.92	31.0	32.1	0.11	0.24	1.85	1.19	0.71	0.28	0.93	6.07	29.8	31.4
12/03/92	216	0.28	1.18	11.34	25.8	29.6	0.16	0.32	1.97	1.14	1.05	0.12	0.86	9.37	24.7	28.5
13/03/92	217	2.68	2.76	4.78	24.1	22.5										
14/03/92	218	0.40	0.37	5.74	12.6	21.6	0.08	0.19	1.35	0.60	0.58	0.32	0.18	4.39	12.0	21.1
16/03/92	220	0.33	0.62	3.13	9.8	12.0	0.07	0.06	1.40	0.81	0.81	0.26	0.56	1.74	9.0	11.2
18/03/92	222	0.35	2.19	12.74	18.9	18.9	0.10	0.23	1.07	0.50	0.37	0.25	1.97	11.67	18.4	18.5
19/03/92	223	0.40	1.65	12.34	30.8	29.1	0.40	0.58	2.26	2.19	3.22	0.00	1.07	10.08	28.6	25.9
20/03/92	224	0.82	1.35	13.85	21.5	21.2	0.43	0.61	3.22	2.16	2.08	0.38	0.74	10.63	19.4	19.2
21/03/92	225	0.82	1.35	13.85	21.5	21.2	0.43	0.61	3.22	2.16	2.07	0.38	0.74	10.63	19.4	19.2
23/03/92	227	1.39	0.49	11.08	22.8	22.3	0.29	0.20	2.77	2.08	2.05	1.10	0.29	8.31	20.7	20.3
24/03/92	228	0.63	2.03	10.08	25.2	28.9	0.46	0.61	3.76	3.76	1.83	0.17	1.42	6.33	21.5	27.1
25/03/92	229	1.29	0.45	12.46	27.1	29.2	0.37	0.33	3.84	2.37	2.37	0.92	0.11	8.62	24.7	26.9
26/03/92	230	1.29	1.58	10.16	24.0	23.7	0.32	0.16	3.57	2.12	2.54	0.97	1.42	6.59	21.9	21.2
27/03/92	231	1.00	0.49	12.77	22.5	23.7	0.38	0.33	3.89	1.84	2.10	0.62	0.17	8.89	20.6	21.6
28/03/92	232	1.46	0.40	12.66	24.5	25.3	0.25	0.17	2.45	1.57	1.84	1.21	0.23	10.22	22.9	23.4
29/03/92	233	2.09	1.18	13.20	26.4	25.0	0.23	0.65	2.31	2.09	1.99	1.86	0.53	10.89	24.3	23.0
30/03/92	234	0.76	0.95	11.84	25.0	26.4	0.16	0.57	2.37	1.98	2.13	0.60	0.38	9.47	23.0	24.3
1/04/92	236	1.14	1.21	10.46	20.6	24.2	0.25	0.52	3.57	1.99	1.93	0.90	0.69	6.89	18.6	22.3
2/04/92	237	1.42	0.29	5.54	14.8	12.4	0.25	0.10	1.56	2.39	1.03	1.17	0.19	3.98	12.4	11.4
3/04/92	238	1.53	0.41	4.28	15.3	16.1	0.22	0.22	1.29	2.44	1.78	1.31	0.19	2.99	12.9	14.3
6/04/92	241	1.00	0.28	0.57	10.6	12.4	0.33	0.16	0.32	0.72	0.63	0.67	0.12	0.25	9.9	11.8
7/04/92	242	1.09	0.29	0.31	9.8	10.8	0.34	0.20	0.28	1.12	0.50	0.76	0.09	0.03	8.7	10.3
8/04/92	243	0.89	0.31	1.24	13.7	13.7	0.75	0.15	0.11	1.88	1.15	0.15	0.16	1.13	11.9	12.6
9/04/92	244	1.11	0.43	1.24	14.0	14.0	0.85	0.15	0.13	0.87	1.11	0.26	0.28	1.11	13.1	12.9
10/04/92	245	1.58	0.45	1.27	15.0	15.0	0.55	0.16	0.14	0.73	0.90	1.03	0.29	1.14	14.3	14.1
11/04/92	246	0.49	0.53	1.63	15.0	15.3	0.25	0.13	0.12	0.47	0.85	0.24	0.40	1.51	14.5	14.4
13/04/92	248	1.56	0.45	1.27	14.2	16.6	0.58	0.15	0.11	0.50	1.04	0.99	0.31	1.16	13.7	15.5
14/04/92	249	0.60	0.40	1.21	13.5	14.8	0.30	0.12	0.10	1.67	0.94	0.30	0.28	1.11	11.8	13.8
15/04/92	250	0.61	0.42	1.24	12.7	15.8	0.36	0.14	0.11	2.61	1.76	0.25	0.27	1.13	10.1	14.0
16/04/92	251	1.60	0.49	1.30	13.5	16.3	0.15	0.18	0.13	1.95	1.79	1.45	0.31	1.17	11.5	14.5
17/04/92	252	1.46	0.27	0.16	12.5	12.5	0.41	0.17	0.08	1.06	1.03	1.04	0.10	0.08	11.4	11.5
18/04/92	253	1.27	0.36	0.16	11.0	11.0	0.27	0.10	0.13	0.86	0.60	1.00	0.26	0.04	10.1	10.4
20/04/92	255	1.10	0.27	0.14	13.0	13.3	0.21	0.13	0.09	0.60	0.80	0.89	0.14	0.05	12.4	12.5
21/04/92	256	1.46	0.29	0.15	13.5	13.5	0.52	0.18	0.13	0.75	1.23	0.94	0.12	0.02	12.7	12.3
23/04/92	258	0.27	0.39	0.32	8.6	10.1	0.23	0.23	0.23	0.65	0.69	0.04	0.16	0.09	8.0	9.4
24/04/92	259	1.19	0.33	0.22	10.9	13.8	0.18	0.26	0.18	0.94	1.42	1.01	0.08	0.03	10.0	12.4
25/04/92	260	2.05	0.37	0.27	10.9	10.1	0.17	0.16	0.20	1.07	1.00	1.88	0.21	0.07	9.8	9.1
27/04/92	262	2.18	0.43	0.23	10.1	14.1	0.24	0.20	0.17	0.94	1.02	1.95	0.22	0.05	9.2	13.1
28/04/92	263	1.64	0.40	0.18	9.1	12.0	0.31	0.20	0.15	0.94	0.72	1.33	0.20	0.02	8.1	11.2
29/04/92	264	1.66	0.35	0.20	8.8	13.0	0.45	0.20	0.19	1.50	0.89	1.21	0.15	0.02	7.3	12.1
30/04/92	265	0.33	0.22	0.29	13.0	13.8	0.18	0.14	0.17	1.96	2.60	0.16	0.08	0.12	11.1	11.2

NO_3 dose stopped

		NITRATE & NITRITE					NITRITES					NITRATES				
DATE	DAY	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
1/5/92	266	0.33	0.22	0.18	8.8	11.7	0.14	0.13	0.15	1.85	1.77	0.20	0.09	0.03	6.9	9.9
2/05/92	267	0.36	0.19	0.20	8.8	10.9	0.16	0.15	0.17	1.94	1.42	0.20	0.04	0.03	6.9	9.5
4/05/92	269	0.29	0.27	0.19	7.5	10.1	0.21	0.14	0.13	3.15	1.44	0.09	0.13	0.06	4.3	8.7
5/05/92	270	1.50	0.31	0.21	15.6	20.9	0.10	0.10	0.13	1.90	1.90	1.41	0.21	0.08	13.7	19.0
6/05/92	271	0.54	0.97	0.25	16.4	16.1	0.26	0.27	0.10	1.60	1.44	0.28	0.70	0.15	14.8	14.7
7/05/92	272	0.29	0.20	0.15	10.5	16.9	0.12	0.09	0.09	0.71	1.94	0.16	0.11	0.06	9.8	14.9
8/05/92	273	0.30	0.50	1.10	8.5	11.6	0.09	0.12	0.17	0.51	0.37	0.21	0.39	0.93	8.0	11.2
9/05/92	274	1.56	0.57	0.24	7.5	10.8	0.32	0.12	0.11	0.21	0.23	1.25	0.45	0.12	7.3	10.6
11/05/92	276															
14/05/92	279	1.27	0.48	0.28	7.5	7.2	0.13	0.05	0.08	0.17	0.21	1.15	0.43	0.20	7.3	7.0
15/05/92	280	0.22	0.27	0.91	6.9	6.7	0.05	0.04	0.08	0.35	0.29	0.17	0.23	0.83	6.6	6.4
16/05/92	281	1.59	0.41	0.35	7.2	7.2	0.41	0.09	0.05	0.15	0.17	1.17	0.33	0.29	7.1	7.0
18/05/92	283	0.93	0.35	0.31	7.7	7.7	0.09	0.06	0.06	0.17	0.21	0.84	0.29	0.25	7.5	7.5
19/05/92	284	0.19	0.27	0.99	7.5	7.5	0.06	0.06	0.12	0.67	0.59	0.13	0.21	0.86	6.8	6.9
20/05/92	285	0.22	0.35	1.10	8.5	6.9	0.07	0.08	0.14	0.59	0.49	0.14	0.27	0.97	7.9	6.4
21/05/92	286	0.22	0.32	1.17	9.3	8.5	0.06	0.06	0.11	0.51	0.51	0.15	0.26	1.06	8.8	8.0
22/05/92	287	0.34	0.31	1.26	9.0	9.3	0.12	0.09	0.18	1.17	0.97	0.21	0.22	1.08	7.8	8.3
25/05/92	290	0.18	0.32	1.03	7.6	8.4	0.10	0.16	0.21	0.82	0.54	0.08	0.16	0.81	6.8	7.9
26/05/92	291	1.32	0.58	0.20	7.3	8.7	0.31	0.12	0.08	0.41	0.68	1.01	0.46	0.11	6.9	8.0
27/05/92	292															
01/06/92	297	0.98	0.43	0.84	9.5	10.6	0.09	0.07	0.36	0.61	0.75	0.89	0.37	0.48	8.9	9.8
02/06/92	298	0.21	0.39	2.07	16.1	11.7	0.13	0.19	0.32	2.85	2.63	0.09	0.20	1.75	13.2	9.1
03/06/92	299	0.21	0.38	1.97	15.8	11.7	0.18	0.15	0.39	2.51	1.71	0.03	0.23	1.58	13.3	10.0
04/06/92	300	0.50	0.42	0.36	12.4	16.9	0.11	0.09	0.10	1.45	0.92	0.39	0.34	0.26	11.0	16.0
05/06/92	301	0.19	1.73	2.40	14.5	14.8	0.10	0.50				0.09	1.23	2.40	14.5	14.8
06/06/92	302	0.33	0.29	0.52	8.2	12.7	0.15	0.21	0.36	1.82	2.40	0.18	0.08	0.16	6.4	10.3
10/06/92	306	0.83	0.56	0.63	4.8	8.0	0.43	0.40	0.51	2.49	2.51	0.40	0.16	0.13	2.3	5.4
11/06/92	307	0.22	0.39	1.23	13.7	14.0	0.08	0.08	0.69	1.26	2.06	0.14	0.31	0.54	12.4	11.9
12/06/92	308	2.00	0.88	0.39	8.2	10.7	0.28	0.10	0.23	0.51	0.47	1.72	0.78	0.16	7.7	10.2
13/06/92	309	0.18	0.39	1.61	18.7	15.3	0.09	0.12	0.90	3.59	1.50	0.09	0.26	0.71	15.1	13.8
15/06/92	311	0.60	0.44	0.79	11.6	14.3	0.23	0.10	0.47	0.75	0.79	0.37	0.34	0.32	10.9	13.5
16/06/92	312	0.30	0.45	1.69	10.2	11.7	0.12	0.15	0.74	2.42	1.42	0.18	0.30	0.95	7.8	10.3
17/06/92	313	0.22	0.36	1.17	11.2	13.3	0.08	0.09	0.78	1.74	3.99	0.14	0.27	0.39	9.5	9.4
19/06/92	315	1.68	1.53	0.38	9.4	10.9	0.31	0.33	0.15	1.24	2.46	1.36	1.20	0.23	8.2	8.5
22/06/92	318	1.74	0.44	0.28	9.4	11.5	0.40	0.20	0.16	2.42	3.41	1.34	0.24	0.12	7.0	8.1
23/06/92	319	1.72	0.58	0.31	8.2	11.5	0.35	0.17	0.14	2.01	3.68	1.38	0.41	0.17	6.2	7.8
24/06/92	320						0.11	0.12	0.39	2.91	4.81					
26/06/92	322	0.45	0.27	0.80	14.3	18.2	0.28	0.08	0.19	1.06	3.18	0.17	0.19	0.61	13.2	15.0
29/06/92	325	0.31	0.34	1.02	20.8	20.8	0.04	0.06	0.21	2.04	2.04	0.26	0.28	0.81	18.7	18.7
01/07/92	327	2.17	0.45	1.31	19.5	19.5	0.09	0.07	0.09	0.96	0.96	2.08	0.38	1.21	18.5	18.5
03/07/92	328	2.26	0.75	1.35	21.4	21.4	0.36	0.13	0.11	2.10	2.00	1.90	0.62	1.24	19.3	19.4
06/07/92	331	2.98	0.26	1.14	20.8	20.8	0.47	0.14	0.86	2.20	2.20	2.51	0.13	0.28	18.6	18.6
07/07/92	332	0.92	0.94	1.44	19.5	19.5	0.47	0.50	0.24	0.76	0.76	0.46	0.44	1.20	18.7	18.7
09/07/92	334	0.85	1.05	2.60	28.5	28.5	0.57	0.82	0.39	3.65	3.65	0.28	0.23	2.21	24.9	24.9
13/07/92	338	1.00	1.54	0.60	19.2	19.2	0.45	1.20	0.39	0.51	0.56	0.55	0.33	0.20	18.6	18.6
14/07/92	339	2.27	0.83	0.63	11.7	15.7	0.25	0.15	0.13	0.54	0.46	2.02	0.68	0.50	11.1	15.3
15/07/92	340	1.69	0.44	0.46	12.9	17.3	0.30	0.15	0.15	0.98	0.56	1.39	0.29	0.31	11.9	16.7

Experimental data measured for the MUCT2 system.
COD, TKN, solids & phosphorus concentrations,
OUR and DSVI.

												PHOSPHORUS						
Month/ Date	DAY	Infl. COD mg/l	Effl. COD mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Settl ml/l	Settl Vol. ml	DSVI ml/g	OUR mgO/ l/h	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem mgP/l
27/01/92	171	942	73.7	89.3	5.04	4392	3604	173	300	131	62.6	22.7	37.3	32.5	15.2	8.7	7.5	15.2
28/01/92	172	1016	67.6	89.5	4.62	4315	3528	160	300	124		23.7	44.1	37.9	17.1	11.9	8.9	14.8
29/01/92	173	1008	65.5	91.3	4.62	4468	3682	175	300	131		24.4	52.4	41.5	19.1	13.2	9.9	14.5
30/01/92	174	995	59.4	98.6	5.6	4486	3702	165	300	123	62.6	19.9	50.0	44.3	18.0	7.0	7.0	12.9
31/01/92	175	992	53.2	81.8	2.87	4322	3556	168	300	130	72.3	21.5	48.0	42.0	19.2	9.3	9.3	12.3
01/02/92	176	989	41.2	90.2	10.7	4337	3553	165	300	127		16.6	42.2	47.3	17.9	7.7	10.9	5.8
03/02/92	178	861	26.8	66.9	4.62	4009	3261	155	300	129		19.5	39.3	36.5	17.9	10.9	8.3	11.2
05/02/92	180	935	53.6	73.9	4.76	3837	3156	145	300	126		19.6	39.3	36.0	18.7	12.4	10.8	8.8
06/02/92	181	915	78.3	66.6	4.5	3813	3092	140	300	122		20.0	37.6	31.1	15.1	10.8	11.8	8.2
07/02/92	182	861	67.8	72.8	6.79	3975	3235	150	300	126	41.9	20.6	43.9	36.7	15.7	10.8	8.2	12.4
08/02/92	183	816	45.3	75.9	4.76	3852	3145	140	300	121		23.4	36.3	34.0	18.0	10.1	8.5	14.9
10/02/92	185	824	41.2	64.1	5.88	3780	3108	120	300	106		21.3	27.4	31.6	31.6	8.9	8.9	12.4
11/02/92	186	836	51.5	82.6	12	3640	3049	150	350	118	74.1	18.1	35.7	33.6	26.6	11.7	11.7	6.4
12/02/92	187	826	52.5	78.4	10	3746	3089	150	350	114		18.7	26.6	33.6	14.9	8.5	8.8	9.9
13/02/92	188	853	55.6	81.2	6.02	3867	3180	152	350	112	47.3	17.0	35.2	33.5	16.5	9.5	8.1	8.9
14/02/92	190	913	67.6	68.3	4.41	3942	3256	160	350	116		15.9	34.3	28.8	11.7	6.4	6.4	9.5
15/02/92	191	909	47.1	82.9	3.05	3794	3090	150	350	113	48.7	20.3	32.8	30.5	15.5	9.9	6.0	14.3
17/02/92	193	885	59.4	73.4	4.76	3654	3060	155	350	121	42.9	19.4	32.8	31.4	14.6	7.5	6.6	12.8
18/02/92	194	881	63.5	76.2	4.9	3842	3180	150	350	112		17.6	36.1	32.9	14.4	7.9	6.8	10.9
19/02/92	195	848	49.2	72.5	4.62	3744	3098	150	350	114	53.9	17.3	33.4	34.0	17.0	10.0	9.7	7.6
20/02/92	196	828	66.6	63.3	6.16	3784	3170	151	350	114		17.4	34.5	30.7	12.7	8.3	11.2	6.2
21/02/92	197	811	47.1	64.5	6.09	3926	3300	160	350	116		16.5	24.5	30.1	8.8	6.2	6.5	10.0
24/02/92	200											18.9	22.7	24.2	11.5	5.9	6.2	12.7
25/02/92	201	800	61.4	72.0	4.76	3498	2894	160	350	131	49.3	18.6	35.7	39.9	20.7	10.3	8.9	9.8
26/02/92	202	863	77.4	53.2	6.65	3386	2808	150	350	127		18.9	32.2	40.5	23.0	10.0	8.6	10.3
27/02/92	203	745	63.1	64.4	5.39	3530	2928	150	350	121		17.6	36.9	33.0	21.4	8.6	7.7	9.8
28/02/92	204	806	57	77.8	4.2	3470	2506	169	400	122		17.0	35.4	34.8	13.4	7.7	6.6	10.4
29/02/92	205	839	63.1	68.6	5.11	3452	2822	170	400	123	47.8	18.2	54.6	38.8	14.0	4.6	4.9	13.3
02/03/92	207	794	69.2	57.1	5.81	3594	2964	170	400	118		17.9	31.5	25.0	10.6	4.6	4.2	13.6
03/03/92	208											18.6	38.9	36.3	17.4	9.4	6.2	12.4
04/03/92	209	843	69.2	61.0	6.16	3426	2828	155	400	113		17.8	32.5	27.1	15.1	10.5	10.2	7.5
05/03/92	210	827	61.1	72.5	6.09	3428	2806	155	400	113	49.6	16.6	28.9	25.6	11.4	7.5	9.0	7.5
06/03/92	211	916	65.2	59.6	4.69	3524	2942	155	400	110		16.5	33.0	28.5	14.3	6.7	6.3	10.1
07/03/92	212	916	79.4	67.8	4.9	3344	2766	155	400	116		18.1	28.2	25.7	10.8	8.9	3.8	14.3
09/03/92	214	863	40.7	65.5	3.36	3330	2718	160	400	120	55.8	17.7	36.6	29.5	13.0	5.3	5.3	12.4
10/03/92	215	880	65.2	74.2	3.15	4110	3352	180	400	109	60.9	16.8	29.5	26.7	15.5	7.1	5.9	10.9
11/03/92	216	749	61.1	62.4	4.9	3758	3056	182	400	121		14.0	26.8	19.6	7.0	2.8	4.1	9.8
13/03/92	218	906	80.2	63.6	2.73	3860	3150	175	400	113		12.9	20.1	22.7	5.9	4.4	2.4	10.5
14/03/92	219	770	120	71.1	3.78	3852	3220	115	300	100		19.1	34.4	30.0	11.6	4.4	2.0	17.0
16/03/92	221	1018	48.1	79.0	5.74	3838	3154	168	400	109		19.7	39.1	36.1	15.0	5.8	2.4	17.4
17/03/92	222	862	92.2	64.4	3.92	3894	3174	170	400	109		19.9	38.9	35.5	16.5	7.7	4.0	15.9
18/03/92	223	1034	112	87.9	5.6	4072	3340	165	400	101		19.0	34.5	34.5	14.7	4.9	3.6	15.4
20/03/92	225	914	52.1	95.2	5.6	3210	2684	139	400	108	32.7	18.7	39.2	33.1	10.7	4.9	2.1	16.5
21/03/92	226	988	57.1	95.2	5.46	3324	2772	100	300	100		19.3	40.1	30.3	12.9	4.0	4.3	15.0
23/03/92	228	900	53.1	95.2	5.32	3196	2632	131	400	102		18.4	42.0	33.1	14.7	3.7	3.1	15.3
24/03/92	229	878	50.1	85.1	5.04	3280	2710	136	400	104	54.8	18.6	40.3	30.7	15.8	5.9	1.9	16.8
25/03/92	230	964	96.8	90.2	5.53	3434	2828	141	400	103	34.7	23.3	41.0	32.3	14.0	5.0	3.1	20.2
26/03/92	231	980	56.4	77.8	5.67	3756	3168	110	300	98		18.1	41.1	35.7	17.5	6.0	4.2	13.9
27/03/92	232	980	66.5	78.4	5.6	3496	3234	141	400	101	63.5	18.4	39.6	35.7	18.4	9.1	4.8	13.6
28/03/92	233	1032	68.5	105	4.48	4078	3146	140	400	86		21.5	44.1	43.1	19.5	9.1	5.4	16.2
29/03/92	234	1008	60.5	96.9	5.6	4112	3476	150	400	91		21.5	37.7	40.4	24.2	9.8	6.7	14.8
30/03/92	235	851	72.6	88.5	6.09	4004	3338	150	400	94		21.5	42.4	36.0	18.2	10.4	7.7	13.8

												PHOSPHORUS						
Month/ Date	DAY	Infl. COD mg/l	Effl. COD mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Settl ml/l	Settl Vol. ml	DSVI ml/g	OUR mgO/l	Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem mgP/l
01/04/92	237	948	107	92.4	11.2	3568	3048	120	400	84	72.9	20.8	36.2	39.1	24.6	14.8	13.2	7.6
02/04/92	238	911	72.6	93.5	6.86	3608	2770	130	400	90	59.2	22.1	39.1	35.6	19.5	10.1	11.3	10.7
03/04/92	239	1056	72.6	89.3	5.18	3970	3025	145	400	91		21.4	35.9	30.9	20.5	11.7	10.1	11.3
06/04/92	242	984	74.6	82.0	4.97	3672	3064	141	400	96		20.3	35.7	30.2	20.0	12.0	9.9	10.5
07/04/92	243	1000	84.7	87.4	3.92	3922	3306	148	400	94		21.9	32.0	27.1	17.9	9.9	11.1	10.8
08/04/92	244	1008	83.7	78.4	11.3	3954	3332	130	400	82	55.9	19.6	32.5	35.0	21.2	10.7	13.5	6.1
09/04/92	245	901	47.3	82.6	5.53	3094	2946	129	400	104		19.3	31.0	31.9	17.8	9.5	8.0	11.4
10/04/92	246	954	90.5	94.9	5.74	3176	2394	130	400	102	64.3	18.7	29.8	26.4	15.4	8.0	6.1	12.6
11/04/92	247	880	57.6	96.9	6.58	3532	3006	145	400	103		19.0	29.2	27.6	16.3	8.9	7.1	12.0
13/04/92	249	1028	65.8	91.3	6.86	3852	3252	140	400	91	68.8	19.6	29.2	27.0	17.2	10.1	8.6	11.0
14/04/92	250	958	57.6	88.8	7.77	3912	3084	135	400	86		21.3	33.4	30.5	19.7	12.5	9.5	11.8
15/04/92	251	962	61.7	93.2	6.51	3942	3160	130	400	82		20.6	35.4	31.8	18.3	10.8	9.8	10.8
16/04/92	252	1123	78.1	98.6	6.37	3834	3186	131	400	85		21.0	34.1	36.8	22.7	9.5	10.2	10.8
17/04/92	253	810	105	83.7	4.69	3898	3282	138	400	89		18.1	28.9	26.3	13.8	10.5	11.5	6.6
18/04/92	254	913	69.9	77.3	3.92	3664	2996	135	400	92		17.4	30.2	25.9	17.4	10.2	11.2	6.2
20/04/92	256	880	82.2	82.9	6.16	3688	3078	139	400	94		18.4	32.8	24.3	15.1	9.5	9.9	8.5
21/04/92	257	855	65.8	71.1	5.81	3610	3048	140	400	97		17.7	30.9	25.6	15.1	9.9	9.2	8.5
22/04/92	258																	
27/04/92	263	1016	77.2	90.7	4.69	3302	2784	135	400	102	61.2	21.3	34.1	26.6	13.8	9.2	8.5	12.8
28/04/92	264	959	83.3	79.8	4.62	3442	2808	131	400	95		22.7	34.1	30.9	17.1	11.5	9.2	13.5
29/04/92	265	992	93.5	94.6	5.11	3448	2916	130	400	94	53.4	20.7	35.1	29.2	15.4	10.5	10.5	10.2
30/04/92	266	939	61	97.4	6.79	3544	2900	130	400	92		18.7	36.4	31.4	13.7	9.7	9.3	9.3
01/05/92	267	1016	97.5	94.4	6.23	3368	2806	130	400	96		20.6	35.0	33.2	14.1	5.1	8.6	12.0
02/05/92	268	967	89.4	100	4.2	3030	2514	131	400	108		21.9	36.3	30.8	13.7	8.9	8.6	13.4
04/05/92	269	951	61	84.6	4.2	3634	3052	140	400	96		21.9	28.1	29.5	15.4	9.3	8.9	13.0
05/05/92	270	898	56.9	85.4	4.48	3858	3246	130	400	84	77.7	20.2	32.6	29.5	13.0	10.6	7.9	12.3
06/05/92	271	878	44.7	104	4.62	3812	3198	148	400	97		18.3	32.2	27.5	11.1	7.9	6.0	12.3
07/05/92	272	894	63	76.7	5.95	3908	3302	145	400	93	61.9	18.0	26.5	25.9	10.7	11.7	7.0	11.1
08/05/92	273	898	63	67.2	4.69	4070	3420	151	400	93		18.0	32.5	29.1	13.6	8.8	8.8	9.2
09/05/92	274	862	69.1	67.8	4.9	4116	3470	151	400	92		18.8	32.8	31.2	13.1	9.9	9.9	8.9
11/05/92	276	894	73.2	71.7	3.5	3916	3362	150	400	96		18.5	33.4	29.6	17.2	11.1	10.2	8.3
12/05/92	277	862	48.8	63.3	5.81	3906	3316	145	400	93		20.7	30.6	31.3	18.6	12.3	10.9	9.8
13/05/92	278	918	93.5	59.9	5.18	4190	3504	146	400	87	41.9	20.7	38.7	38.3	21.1	10.9	6.7	14.1
14/05/92	279	935	44.7	67.8	4.69	3758	3152	150	400	100		21.1	40.8	33.0	21.4	9.8	7.0	14.1
15/05/92	280	870	48.8	65.5	4.48	3816	3104	145	400	95	40.3	19.1	35.9	31.4	15.9	8.7	8.7	10.4
16/05/92	281	959	77.2	65.5	4.34	4210	3536	149	400	88		18.8	30.4	29.5	14.9	7.1	6.8	12.0
18/05/92	283	959	73.2	68.9	6.02	3380	2824	140	400	104		19.7	30.1	27.5	14.9	10.0	6.5	13.3
19/05/92	284	927	44.7	79.2	5.81	3732	3072	140	400	94	75.9	20.1	35.4	29.9	15.0	10.5	13.7	6.4
20/05/92	285	925	49.3	59.9	6.51	3534	2926	139	400	98		23.6	30.6	22.0	15.3	9.2	10.2	13.4
21/05/92	286	896	53.5	65.5	4.34	3370		125	400	93		19.7	32.3	27.5	16.5	10.7	9.7	10.0
22/05/92	287	958	80.2	63.6	9.45	3584	3096	125	400	87		21.3	32.3	24.6	12.6	8.1	12.3	9.1
25/05/92	290	991	36	68.6	4.13	3194	2708	115	400	90	38.5	22.5	35.9	26.4	14.4	8.8	10.2	12.3
26/05/92	291	983	77.8	59.4	5.25	3222	2718	115	400	89		25.0	38.7	32.0	18.7	10.2	8.4	16.6
27/05/92	292	1016	69.6	75.0	3.29	3146	2650	119	400	95		16.8	32.5	28.6	10.6	7.7	5.9	10.9
28/05/92	293	934	69.6	94.6	5.53	2906	2384	120	400	103		15.9	29.8	23.6	12.4	9.2	7.1	8.9
29/05/92	294	901	109	92.1	9.45	3040	2526	113	400	93	30	15.1	28.9	21.3	13.0	11.5	8.9	6.2

Month/ Date	DAY	Infl. COD mg/l	Effl. COD mg/l	Infl. TKN mg/l	Effl. TKN mg/l	TSS mg/l	VSS mg/l	Settl ml/l	Settl Vol. ml	DSVI ml/g	OUR mgO/l	PHOSPHORUS						
												Infl. mgP/l	Anae. mgP/l	Anox. 1 mgP/l	Anox. 2 mgP/l	Aer. mgP/l	Effl. mgP/l	Prem mgP/l
01/06/92	297	853	71.4	99.7	6.51	3212	2682	130	400	101	70.2	18.3	30.1	20.4	9.2	8.0	7.1	11.2
02/06/92	298	934	104	85.1	5.46	3312	2802	135	400	102		19.0	31.1	23.7	11.0	9.5	7.8	11.2
03/06/92	299	877	61.2	105	5.95	3338	2924	146	400	109		19.3	24.5	24.5	11.3	9.5	8.9	10.4
05/06/92	301	1053	65.3	72.5	5.32	3320	2810	155	400	117		24.2	34.7	28.1	12.8	10.3	8.9	15.3
06/06/92	302	1012	135	96.3	5.32	3390	2898	148	400	109		23.3	42.5	28.6	15.3	12.8	10.8	12.5
10/06/92	306	1012	53	85.1	3.5	3616	2964	150	400	104	36.2	22.5	40.3	38.3	16.7	12.5	11.7	10.8
11/06/92	307	1044	81.6	77.6	4.15	3870	3512	180	400	116		20.3	31.3	23.7	12.7	8.6	10.5	9.8
12/06/92	308	1073	60.5	58.2	5.6	3514	2908	163	400	116	37.4	23.0	31.5	22.7	14.4	12.7	8.6	14.4
13/06/92	309	1057	67.3	86.2	4.76	3594	2984	169	400	118		14.9	31.7	28.6	11.7	8.1	7.6	7.3
15/06/92	311	959	59.2	89.0	2.38	3562	3158	171	400	120	47.7	19.3	33.0	25.4	12.5	10.5	10.8	8.6
16/06/92	312	1473	83.6	118	6.3	3736	3086	180	400	120		19.8	31.5	27.6	15.4	9.5	9.8	10.0
17/06/92	313	992	64	87.1	4.9	3676		175	400	119		18.6	24.5	19.8	8.8	10.3	6.1	12.5
20/06/92	316					2678	2280	180	500	134								
21/06/92	317					2912	2386	151	400	130								
22/06/92	318	1116	104	106	7.7	3032	2476	151	400	125		20.1	27.1	22.0	11.7	10.8	9.3	10.8
23/06/92	319	1004	106	93.5	4.9	3114	2670	155	400	124	84.3	18.9	36.0	29.5	26.0	13.1	9.8	9.1
24/06/92	320	888	54	93.0	5.32	3338	2900	172	400	129		17.4	27.8	23.0	9.6	8.6	8.1	9.3
25/06/92	321	1004	76	102	6.72	3726	3108	195	400	131		18.9	30.5	23.5	9.1	8.1	8.8	10.1
26/06/92	322	1052	72	105	4.34	3458	2992	182	400	132		18.0	31.4	22.5	10.5	8.9	8.4	9.7
27/06/92	323					3438	2846	190	400	138								
28/06/92	324					3604	2878	155	300	143								
29/06/92	325	1020	80	102	4.62	3688	3106	160	300	145	68.9	18.0	31.9	22.5	11.5	9.9	10.5	7.6
30/06/92	326					3294	2862	145	300	147								
01/07/92	327	940	64	111	4.2	3054	2660	128	300	140		18.0	30.3	27.7	11.8	7.3	5.8	12.3
02/07/92	328	888	84	115	6.58	3622	3094	155	300	143	66							
03/07/92	329	964	80	124	5.18	3452	3018	150	300	145		18.1	26.5	20.4	10.5	9.3	7.4	10.8
04/07/92	330					3656	3084	155	300	141								
05/07/92	331					3578	2930	155	300	144								
06/07/92	332	996	126	118	8.12	3496	2646	151	300	144	45.2	17.4	23.0	19.9	12.3	10.3	10.1	7.3
07/07/92	333	985	73.4	116	2.1	3434	2850	150	300	146		17.5	23.8	15.7		10.1	9.4	8.1
08/07/92	334					3472	2942	155	300	149								
09/07/92	335	1054	104	129	10.1	3178	2676	145	300	152	52.3	20.0	27.1	22.3	9.4	8.6	10.4	9.6
10/07/92	336					3458	2906	155	300	149								
11/07/92	337	1106	106	85.4	4.62	3420	2848	155	300	151		25.6	27.2	13.5	11.6	11.3	8.1	17.5
12/07/92	338					3870	3190	189	300	163								
13/02/92	339					3610	3028	175	300	162								
14/07/92	340	1110	106	96.6	4	3458	2890	180	300	174	45	21.8	28.8	17.0	9.4	5.7	9.7	12.1

Experimental data measured for the MUCT2 system.
Nitrate and nitrite concentrations.

		NITRATES AND NITRITES					NITRITES					NITRATES				
Month/ Date	Day	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
27/01/92	171	1.70	0.31	0.41	6.9	10.6	0.26	0.27	0.24	1.58	1.44	1.44	0.04	0.17	5.4	9.2
28/01/92	172	1.01	0.32	0.25	7.7	11.4	0.31	0.25	0.25	1.65	1.35	0.70	0.07	0.00	6.0	10.0
29/01/92	173	0.77	0.51	0.87	8.4	8.7	0.41	0.28	0.26	1.82	1.68	0.36	0.23	0.61	6.6	7.0
30/01/92	174	0.38	0.52	1.05	9.9	10.0	0.27	0.39	0.48	0.82	0.46	0.11	0.13	0.57	9.0	9.6
31/01/92	175	0.26	0.24	0.20	6.5	8.3	0.09	0.10	0.10	1.03	0.78	0.17	0.14	0.10	5.5	7.5
01/02/92	176	0.75	0.42	0.18	8.7	5.5	0.11	0.33	0.09	0.59	0.92	0.64	0.09	0.09	8.1	4.6
03/02/92	178	0.72	0.31	0.22	6.0	6.8	0.08	0.08	0.08	0.69	0.34	0.64	0.23	0.14	5.3	6.4
05/02/92	180	0.31	0.43	0.91	8.0	5.7	0.16	0.10	0.10	0.47	0.51	0.15	0.32	0.82	7.6	5.2
06/02/92	181	0.81	0.20	0.18	5.7	6.2	0.10	0.09	0.09	0.40	0.40	0.71	0.11	0.08	5.3	5.8
07/02/92	182	0.61	0.29	0.18	4.9	4.9	0.12	0.10	0.10	0.82	0.82	0.49	0.19	0.08	4.1	4.0
08/02/92	183	1.40	0.35	0.20	4.9	5.2	0.10	0.12	0.12	0.69	0.75	1.29	0.23	0.08	4.2	4.5
10/02/92	185	0.26	0.23	0.35	4.9	6.6	0.26	0.16	0.13	0.55	0.55	0.00	0.07	0.22	4.3	6.0
11/02/92	186	0.50	0.36	0.21	2.7	2.9	0.15	0.13	0.06	0.38	0.38	0.35	0.24	0.14	2.3	2.6
12/02/92	187	2.20	0.47	0.23	7.4	12.2	0.16	0.10	0.15	1.18	0.73	2.04	0.37	0.08	6.2	11.5
13/02/92	188	0.16	0.14	0.35	5.5	6.7	0.09	0.10	0.11	0.09	0.13	0.07	0.04	0.24	5.4	6.6
14/02/92	190	0.11	0.11	0.29	5.9	5.9	0.09	0.08	0.07	0.08	0.12	0.02	0.03	0.22	5.8	5.8
15/02/92	191	0.46	0.28	0.14	6.3	6.2	0.12	0.11	0.10	0.12	0.11	0.34	0.17	0.04	6.1	6.1
17/02/92	193	0.55	0.25	0.11	5.4	5.4	0.54	0.09	0.09	0.27	0.12	0.01	0.16	0.01	5.1	5.3
18/02/92	194	0.14	0.10	0.13	4.6	4.5	0.10	0.08	0.08	0.25	0.34	0.04	0.02	0.06	4.3	4.2
19/02/92	195	0.69	0.16	0.19	3.1	4.3	0.10	0.09	0.10	0.36	0.14	0.59	0.06	0.09	2.8	4.2
20/02/92	196	0.50	0.85	0.23	8.7	8.7	0.13	0.12	0.12	0.12	0.11	0.37	0.73	0.11	8.6	8.6
21/02/92	197	0.16	0.16	0.37	4.5	5.8	0.15	0.13	0.06	0.05	0.05	0.01	0.04	0.31	4.4	5.8
24/02/92	200	0.55	0.20	0.48	6.6	7.4	0.46	0.16	0.13	0.11	0.11	0.09	0.04	0.35	6.5	7.3
25/02/92	201	0.93	0.50	0.31	8.7	9.5	0.10	0.12	0.12	0.14	0.15	0.83	0.39	0.19	8.6	9.4
26/02/92	202	1.26	0.27	0.14	4.8	5.4	0.12	0.10	0.10	0.16	0.17	1.14	0.16	0.04	4.6	5.2
27/02/92	203	1.46	0.20	0.11	4.3	5.8	0.16	0.11	0.10	0.10	0.08	1.29	0.09	0.01	4.2	5.8
28/02/92	204	0.22	0.16	0.51	6.4	8.2	0.16	0.15	0.14	0.18	0.19	0.06	0.01	0.37	6.2	8.0
29/02/92	205	0.15	0.25	0.34	4.4	6.4	0.14	0.15	0.14	0.26	0.13	0.00	0.10	0.20	4.1	6.3
02/03/92	207	2.56	0.28	0.27	3.2	5.8	0.20	0.18	0.14	0.23	0.17	2.37	0.09	0.14	3.0	5.7
03/03/92	208	0.28	0.29	0.35	4.7	6.7	0.19	0.16	0.18	0.46	0.38	0.08	0.13	0.17	4.2	6.3
04/03/92	209	0.23	0.22	0.42	3.5	5.5	0.16	0.17	0.17	0.36	0.28	0.07	0.05	0.26	3.1	5.3
05/03/92	210	2.88	0.39	0.44	5.5	5.5	0.23	0.17	0.15	0.32	0.38	2.66	0.23	0.29	5.2	5.2
06/03/92	211	0.72	0.19	0.12	4.1	3.8	0.11	0.13	0.11	0.20	0.22	0.61	0.06	0.01	3.9	3.6
07/03/92	212	0.13	0.10	0.42	4.1	4.9	0.10	0.09	0.14	0.07	0.10	0.04	0.01	0.28	4.0	4.8
09/03/92	214	0.10	0.13	0.32	3.2	4.1	0.09	0.12	0.15	0.23	0.06	0.01	0.01	0.17	3.0	4.0
10/03/92	215	0.16	0.25	0.18	2.1	3.2	0.12	0.10	0.09	0.24	0.29	0.04	0.15	0.09	1.8	2.9
11/03/92	216	0.26	0.22	0.19	4.4	4.5	0.09	0.07	0.08	0.08	0.68	0.17	0.15	0.12	4.3	3.8
13/03/92	218	0.42	0.22	0.23	7.0	10.0	0.09	0.07	0.06	0.11	0.16	0.34	0.15	0.17	6.9	9.8
14/03/92	219	0.35	0.23	0.31	6.4	8.9	0.08	0.07	0.06	0.13	0.26	0.28	0.16	0.25	6.3	8.6
16/03/92	221	0.40	0.37	0.46	7.8	12.5	0.18	0.16	0.16	0.43	0.28	0.21	0.21	0.30	7.4	12.2
17/03/92	222	1.37	0.44	0.37	7.1	7.9	0.24	0.13	0.13	0.20	0.22	1.13	0.30	0.24	6.9	7.7
18/03/92	223	0.37	0.35	0.25	6.1	5.2	0.09	0.15	0.13	0.53	0.28	0.28	0.20	0.12	5.6	5.0
20/03/92	225	0.31	0.38	0.69	8.6	6.9	0.16	0.24	0.19	0.89	0.87	0.15	0.15	0.51	7.7	6.1
21/03/92	226	0.68	0.78	0.38	7.1	8.2	0.09	0.09	0.19	1.24	1.08	0.59	0.69	0.19	5.8	7.1
23/03/92	228	1.85	0.62	0.57	6.9	6.9	0.27	0.13	0.10	0.50	0.60	1.58	0.48	0.47	6.4	6.3
24/03/92	229	0.37	0.43	1.18	6.9	7.1	0.35	0.17	0.18	0.67	0.58	0.02	0.26	0.99	6.3	6.5
25/03/92	230	0.31	0.28	0.32	6.9	7.2	0.13	0.11	0.13	0.65	0.79	0.18	0.17	0.20	6.3	6.4
26/03/92	231	1.60	0.55	0.38	6.1	6.2	0.12	0.10	0.13	0.83	0.83	1.48	0.46	0.26	5.2	5.3
27/03/92	232	2.02	0.61	0.37	9.4	11.0	0.61	0.18	0.13	0.73	0.87	1.41	0.43	0.24	8.6	10.1
28/03/92	233	0.33	0.37	0.85	9.6	9.4	0.16	0.13	0.19	1.04	0.93	0.17	0.25	0.66	8.6	8.4
29/03/92	234	0.50	0.37	0.21	8.8	8.8	0.14	0.11	0.11	1.02	1.10	0.36	0.26	0.10	7.8	7.7
30/03/92	235	0.25	0.24	0.24	7.2	8.0	0.14	0.13	0.11	0.69	1.09	0.11	0.11	0.12	6.5	6.9

Month/ Date	DAY	NITRATES AND NITRITES					NITRITES					NITRATES				
		Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
01/04/92	237	0.18	0.53	1.51	9.7	9.3	0.14	0.26	0.50	1.84	1.33	0.04	0.27	1.01	7.9	7.9
02/04/92	238	0.24	0.39	0.99	13.7	15.3	0.22	0.20	0.28	1.09	1.03	0.02	0.18	0.71	12.6	14.3
03/04/92	239	1.42	0.84	0.28	11.4	12.4	0.49	0.37	0.20	1.00	0.87	0.93	0.48	0.08	10.4	11.5
06/04/92	242	0.80	0.15	0.11	8.2	8.5	0.47	0.13	0.11	0.71	0.60	0.34	0.02	0.00	7.5	7.9
07/04/92	243	0.35	0.21	0.49	10.8	12.9	0.15	0.12	0.22	0.65	0.58	0.20	0.10	0.27	10.2	12.4
08/04/92	244	0.34	0.15	0.14	11.9	15.5	0.34	0.15	0.14	0.44	3.71				11.5	11.8
09/04/92	245	1.19	0.45	0.40	10.6	11.4	0.42	0.14	0.16	0.94	1.01	0.77	0.32	0.25	9.7	10.4
10/04/92	246	0.49	0.56	0.98	12.2	11.7	0.15	0.15	0.19	0.92	0.78	0.34	0.41	0.79	11.3	10.9
11/04/92	247	1.18	0.55	0.43	12.2	12.4	0.32	0.13	0.13	0.57	0.85	0.86	0.41	0.30	11.6	11.6
13/04/92	249	1.47	0.51	0.43	13.5	13.0	0.16	0.12	0.12	0.92	0.87	1.32	0.39	0.31	12.6	12.1
14/04/92	250	1.14	0.42	0.34	11.7	12.2	0.17	0.12	0.11	1.25	0.94	0.96	0.30	0.23	10.4	11.2
15/04/92	251	0.43	0.40	0.92	12.7	11.9	0.10	0.12	0.21	1.46	1.15	0.33	0.29	0.71	11.2	10.8
16/04/92	252	1.04	0.43	0.36	11.4	12.7	0.19	0.10	0.10	1.15	1.15	0.85	0.33	0.26	10.3	11.5
17/04/92	253	0.31	0.23	0.52	8.3	12.2	0.13	0.12	0.16	0.73	0.90	0.18	0.11	0.36	7.5	11.3
18/04/92	254	0.27	0.31	0.60	7.2	9.8	0.11	0.11	0.15	0.78	0.73	0.16	0.20	0.45	6.4	9.1
20/04/92	256	0.33	0.31	0.68	7.5	9.1	0.16	0.12	0.12	0.47	0.80	0.18	0.19	0.56	7.0	8.3
21/04/92	257	1.85	0.45	0.44	14.3	13.5	0.19	0.13	0.12	0.86	0.90	1.66	0.32	0.32	13.5	12.6
22/04/92	258															
27/04/92	263	0.51	0.40	0.88	8.8	9.6	0.37	0.15	0.17	0.67	0.83	0.14	0.25	0.70	8.1	8.8
28/04/92	264	1.38	0.36	0.27	8.0	9.6	0.20	0.16	0.17	0.91	0.87	1.18	0.20	0.09	7.1	8.7
29/04/92	265	0.33	0.35	0.77	8.5	9.1	0.17	0.17	0.16	1.31	1.55	0.17	0.18	0.61	7.2	7.5
30/04/92	266	0.32	0.37	1.00	9.6	10.9	0.23	0.24	0.24	2.14	2.20	0.10	0.13	0.76	7.4	8.7
01/05/92	267	0.43	0.39	0.82	10.4	9.6	0.25	0.20	0.21	1.57	1.85	0.18	0.19	0.61	8.8	7.7
02/05/92	268	0.40	0.42	0.93	10.1	11.4	0.25	0.18	0.22	1.83	1.99	0.15	0.24	0.71	8.3	9.4
04/05/92	269	0.29	0.33	0.76	8.0	8.0	0.25	0.16	0.19	0.83	0.83	0.05	0.18	0.57	7.2	7.2
05/05/92	270	1.56	0.40	0.27	12.6	13.1	0.03	0.23	0.11	0.64	0.69	1.54	0.17	0.16	11.9	12.4
06/05/92	271	0.70	0.58	1.41	11.6	13.8	0.04	0.06	0.33	1.49	1.63	0.67	0.51	1.08	10.1	12.2
07/05/92	272	0.38	0.41	2.08	12.8	13.3	0.17	0.29	0.28	0.35	0.19	0.21	0.13	1.81	12.5	13.1
08/05/92	273	0.49	1.12	2.07	9.8	10.8	0.12	0.06	0.07	0.09	0.18	0.37	1.06	2.00	9.7	10.6
09/05/92	274	1.06	0.43	0.25	6.8	7.5	0.41	0.08	0.08	0.18	0.18	0.65	0.35	0.17	6.6	7.3
11/05/92	276	1.44	0.83	0.34	6.2	6.8	0.07	0.07	0.05	0.16	0.27	1.37	0.76	0.29	6.1	6.5
12/05/92	277	1.04	0.29	0.16	7.2	8.0	0.09	0.10	0.09	0.25	0.27	0.95	0.19	0.08	6.9	7.7
13/05/92	278	1.37	0.53	0.29	6.7	7.7	0.21	0.09	0.08	0.17	0.25	1.16	0.44	0.21	6.5	7.5
14/05/92	279	0.87	0.33	0.16	6.7	7.2	0.08	0.08	0.07	0.23	0.27	0.79	0.25	0.09	6.4	6.9
15/05/92	280	0.20	0.22	0.75	8.0	9.3	0.06	0.05	0.07	0.27	0.21	0.15	0.16	0.68	7.7	9.1
16/05/92	281	1.13	0.33	0.22	5.6	7.5	0.07	0.05	0.06	0.15	0.31	1.06	0.28	0.15	5.5	7.1
18/05/92	283	0.73	0.29	0.22	5.9	5.1	0.09	0.07	0.07	0.45	0.27	0.64	0.23	0.15	5.4	4.8
19/05/92	284	0.19	0.27	1.01	8.2	9.8	0.05	0.05	0.09	0.43	0.33	0.14	0.21	0.92	7.8	9.5
20/05/92	285	0.16	0.27	1.16	8.8	9.3	0.06	0.06	0.10	0.45	0.37	0.10	0.21	1.06	8.3	8.9
21/05/92	286	0.20	0.27	1.00	6.7	7.2	0.08	0.05	0.08	1.00	1.23	0.12	0.22	0.93	5.7	6.0
22/05/92	287	0.15	0.25	0.98	7.3	7.0	0.08	0.08	0.12	0.46	0.88	0.08	0.17	0.86	6.8	6.1
25/05/92	290	0.20	0.32	1.33	9.0	9.5	0.13	0.12	0.16	0.48	0.37	0.07	0.21	1.18	8.5	9.2
26/05/92	291	1.04	0.32	0.18	6.5	7.9	0.10	0.14	0.10	0.58	0.92	0.94	0.19	0.09	5.9	6.9
27/05/92	292	1.56	0.52	2.02	7.0	7.3	0.28	0.13		0.78	0.56	1.28	0.39	2.02	6.2	6.7
28/05/92	293	1.97	0.52	14.59	24.0	20.8	0.40	0.15	13.15	19.38	14.71	1.57	0.37	1.44	4.6	6.0
29/05/92	294	1.92	0.90	15.00	36.4	43.3	0.75	0.19	14.18	16.12	16.12	1.17	0.71	0.83	20.3	27.1

		NITRATES AND NITRITES					NITRITES					NITRATES				
Month/ Date	DAY	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l	Anae. mgN/l	Anox. 1 mgN/l	Anox. 2 mgN/l	Aer. mgN/l	Effl. mgN/l
01/06/92	297	0.74	3.82	12.00	25.9	27.5	0.12	0.53	10.52	8.55	9.79	0.61	3.29	1.47	17.3	17.7
02/06/92	298	0.84	0.63	19.64	41.4	41.3	0.52	0.39	15.37	20.63	20.52	0.32	0.23	4.28	20.8	20.8
03/06/92	299	0.58	0.48	19.28	33.5	32.8	0.34	0.24	17.28	19.25	18.32	0.24	0.24	2.01	14.3	14.5
05/06/92	301	0.82	1.32	12.00	35.1	35.1	0.10	0.50	10.18	13.00	12.91	0.72	0.82	1.82	22.1	22.2
06/06/92	302	2.21	0.84	10.17	26.4	34.3	1.40	0.72	8.22	10.70	19.70	0.81	0.12	1.95	15.7	14.6
10/06/92	306	0.37	1.33	7.14	16.1	17.2	0.25	0.85	2.70	2.52	2.35	0.12	0.48	4.44	13.6	14.8
11/06/92	307	0.22	0.18	3.97	19.9	19.3	0.08	0.10	2.83	1.99	3.00	0.14	0.08	1.14	17.9	16.3
12/06/92	308	0.28	0.56	8.83	23.0	23.8	0.20	0.40	6.42	7.89	7.89	0.08	0.16	2.41	15.1	15.9
13/06/92	309	0.45	2.00	16.20	15.2	15.2	0.29	1.53	15.20	6.88	6.88	0.16	0.47	1.00	8.3	8.3
15/06/92	311	0.63	1.86	16.52	16.0	15.2	0.42	1.46	12.70	13.24	11.62	0.21	0.40	3.82	2.8	3.6
16/06/92	312	0.71	2.55	15.45	17.2	19.9	0.50	1.50	14.25	8.46	8.46	0.21	1.05	1.20	8.8	11.5
17/06/92	313	0.67	2.27	15.20	17.9	17.9	0.47	1.27	12.14	11.38	14.27	0.20	1.00	3.06	6.5	3.6
20/06/92	316															
21/06/92	317															
22/06/92	318	2.20	3.94	15.73	22.5	25.3	0.16	1.18	14.98	12.79	13.24	2.04	2.76	0.74	9.7	12.1
23/06/92	319	0.68	2.14	12.79	24.0	27.1	0.60	1.52	10.69	14.57	12.81	0.08	0.62	2.10	9.4	14.3
24/06/92	320	1.58	1.96	15.03	27.2	30.0	0.94	1.52	14.25	14.30	16.09	0.64	0.44	0.78	12.9	13.9
25/06/92	321															
26/06/92	322	0.82	3.69	12.31	28.2	28.9	0.31	2.71	11.24	11.64	11.52		0.98	1.07	16.6	17.3
27/06/92	323	0.62	3.50	18.37	26.8	27.3	0.34	2.50	17.40	17.12	18.12	0.29	1.00	0.97	9.7	9.1
28/06/92	324															
29/06/92	325	0.62	3.50	18.37	26.8	27.3	0.56	2.49	17.40	17.40	18.12	0.06	1.01	0.97	9.4	9.1
30/06/92	326															
01/07/92	327	2.38	1.48	9.21	21.9	21.9	1.21	0.36	8.08	12.96	11.52	1.17	1.12	1.13	8.9	10.4
02/07/92	328															
03/07/92	329	2.43	1.15	10.06	26.3	26.3	1.49	0.34	9.84	16.56	16.20	0.94	0.81	0.22	9.7	10.1
04/07/92	330															
05/07/92	331															
06/07/92	332	1.41	0.85	14.46	41.2	41.2	0.28	0.14	13.44	10.28	14.56	1.13	0.71	1.02	31.0	26.7
07/07/92	333	0.87	2.48	17.54	43.9	40.5	0.62	2.10	15.00	17.00	17.00	0.25	0.38	2.54	26.9	23.5
08/07/92	334															
09/07/92	335	2.55	2.00	15.45	33.9	40.9	0.62	0.92	14.87	11.57	14.54	1.93	1.08	0.58	22.3	26.4
10/07/92	336															
11/07/92	337	1.72	3.78	12.26	36.6	37.9	1.14	3.23	10.47	15.28	11.72	0.58	0.55	1.79	21.3	26.2
12/07/92	338															
13/02/92	339															
14/07/92	340	1.51	5.36	17.07	34.5	39.3	1.08	5.28	15.17	13.54	14.18	0.43	0.08	1.90	20.9	25.1

APPENDIX B

NITROGEN AND COD MASS BALANCES

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 and illustrated by an example using the data of MUCT1 steady state period 7 (See Table B1 below).

I. 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 nitrate and nitrite.

(i) Mass of nitrogen denitrified

For the MUCT configuration (Fig B.1) this mass is obtained by a nitrate and nitrite mass balance around the [1]anaerobic and anoxic sections of the system. Where significant amounts of nitrite are generated it is necessary to split the nitrate and nitrite in order to produce an accurate calculation particularly for the COD mass balance.

Mass of nitrite denitrified considering 3 unaerated zones together

= (Mass of nitrite into unaerated zones)

- (Mass of nitrite out of unaerated zones)

$$MNO_{2d} = (a+s)QNO_{2aer.} + MNO_2 \text{ added} - (1+a+s)QNO_{2anox.2} \quad (mgNO_2\text{-}N/d) \tag{B.1}$$

---

[1] It is also normal practice to do this balance around the anoxic section only but in systems where nitrate and nitrite concentrations of more than 1 mgN/l were measured it is recommended to include the anaerobic section.

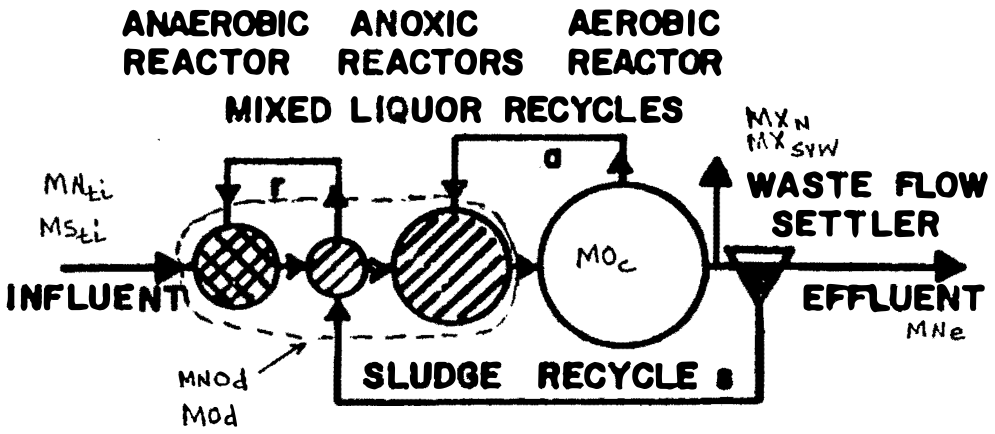


Fig B.1 Layout out of the MUCT system showing the denitrification zone for the N and COD mass balances.

and

Mass of nitrate denitrified

= (Mass of nitrate into unaerated zones)

- (Mass of nitrate out of unaerated zones)

$$MNO_{3d} = (a+s)QNO_{3aer.} + MNO_3 \text{ added} - (1+a+s)QNO_{3anox.2} \quad (mgNO_3\text{-}N/d) \qquad (B.2)$$

where

MNO_{2d} = mass of nitrite denitrified per day ($mgNO_2$-N/d)

MNO_{3d} = mass of nitrate denitrified per day ($mgNO_3$-N/d)

$NO_{2aer.}$ = effluent nitrite concentration from aerobic reactor ($mgNO_2$-N/ℓ)

$NO_{3aer.}$ = effluent nitrate concentration from aerobic reactor ($mgNO_3$-N/ℓ)

$NO_{2anox.2}$ = effluent nitrite concentration from 2nd anoxic reactor ($mgNO_2$-N/ℓ)

$NO_{3anox.2}$ = effluent nitrate concentration from 2nd anoxic reactor ($mgNO_3$-N/ℓ)

Q = daily influent flow rate (ℓ/d)

a,r,s = recycle ratios

Substituting the appropriate average values into the above equations for steady state period 7 of MUCT1 which includes nitrate dosing.

$$\begin{aligned} MNO_{2d} &= (3+1)(10)(1,13)+0-(1+3+1)(10)(1,92) \\ &= -50,9 \text{ } mgNO_2\text{-}N/d \end{aligned}$$

i.e 50,9 mg NO_2 are formed by the reduction of NO_3 to NO_2.

$$\begin{aligned} MNO_{3d} &= (3+1)(10)(18,17)+720-(1+3+1)(10)(6,65) \\ &= 1114 \text{ } mgNO_3\text{-}N/d \end{aligned}$$

i.e 1114 mg NO_3 are reduced.

Repeating the calculations with nitrate plus nitrite concentrations yield the nitrogen removal to be 1063 $mgNO_3$-N/d which is confirmed by the 1114 $mgNO_3$-N/d denitrified but 50,9 $mgNO_2$-N/d nitrite generated.

(ii) Nitrogen in the waste sludge

The mass of N in the waste sludge is given by the product of the TKN/VSS ratio and the mass of VSS wasted per day.

$M X_N = f_n M X_v$ (mgN/d) (B.3)

where $f_n = 0,10$ mgN/mgVSS

Substituting the appropriate values gives

$M X_N = (0,10)(2890)$

$= 289$ mgN/d

(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.

$MN_e = (N_{te} + NO_{2e} + NO_{3e})Q$ (B.4)

$= (5,91 + 0,95 + 18,85)(10)$

$= 257$ mgN/d

(iv) Nitrogen mass balance

The % N mass balance is given by

% N balance $= 100(MNO_{2d} + MNO_{3d} + MX_N + MN_e)/MN_i$ (B.5)

Substituting the values calculated above

% N balance $= (100)(-50,9 + 1114 + 289 + 257)/(789 + 720)$

$= 106,6\%$

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 or nitrite dosed,i.e

$MN_i = N_{ti}.Q + MNO_{x\ dosed}$ (B.6)

II.COD MASS BALANCE

The daily mass of COD (MS_{ti}) that enters the system should be accounted by:

(i) the mass oxygen demand required per day for degradation of carbonaceous material in the aerobic reactor.

(ii) the equivalent mass 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 oxygen demand and the carbonaceous oxygen demand. Since nitrification does not consume any of the influent COD, the oxygen demand due to nitrification must be subtracted from the total measured oxygen demand. Stoichiometrically the oxygen requirements for nitrification of ammonia to nitrite (by *nitrosomonas*)and to nitrate (by both *nitrosomonas and nitrobacter*) is different being slightly less in the former reaction (i.e 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:

(a) The mass of nitrate and nitrite generated by nitrification is obtained by doing a nitrate and nitrite mass balance around the aerobic reactor of the system.

Mass of nitrate or nitrite generated =
(Mass of nitrate/nitrite out of aerobic reactor)-(Mass of nitrate/nitrite into aerobic reactor)

$$MNO_{2g} = (1+a+s)QNO_{2aer.}-(1+a+s)QNO_{2anox.2} \qquad (B.7)$$

Substituting the appropriate values for steady state period 7 of MUCT1;

$$MNO_{2g} = (1+3+1)(10)(1,13)-(1+3+1)(10)(1,92)$$

= -39,5 mgN/d i.e 39,5 mg nitrite is nitrified to nitrate

and

$$MNO_{3g} = (1+a+s)QNO_{3aer.}-(1+a+s)QNO_{3anox.2} \qquad (B.8)$$

$$= (1+3+1)(10)(18,17)-(1+3+1)(10)(6,62)$$

= 577 mgN/d i.e 577 mg NO_3 are generated from NH_4^+ or NO_2-.

Since 39,5 $mgNO_3$-N/d were formed by nitrification of nitrite, (577-39,5)= 537,5 $mgNO_3$-N/d were formed from ammonia i.e

MNO_{3ga} = 537,5 $mgNO_3$-N/d

(b) The nitrification oxygen demand is then given by

MO_n $= 4,57MN_{O3ga}+1,14MN_{O2g}$ (B.9a)

$= (537,5)(4,57)+(39,5)(1,14)$

= 2501 mgO/d

or equivalently

MO_n $= 4,57MN_{O3g}+3,43MNO_{2g}$ (mgO/d) (B.9b)

$= (4,57)(577)+(3,43)(-39,5)$

= 2501 mgO/d

where

4,57 = mass of oxygen required to form a unit mass of nitrate (mgO/mgN)

1,14 = mass of oxygen required to form a unit mass of nitrate from nitrite (mgO/mgN)

(c) The carbonaceous oxygen demand in the aerobic reactor is determined as follows

MO_c $= (OUR).V_a.24-MO_n$ (mgO/d) (B.10)

$= (40)(4)(24)-2501$

= 1339 mgO/d

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 $= 2,86MNO_{3d}+1,71MNO_{2d}$ (mgO/d) (B.11)

where

2,86 = equivalent mass of oxygen demand in denitrifying one mgN of nitrate to N_2 ($mgO/mgNO_3$-N)

1,71 = equivalent mass of oxygen demand in denitrifying one mgN of nitrite to N_2 ($mgO/mgNO_2$-N)

MNO_{3d} = mass of nitrate denitrified to nitrogen gas ($mgNO_3$-N/d)

MNO_{2d} = mass of nitrite denitrified to nitrogen gas ($mgNO_2$-N/d)

In a more convenient form for the COD balance the equivalent total oxygen demand for denitrification can also be written as

$$MO_d = 2{,}86MNO_{3r}-(2{,}86-1{,}71)MNO_{2f} \qquad (B.12)$$

where now

MNO_{3r} = mass of nitrate disappeared to either N_2 gas or NO_2^- ($mgNO_3$-N/d)

MNO_{2f} = mass of nitrite formed in denitrification of nitrate

= $-MNO_{2d}$

Substituting the relevant values

MO_d = (2,86)(1114)-(2,86-1,71)(50,9)

= 3128 mgO/d

(iii) **COD in waste sludge**

The amount of COD that passes out of the system via the waste sludge is given by:

$$MX_{svw} = f_{cv}MX_v \quad (mgO/d) \qquad (B.13)$$

where

f_{cv} = COD/VSS ratio of activated sludge

= 1,48 mgCOD/mgVSS

MX_v = mass of sludge wasted per day (mgVSS/d)

= $X_v.q$

where

X_v = aerobic reactor VSS concentration (mgVSS/ℓ)

q = waste flow rate (ℓ/d)

Substituting for the values gives

MX_{svw} = (1,48)(2890)(1,0)

= 4277 mgO/d

(iv) **COD in effluent**

This is given by the daily flow multiplied by the effluent COD concentration;

$$MS_{te} = Q.S_{te} \tag{B.14}$$

$$= (10)(65{,}6)$$

$$= 656 \text{ mgCOD/d}$$

(v) **COD balance**

The percentage COD balance is then given by

$$\% \text{ COD balance} = 100.(MO_c + MO_d + MX_{svw} + MS_{te})/MS_{ti} \tag{B.15}$$

thus substituting

$$\% \text{ COD balance} = 100(1339+3128+4277+656)/(10)(929)$$

$$\doteq 101 \%$$

Table B.1 N and COD mass balances for each steady state period for the MUCT1 system.

MUCT1: Nitrogen balance

				NITRATE & NITRITE					NITRITE											
PRD.	DAY	Infl. TKN mgN/l	Effl. TKN mgN/l	Anaer mgN/l	Anox.1 mgN/l	Anox.2 mgN/l	Aero. mgN/l	Effl. mgN/l	Anaer mgN/l	Anox. mgN/l	Anox. mgN/l	Aero. mgN/l	Effl. mgN/l	MLVSS mgVSS	MNO2d mgN/d	MNO3d mgN/d	MNOd mgN/d	MXn mgVSS	MNe mgN/d	N bal. %
1	1-22	81.4	2.91	0.8	0.64	0.63	13	13.4	0.13	0.06	0.05	0.88	1.67	2926	24.5	318	343	293	163	98.04
2	23-55	97.9	5.21	0.94	0.58	0.95	13.4	13.4	0.31	0.17	0.29	3.68	3.93	2980	133	356	489	298	186	99.4
3	56-92	69	3.98	0.65	0.52	0.52	8.6	9.14	0.14	0.1	0.15	1.19	1.01	2858	40.2	275	315	286	131	105.5
4	93-125	76.8	4.89	0.7	0.44	0.58	9.7	9.74	0.26	0.19	0.23	1.32	1.21	3059	41.2	318	359	306	146	105.6
5	126-137	62.4	2.77	0.38	0.53	3.56	10.4	10.3	0.2	0.25	1.47	2.12	2.03	3116	11.2	948	959	312	131	104.3
6	138-152	96.1	5.9	0.98	0.81	6.97	19.2	19.8	0.3	0.5	2.87	1.97	1.9	2943	-65	1204	1139	294	257	100.6
7	153-196	79.8	5.91	0.79	0.59	8.54	19.3	19.8	0.23	0.25	1.92	1.13	0.95	2890	-51	1114	1064	289	257	106.6
8	197-220	66.7	5.85	0.66	1.47	10.96	22.1	22.2	0.22	0.2	2.18	0.97	0.84	2440	-70	1127	1057	244	222	114
9	221-239	91.2	6.49	1.14	0.99	13.41	23	23.5	0.13	0.4	2.85	2.09	1.97	2350	-59	1028	970	236	300	92.2
10	240-269	88.9	5.89	1.12	0.59	0.59	11.5	13.7	0.35	0.3	0.18	3.18	3.35	3083	31.6	335	367	281	231	106.6
11	270-290	67.7	4.86	0.74	0.39	0.73	8	8.1	0.16	0.08	0.1	0.4	0.52	3195	11.2	274	285	320	130	108.4
12	291-308	87.2	5.28	0.57	0.54	1.06	12.1	12.8	0.17	0.22	0.62	1.78	1.93	3417	40.3	392	433	342	181	109.6
13	309-340	106	6.59	1.52	0.74	0.641	15.5	16.7	0.38	0.93	0.47	1.86	1.86	3564	51.2	523	574	356	236	109.7

MUCT1: COD balance

PRD	DAY	Infl. COD mgCOD	Effl. COD mgCOD	OUR mgO/l/h	MOt mgO/d	MNO2 mgN/d	MNO3 mgN/d	MOn mgN/d	MOc mgO/d	MOd mgO/d	MXSvw mgVSS	MSte mgCOD	COD bal. %
1	1-22	990	65.7	44.2	4243	33.2	432	2087	2156	951	4331	657	81.8
2	23-55	993	68.7	50.9	4886	170	453	2654	2230	1246	4410	687	86.3
3	56-92	914	69	35.5	3408	52	349	1774	1636	855	4229	690	81.1
4	93-125	921	66.2	47.8	4589	54.4	402	2022	2563	979	4527	662	94.8
5	126-137	1036	81.2	56.4	5414	32.4	311	1532	3880	2730	4611	812	116
6	138-152	1003	69.1	37.4	3590	-45	656	2844	742	3332	4357	691	90.9
7	153-196	929	65.6	40	3840	-40	577	2500	1337	3103	4277	656	101
8	197-220	853	70.3	41.6	3994	-61	619	2620	1372	3104	3611	703	103
9	221-239	950	74	47.1	4522	-38	517	2233	2292	2840	3491	740	98.5
10	240-269	946	72.2	51.7	4963	63.4	460	2319	2639	1013	4171	722	98.1
11	270-290	923	64.7	67.8	6509	15.2	350	1651	4860	802	4729	647	120
12	291-308	980	71	69.6	6682	58.1	496	2466	4212	1191	5057	710	114
13	309-340	1053	69.8	77.9	7478	69.8	659	3252	4228	1582	5275	698	112

Table B.2 N and COD mass balances for each steady state period for the MUCT2 system.

MUCT2: Nitrogen mass balance

				NITRATE & NITRITE					NITRITE											
PRD.	DAY	Infl. TKN mgN/l	Effl. TKN mgN/l	Anaer mgN/l	Anox.1 mgN/l	Anox.2 mgN/l	Aero. mgN/l	Effl. mgN/l	Anaer mgN/l	Anox. mgN/l	Anox. mgN/l	Aero. mgN/l	Effl. mgN/l	MLVSS mgVSS	MNO2d mgN/d	MNO3d mgN/d	MNOd mgN/d	MXn mgVSS	MNOe mgN/d	N bal. %
1	171-196	80.3	5.9	0.68	0.32	0.38	6.55	7.13	0.2	0.18	0.16	0.88	0.8	3359	27.3	216	243	336	130	88.4
2	197-220	66.7	4.78	0.77	0.25	0.29	5.65	6.97	0.14	0.12	0.14	0.22	0.23	2946	1.75	210	212	295	118	93.5
3	221-269	89.2	5.79	0.74	0.42	0.6	10.4	11.1	0.23	0.16	0.18	0.97	1.07	3014	29.9	357	387	301	169	96.1
4	270-290	66.9	5.32	0.66	0.41	0.76	7.63	8.36	0.12	0.09	0.1	0.36	0.4	3167	9.42	258	267	317	137	107.7
5	291-308	85.9	5.17	0.88	1.12	17.08	24.6	25.6	0.42	0.59	8.26	8.06	7.94	2862	809	221	1031	286	309	92.4
6	309-340	106	5.61	2.14	4.06	34.81	42.5	43.8	0.99	2.73	23.1	28.7	33	2860	893	-32	860	286	493	83.6

MUCT2: COD balance

PRD	DAY	Infl. COD mgCOD	Effl. COD mgCOD	OUR mgO/l/h	MOt mgO/d	MNO2 mgN/d	MNO3 mgN/d	MOn mgN/d	MOc mgO/d	MOd mgO/d	MXSvw mgVSS	MSte mgCOD	COD balan %
1	171-196	922	55.8	62.7	6019	36.1	272	1369	4650	664	4972	558	117
2	197-220	847	69	52.7	5059	3.9	264	1222	3836	604	4361	690	112
3	221-269	954	72.6	58.3	5597	39.6	452	2199	3393	1072	4461	726	101
4	270-290	921	62.3	51.7	4963	13	330	1554	3410	753	4688	621	103
5	291-308	979	77.4	44.3	4253	-10	387	1733	2519	2017	4235	774	97.5
6	309-340	1037	86.4	76.6	7354	280	106	1445	5911	1435	4232	864	120

APPENDIX C

Results of the batch tests for the MUCT1 and MUCT2 systems.

Anoxic batch tests for the MUCT1 system.
1. Batch tests to determine nitrate denitrification rate.

Day 104

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	12.40	0.60	11.80	177	10.92
5	12.56	0.77	11.79	180	11.9
10	12.56	0.99	11.57	101	9.24
15	12.40	1.13	11.27	93.1	9.15
20	12.16	1.47	10.70	101	8.4
25	10.94	1.89	9.06	76.5	15.68
30	11.32	2.22	9.11	201	9.24
40	8.88	2.60	6.28	97.2	12.88
50	7.74	3.06	4.68	106	12.46
60	6.88	3.25	3.63	143	6.86
90	0.72	0.45	0.27	80.7	8.68
120	0.21	0.16	0.04	84.8	10.08
150	0.22	0.11	0.11	139	10.08
180	0.15	0.08	0.07	99.3	12.6
210	0.13	0.08	0.05	172	11.9
240	0.14	0.07	0.07	106	13.72
270	0.12	0.06	0.06	93.1	11.34
300	0.10	0.06	0.04	312	10.08
330	0.09	0.05	0.04	118	11.2
360	0.12	0.05	0.06	143	12.88
390	0.11	0.06	0.05	192	12.18

Day 113

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	6.80	0.50	6.30	74	13.16
5	7.21	0.63	6.57	144	12.88
10	6.93	0.74	6.20	123	15.12
15	6.80	0.85	5.95	111	12.6
20	5.45	0.91	4.53	193	15.96
25	4.50	1.00	3.50	98.7	14.28
30	3.96	1.02	2.95	123	12.88
40	1.20	1.10	0.09	148	11.76
50	0.41	0.29	0.12	164	14.56
60	0.29	0.15	0.14	164	15.96
70	0.24	0.13	0.11	115	17.64
120	0.46	0.15	0.31	164	16.24
150	0.27	0.12	0.15	152	12.6
180	0.23	0.12	0.11	144	18.2
200	0.23	0.12	0.11	148	14.28
240	0.27	0.13	0.14	201	15.68
270	0.21	0.11	0.10	144	14.28
300	0.29	0.11	0.18	127	13.25
330	0.24	0.11	0.13	152	17.92
360	0.25	0.12	0.13	148	17.08

Day 179

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	102.74	0.57	102.17	116	13.72
20	95.89	0.93	94.96	190	13.92
40	95.62	1.42	94.20	149	16.58
60	91.40	1.91	89.49	145	15.68
80	86.92	2.49	84.43	165	15.54
100	92.46	2.91	89.55	120	9.31
120	89.82	3.28	86.54	132	8.82
140	89.30	4.08	85.22	152	8.54
150	88.77	4.38	84.39	165	11.06
160	84.29	4.55	79.74	85	15.88
170	84.29	4.95	79.34	154	18.34
180	82.18	5.04	77.14	74.5	9.8
200	79.80	5.47	74.33	132	11.62
220	76.64	5.81	70.83	277	15.6
240	81.91	6.20	75.71	101	14.25
260	76.90	6.47	70.43	120	15.68
280	80.07	6.97	73.10	82.7	19.18
300	77.43	7.25	70.18	120	18.76
320	76.10	7.37	68.73	165	12.32
340	66.79	7.72	59.07	157	18.62
360	76.10	7.99	68.11	182	16.8
390	67.59	8.36	59.23	103	16.8
420	74.51	9.09	65.42	150	17.08
450	66.26	9.11	57.15	103	15.96
480	62.89	9.21	53.68	161	15.12
510	70.25	9.60	60.65	78.6	13.72
540	65.99	9.41	56.58	166	15.4
600	56.25	9.51	46.74	158	10.5
660	49.55	9.42	40.13	121	11.35
720	44.35	9.31	35.04	135	

Day 238

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	97.50	1.23	96.27	119	17.25
30	98.80	1.19	97.61	77.1	14.28
60	96.90	1.02	95.88	85.3	12.6
90	90.10	1.23	88.87	68.9	5.6
120	84.04	1.35	82.69	91.5	4.76
240	74.26	3.05	71.21	60.7	15.68
390	56.77	4.59	52.18	68.9	12.6
420	57.28	4.89	52.39	102	12.88
450	51.62	5.25	46.37	167	9.8
480	51.11	5.37	45.74	83	12.32
510	47.51	6.33	41.18	83	13.44
540	46.48	6.61	39.87	118	12.6
570	44.42	5.61	38.81	104	13.16
600	40.31	6.35	33.96	102	14.28
660	38.76	6.39	32.37	73	9.8
720	32.78	6.53	26.25	85.3	10.08

Day 290

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	5.60	0.95	4.64	102	14.28
10	7.17	1.20	5.97	73.25	9.8
20	4.81	0.89	3.92	85.5	10.23
30	4.55	0.95	3.60	109	12.75
40	4.29	0.98	3.31	103	12.88
50	3.50	1.04	2.46	85.5	7.56
60	2.72	1.00	1.72	93.5	10.36
80	1.42	1.16	0.26	89.4	14.84
100	0.69	0.21	0.47	110	
120	0.64	0.23	0.41	68.9	12.32
140	0.66	0.52	0.14	75.1	10.36
160	0.28	0.19	0.09	110	12.6
180	0.27	0.18	0.09	118	13.44
200	0.45	0.21	0.24	233	14.56
220	0.35	0.17	0.17	147	[illegible]
240	0.79	0.14	0.65	106	
270	1.32	0.63	0.69	163	
300	0.86	0.32	0.54	130	[illegible]
330	0.28	0.21	0.07	165	
360	0.54	0.18	0.36	120	

Day 317

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	41.86	1.29	40.57	112	12.45
15	36.52	2.19	34.33	95.3	8.54
30	32.86	2.58	30.28	90.6	9.35
45	34.55	3.56	30.99	110	12.23
60	32.86	4.71	28.15	114	12.45
90	30.62	5.30	25.32	167	16.12
120	28.93	5.93	23.00	104	9.5
150	27.53	6.59	20.94	85.5	10.24
180	25.85	6.79	19.06	104	14.78
210	26.41	7.30	19.11	110	12
240	23.32	7.81	15.51	110	7.65
270		8.08			
300	15.10	7.93	7.17	95.4	16.65
330	14.12	8.12	6.00	101	14.75
360	13.65	7.50	6.15	135	12

2. Batch tests to determine the nitrite denitrification rate.

Day 270

Time (min)	NO2-N (mg/l)
0	19.44
15	18.84
30	18.96
45	21.18
60	20.64
90	19.88
120	19.4
150	17.52
180	14.02
210	12.99
240	12.12
270	10.64
300	10.56
330	10.02

Day 290

Time (min)	NO2-N (mg/l)
0	5
15	5.877
30	4.2
45	3.65
60	2.95
90	2.5
120	1.52
156	1.1
180	0.51
210	0.41
240	0.388
270	0.157
300	0.144
330	0.144

Anoxic batch tests for the MUCT2 system.

1. Batch tests to determine the nitrate denitrification rate.

Day 258

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	34.68	2.12	32.57	120	8.92
15	34.96	1.88	33.09	105	12.34
30	31.78	1.90	29.88	93.6	12.34
45	29.14	1.92	27.22	160	10.03
60	29.44	2.01	27.44	144	5.62
75	30.72	2.18	28.54	135	12.73
90	26.76	2.20	24.56	110	14.29
105	27.82	2.01	25.82	110	9.72
120	26.24	2.14	24.11	109	9.72
150	24.35	2.14	22.22	98.4	11.45
180	21.31	2.16	19.15	107	10.25
210	16.95	2.42	14.54	103	7.98
240	16.82	2.20	14.62	107	8.95

Day 299

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	20.79	1.25	19.54	93.1	9.78
15	18.80	1.38	17.42	97.2	18.97
30	16.82	1.95	14.87	103	12.25
60	14.96	2.25	12.71	125	9.75
90	16.40	2.16	14.24	101	15.25
120	15.18	2.50	12.68	112	13.72
150	11.97	2.55	9.42	97.2	14.28
180	8.66	2.73	5.93	115	5.35
210	12.24	2.90	9.34	101	12.75
240	10.15	3.01	7.14	112	12.32
270	13.19	2.85	10.34	107	13.45
300	12.26	2.36	9.90	125	13.44
330	10.25	2.11	8.14	115	7.98
360	4.37	1.95	2.42	126	12.85

Day 313

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	23.82	0.55	23.27	162	10.05
30	23.31	0.71	22.60	145	9.75
60	21.79	1.21	20.58	92.7	12.25
90	18.46	1.24	17.22	103	12.25
120	17.37	1.50	15.87	107	15.88
150	16.18	1.65	14.53	97.3	9.82
180	14.42	1.91	12.51	110	13.22
210	15.36	2.18	13.18	115	9.82
240	13.17	2.68	10.49	115	12.6
270	10.88	2.95	7.93	98.5	12.25
300	9.36	3.11	6.25	103	11.75
330	7.96	3.05	4.91	135	9.75
360	7.63	3.06	4.57	110	10.01

Day 340

Time (min)	NO3+NO2-N (mg/l)	NO2-N (mg/l)	NO3-N (mg/l)	COD (mg/l)	TKN (mg/l)
0	30.90	2.35	28.55	120	9.84
90	24.03	3.01	21.02	112	15.32
120	22.40	3.25	19.15	98.5	9.85
150	18.72	3.32	15.40	110	12.32
180	16.63	3.41	13.22	120	10.65
210	12.97	3.50	9.47	135	12.57
240	10.74	3.45	7.29	103	12.57
270	8.99	3.43	5.56	125	9.75

2. Batch tests to determine the nitrite denitrification rate.

Day 285

Time (min)	NO2-N (mgN/l)
0	15.30
10	14.17
20	13.37
30	12.25
40	11.36
50	10.24
60	9.03
80	7.10
100	4.69
120	3.33
150	0.82
180	0.30
210	0.30
240	0.30
270	0.21
300	0.23
330	0.17
360	0.17

Day 299

Time (min)	NO2-N (mgN/l)
0	16.71
15	
30	17.49
60	17.02
90	16.47
120	14.20
150	13.02
180	10.90
210	9.10
240	7.53
270	7.22
300	6.20
330	5.02
360	4.29

Day 313

Time (min)	NO2-N (mgN/l)
0	21.63
30	22.11
60	21.63
90	22.75
120	19.54
150	14.41
180	13.12
210	10.55
240	7.49
270	4.95
300	2.94
330	1.18
360	0.78

Day 340

Time (min)	NO2-N (mgN/l)
0	30.98
90	24.95
120	21.45
150	18.60
180	12.11
210	10.55
240	5.88
270	3.28