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THE EFFECT OF THE TYPE, SIZE, POSITION AND RECYCLE RATIO OF THE ANOXIC ZONE ON LOW F/M FILAMENT BULKING IN NITROGEN REMOVAL ACTIVATED SLUDGE SYSTEMS

by

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April, 1992

DECLARATION BY CANDIDATE

I

ANDREW CHARLES HULSMAN

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

April 1992

Signed by candidate

DEDICATION

This thesis is dedicated to my parents for their unquestioning support and generosity given over the study and research period.

SYNOPSIS

Filamentous bulking, which causes deterioration in sludge settleability has been shown, in two nation-wide surveys to be a problem of considerable proportions. Poor sludge settleability in the secondary clarifier limits the daily flow and load that can be treated in activated sludge wastewater treatment plants. Controlling sludge settleability to relatively low levels i.e. Diluted Sludge Volume Index (DSVI < 100 m*l*/g) by controlling filamentous organism proliferation would allow increased daily flow and loads by up to 100% on existing activated sludge wastewater treatment plants.

From the two surveys, Blackbeard *et al.* (1986,1988) found that mainly six filamentous organisms tended to dominate in activated sludges in N and N&P removal plants i.e. types 0092, 0041, 0675, 1851, 0914 and *Microthrix parvicella*. Four of these six filaments are classified by Jenkins *et al* (1984) as low Food/Micro-organism (low F/M) filaments. At the University of Cape Town and in a 4 year research programme (1986 to 1989) Gabb *et al* (1989a) investigated specific methods to control low F/M filament proliferation. Traditionally the promoted specific bulking control method was inclusion of either an anoxic or aerobic selector at the head of the wastewater treatment plant. Gabb *et al* (1989a) found that selectors did not control low F/M filament proliferation but that continuous aeration did. They concluded that the presence of anoxic and aerobic zones in a treatment plant was an important factor in low F/M filament proliferation.

In 1989 a second research programme was initiated at the University of Cape Town to identify the factors that influence low F/M filament proliferation. Completed research thus far has established *inter alia* that fully anoxic and fully aerobic conditions successfully control low F/M filament proliferation but that alternating anoxic-aerobic conditions in single reactor intermittent aeration systems promoted proliferation. The research presented in this thesis focuses on the interchange between anoxic and aerobic conditions in nitrogen removal systems and its effect on low F/M filament proliferation.

The experimental investigation was divided into two parts: In the first part, two systems, both continuously fed completely mixed 2 reactors in series anoxic-aerobic systems were set up: In the 1st system which conformed to the Modified Ludzack-Ettinger (MLE) system, the anoxic reactor was positioned ahead of the aerobic reactor and received the influent flow; in the 2nd system which conformed to a Wuhrmann system, the aerobic reactor was positioned ahead of the anoxic reactor and received the influent flow. These systems were set up to evaluate the effect of the

- type
- size and
- position

of the anoxic reactor on low F/M filament proliferation with artificial sewage as influent feed.

In the second part of the investigation the above experiments with artificial sewage were repeated with real sewage. Experimental systems operated were the MLE and Wuhrmann systems discussed above and later in the investigation a second MLE system was set up. Additional to investigating the effect of type, size and position of the anoxic reactor on low F/M filament proliferation with real sewage feed, the effect of

- frequency of alternation between anoxic and aerobic conditions and
- sludge MLVSS concentration

on low F/M filament proliferation was examined.

The systems were operated at long sludge ages (15 days) and at 20^{o}C. Large anoxic mass fractions (50 to 70%) were maintained in the experimental systems because it was observed from earlier laboratory investigations (Casey *et al.*, 1990) that low F/M filaments tended to proliferate in systems with large anoxic mass fractions.

From the research conducted in the first part of the investigation it was observed that

(1) Low F/M filaments did not proliferate to severely bulking levels in the MLE and Wuhrmann systems. The DSVI values measured (150 - 200 ml/g) were significantly lower than the DSVI's measured in intermittently aerated systems (> 600 ml/g) also fed artificial sewage (Casey *et al.*,1990), but were considerably higher than the DSVI's measured in fully anoxic or fully aerobic systems (± 80 ml/g) fed artificial sewage (Casey *et al.*, 1990, Ketley *et al.*, 1991).

(2) Throughout the 1st part of the investigation filaments *H.hydrossis* and type 1851 were identified as the dominant filaments in both the MLE and Wuhrmann systems. These same filaments were identified in bulking sludges harvested from intermittently aerated systems fed artificial sewage (Casey *et al.*, 1990, Ketley *et al.*, 1991).

(3) Reducing the anoxic mass fraction of the MLE system from 70 to 54% did not have an appreciable effect on low F/M filament proliferation. Similar anoxic mass fraction reductions in intermittently aerated systems fed artificial sewage showed definite reductions in low F/M filament proliferation (Casey *et al.*, 1990).

(4) Regarding the position of the anoxic reactor, the DSVI of the MLE system was on average 200 ml/g while the average DSVI of the Wuhrmann system was 150 ml/g. From this it can be concluded that positioning the anoxic reactor after the aerobic reactor does to some degree influence and retard low F/M filament proliferation.

(5) Because (i) glutinous material production and accumulation in the sludge caused serious operational difficulties and (ii) the frequent dominance of filament *H.hydrossis* which is not one of the principle 6 low F/M filaments dominant in N and N&P removal plants in SA, it was decided to abandon using artificial sewage and to continue the investigation using real sewage.

From the research conducted in the second part of the investigation, in which the same MLE and Wuhrmann systems and additionally a 2nd MLE system were operated with real sewage as influent feed, it was observed that

(1) Low F/M filament proliferation in the 3 systems as reflected by the DSVI test was generally less than the DSVI of a bulking sludge (150 ml/g) and considerably less than the measured DSVI's of intermittently aerated systems with similar operating parameters. However the DSVI's of the 3 systems were generally greater than the DSVI's measured in fully aerobic or fully anoxic laboratory scale systems fed real sewage (Gabb *et al.*,1989a, Warburton *et al.*,1991, Ketley *et al.*, 1991).

(2) The filament *H.hydrossis* was no longer identified in the 3 systems as the dominant filament, but filament types 0092, 0041 and 021N were. Filament types 0092 and 0041 are 2 of the 6 low F/M filament types observed in bulking sludges of full scale N and N&P removal plants. The occurrence of filament type 021N, found to grow in septic sewages, transpired to be a laboratory artifact, the source of which was subsequently identified as a failure to properly clean the sewage transport container.

(3) Increasing the anoxic mass fraction of the 1st MLE system from 54 to 70% had no significant effect on low F/M filament proliferation with the DSVI remaining around 125 ml/g, however for the Wuhrmann system the same increase in anoxic mass fraction caused a distinct but small increase in low F/M filament proliferation; the DSVI increasing from 100 to 125 ml/g.

(4) Comparing the DSVI's and by implication the low F/M filament proliferation of the MLE and Wuhrmann systems, it was evident that the DSVI of the Wuhrmann system (average of 100 ml/g) was consistently lower than the DSVI of the MLE systems (average of 125 ml/g), irrespective of the anoxic mass fraction. From this it was concluded that positioning the anoxic reactor after the aerobic reactor in 2 reactor anoxic-aerobic systems, does to a certain degree retard low F/M filament proliferation.

(5) Progressively increasing the frequency of anoxic/aerobic alternation from 3,1 to 15,4 per day in both the 1st MLE and Wuhrmann systems had no significant effect on low F/M filament proliferation and DSVI's for the 1st MLE system ranged between 100 and 150 ml/g and for the Wuhrmann system between 80 and 120 ml/g. The DSVI's of both systems showed no correlation with the daily anoxic/aerobic frequency of alternation.

(6) From the operation of the 2nd MLE system, identical to the 1st MLE system in all respects except having a greater process volume and accordingly a lower MLVSS concentration than the 1st MLE system, it was observed that (i) the DSVI's of both systems were similar (for the operation period, the DSVI of both MLE systems was ± 140 ml/g) and (ii) the dominant filament types of both MLE systems were the same. From these observations it can be concluded that the MLVSS concentration, in the range 1400 to 2200 mgVSS/*l*, was not a factor influencing the DSVI and by implication low F/M filament proliferation.

Regarding the investigation in its entirety it is evident from the low F/M filament behaviour of the MLE and Wuhrmann systems fed artificial or real sewage that

(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 1st MLE system from 70 to 54% and back again from 54 to 70% did not significantly effect low F/M filament proliferation
(3) Positioning the anoxic reactor after the aerobic reactor did but only to a small degree decrease the DSVI (200 and 150 ml/g respectively for the 1st MLE and Wuhrmann systems fed artificial sewage and 130 and 100 ml/g respectively for the MLE and Wuhrmann systems fed real sewage).

In the research presented in this thesis, the operational differences between (i) single reactor intermittently aerated systems and (ii) the 2 reactor in series (MLE and Wuhrmann) systems operated in this investigation, are studied in an attempt to identify the factors that cause low F/M filament proliferation. The important differences are:

(1) Aeration pattern. In the single reactor intermittently aerated system the transition from aerated to unaerated conditions and *vice versa* is gradual. In the MLE and Wuhrmann systems, however, the transition from aerated to unaerated conditions and *vice versa* is sudden.
(2) Influent RBCOD and PBCOD discharged to the system. In the single reactor intermittently aerated system all the influent COD is discharged to the reactor, in which anoxic and aerobic conditions alternate. By contrast all the influent COD to the MLE and Wuhrmann systems is discharged to either the anoxic or the aerobic reactor.

From the investigation it was observed that the measured DSVI's of the MLE and Wuhrmann systems were considerably lower than the DSVI's reported from single reactor intermittently aerated systems and it was concluded that the 2 operational differences

discussed above were important factors that may help in future research to identify and isolate the specific causes of low F/M filament bulking.

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CHAPTER 1

INTRODUCTION

Two national surveys (Blackbeard *et al.*, 1986,1988) showed that bulking due to excessive growth of filamentous organisms is a problem of considerable proportions in biological N and N&P removal activated sludge plants in South Africa. In these surveys, which examined about 60 N and 35 N&P removal plants, it was found that about 3/4 of these plants experienced sporadic bulking problems.

The filamentous organisms cause a deterioration in the mixed liquor settleability: They extend from the sludge flocs into the bulk liquid to form weblike structures which cause either the floc structure itself to be diffused or bridges to form between the flocs. From measurements of the total extended filament length (TEFL) and settleability in terms of the diluted sludge volume index (DSVI), Lee *et al.* (1983) showed that at TEFL longer than about 30 km/g, for which the DSVI is greater than 150 m*l*/g, the filamentous organisms commence to dominate the settling behaviour of the sludge. As a rough guide therefore, a bulking sludge can be accepted as one having a DSVI > 150 m*l*/g[1].

Sludge settleability governs the daily flow and load that can be treated in an activated sludge plant; the lower the DSVI the higher the permissible daily flow and load on the plant can be. Operating experience of Northern Works (Johannesburg) clearly demonstrates this (Osborn *et al.*, 1986). Also it can be shown that a plant with a sludge of 100 m*l*/g DSVI can treat a flow and load at least 2 times higher than a plant with a 200 m*l*/g DSVI (Ekama and Marais, 1986a). Clearly, keeping sludge settleability under control at a DSVI of 100 m*l*/g by controlling the proliferation of filamentous organisms, that is bulking, will permit significant increases in sewage flow and load to be treated in existing plants and holds promise of large savings in operation costs. The savings that these advantages would bring is the driving force behind research into developing preventative and remedial methods for controlling activated sludge bulking.

In order to control filamentous bulking one needs to know the types of filamentous organisms causing the problems. From the surveys it was found that sludges in the N and N&P removal plants were dominated[2] by six filamentous organism types. Of the 6, 4 i.e.

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[1] The sludge volume index (SVI) is not as discriminating as the DSVI in identifying a bulking sludge because the SVI is not as consistently related to the TEFL (Lee *et al.*,1983). However, taking note of reported data, one can accept, roughly that an SVI between 100 and 200 m*l*/g is possibly a bulking sludge and an SVI > 200 m*l*/g usually is.

[2] Dominance refers to the most abundant filaments in the mixed liquor. In a bulking sludge there can be up to 3 dominant filaments, all contributing to poor settleability; a non

0092, *M.parvicella*, 0675 and 0041 are classified by Jenkins *et al.* (1984) into a group called low F/M (low Food/Micro organism ratio) which presumably means that these filaments tend to proliferate in low F/M or long sludge age plants. Types 0675 and 0041 also fall into a nutrient deficiency group. Because of the frequency of appearance with the so called low F/M filaments, Blackbeard *et al.* (1986, 1988) have suggested that the remaining two i.e. 0914 and 1851 also be classified into the low F/M group.

The promoted specific bulking control method against low F/M filaments in the literature is biological reactor modification so as to incorporate alternating or sequential feed starve conditions into the system such as (1) intermittent (batch) feeding, (2) multi-reactor or plug flow conditions or (3) completely mixed systems including selector reactors. It has been hypothesized that the mechanism whereby these system modifications apparently promote control over the low F/M filaments is that under the readily biodegradable COD (RBCOD) concentration gradient that these 3 modifications induce, the floc formers have, or develop, a higher rate of RBCOD utilization than the filamentous organisms. This mechanism, called the selector effect, and its influence on filamentous bulking has been investigated and discussed in the literature over the past 15 years. However, its influence on the low F/M filaments has not been clearly delineated. Accordingly, the selector effect and its influence on the low F/M filaments was thoroughly investigated in a 4 year research programme at the University of Cape Town (Gabb *et al.*, 1989a).

From this research programme, which is reviewed in Chapter 2 of this thesis, it was established *inter alia* that the selector effect did not control low F/M filament proliferation but that continuous aeration, i.e. the absence of unaerated conditions, did. Control of bulking in N and N&P removal plants by continuous aeration is clearly counter productive because with it, biological N and P removal are lost. So the finding that the selector effect was unable to control low F/M filament proliferation placed the low F/M filament bulking research back into an exploratory phase. In 1989, a wide ranging research programme was initiated into specific control of low F/M filaments in N and N&P removal plants, the focus of which was to establish *inter alia* the influence of

(1) the influent RBCOD and particulate biodegradable COD,
(2) the magnitude of the unaerated mass fraction, in particular the anoxic mass fraction,
(3) the position of the anoxic zone i.e. as primary or secondary anoxic reactors,
(4) the frequency of alternation between the anoxic and aerobic conditions,
(5) continuous anoxic conditions,
(6) the nitrate/nitrite concentration in the anoxic reactor,
(7) the effect of the dissolved oxygen concentration in the aerobic zone, and

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bulking sludge usually has only one filament the dominant. Filaments that are not dominant are termed secondary.

(8) sludge age

on low F/M filament proliferation.

The research reported in this thesis forms part of this comprehensive research programme and aspects of items (2) to (4) above are investigated, in particular an evaluation of the effect on the low F/M filaments of the

(1) type (i.e. anoxic reactors in compartments separated from the aerobic reactor as distinct from the single reactor/ditch type intermittent aeration anoxic-aerobic system)
(2) size (i.e. the proportion of the total mass of sludge in the anoxic reactor i.e. the anoxic sludge mass fraction)
(3) position (i.e. pre-aerobic or primary anoxic reactor receiving influent sewage or post-aerobic i.e. secondary anoxic reactor not receiving influent).

of the anoxic reactor, and

(4) frequency of alternation between anoxic and aerobic conditions.

In the investigation reported in this thesis, the complicating feature of biological excess P removal promoted by the anaerobic reactor in N&P removal plants is obviated by studying N removal systems only. The influence of the above factors was evaluated on laboratory scale long sludge age two reactor continuously fed anoxic-aerobic N removal systems receiving real and artificial sewage and operated at 20^{o}C.

The layout of this thesis is as follows:

In Chapter 2, a comprehensive literature review is set out so that the objectives of the investigation presented in this thesis can be placed in the context of the current status on specific bulking research for control of the low F/M filaments. In Chapter 3, the experimental investigation is described in detail. In Chapter 4, the conclusions from the experimental work are set out.

CHAPTER 2

LITERATURE REVIEW

2.1 PREAMBLE

A comprehensive literature review into specific bulking control has recently been compiled by Casey *et al.* (1992) 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 also can 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 the 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 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).

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).

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.* (1982) showed that in general, high μH rates have high K_S values and ones with low μH rates have low Ks values. Slijkhuis (1983) measured the μH of *Microthrix parvicella* (one of the principal filaments causing low F/M bulking) to be 1,66/d; this is considerably lower than a μH 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 apparently is oxygen whereas for others, the limiting nutrient is the soluble substrate concentration surrounding the organism, as originally conceived by Chudoba *et al.* (1973a).

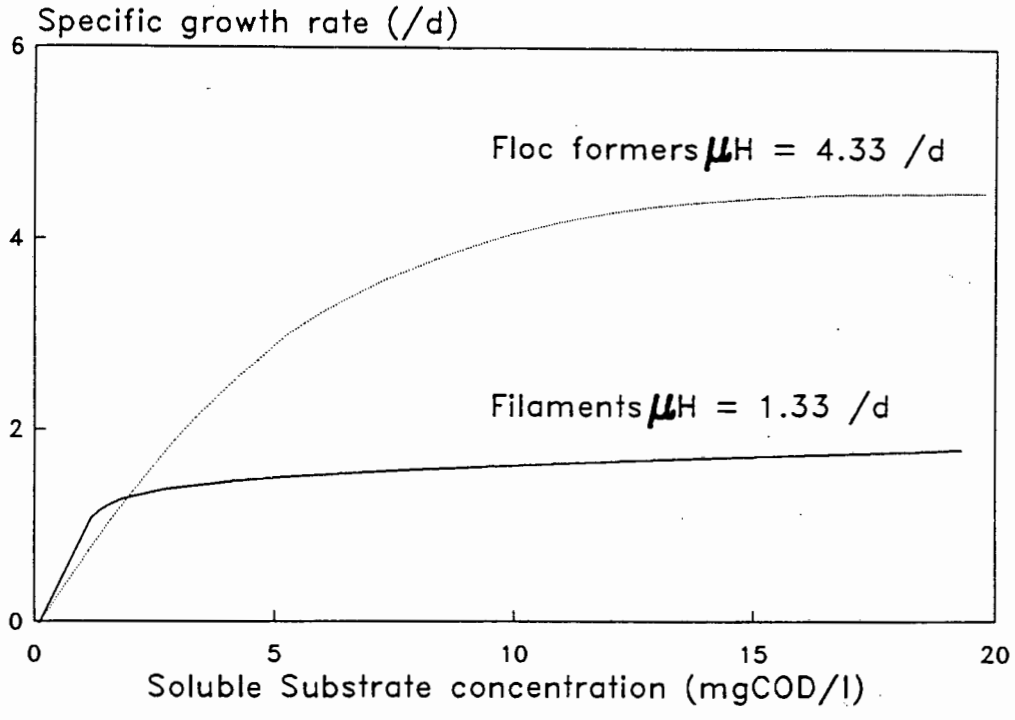


Fig 2.1 Monod specific growth rate functions for *Microthrix parvicella* (filaments) and a floc former isolated from the activated sludge. The selection criterion of Chudoba *et al.* (1973a) is clearly illustrated.

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 substrates: 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 or the main aeration 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 of 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) sludges were 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.*, 1982; Eikelboom, 1982; Rensink *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.

A common characteristic of the three types of systems outlined above is that a soluble COD (<0,μ45m) 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.*, 1982; 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 sewages, 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 (1982,1985) 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.

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. The leakage of soluble biodegradable COD (RBCOD) into the aerobic zone was thought to be the cause for the ineffectiveness of the anoxic 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 m*l*/g) was maintained. In this work on denitrification, the filamentous organisms were not identified so it is difficult to come to any firm conclusions regarding the effect of the different anoxic conditions on the low F/M filaments.

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).

2.4 UNIVERSITY OF CAPE TOWN INVESTIGATION-PHASE 1

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 aeration (3h)/non aeration (1h) periods were imposed on the systems.

The sludge age of all these systems was long (20 days), were fed Mitchell's Plain raw sewage and started up with low F/M filament bulking sludges (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

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 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 (> 20 d) systems by introducing (or eliminating) alternating feed-starve conditions. Acquisition of selector effect by a sludge under alternating feed-starve conditions imposed by the IFFD and CFCM/SEL systems is in agreement with reported results in the literature.

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

   Low F/M filament bulking sludges (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 (> 15 d) 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 incorporated an aerobic selector or the system was intermittently fed or continuously fed, i.e. 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

In the laboratory systems operated by Gabb *et al.* (1989a) the low F/M filaments did not proliferate - indeed the low F/M filament bulking problems in the starter sludge were ameliorated in all the systems operated (see conclusion 2 above). In contrast, in biological N&P removal systems which comprise anaerobic-anoxic-aerobic zones usually in single or multi reactors in series and incorporating appreciable (50%) unaerated sludge mass fractions operated in the laboratory at the time of these experiments, the low F/M filaments did proliferate and cause bulking problems; surprisingly, of the laboratory systems operated at the time (which were those cited above and the N&P removal ones) the N&P removal systems were the only ones wherein the filament populations were similar to their full scale counterparts i.e. low F/M filaments proliferated and there was an absence of *S.natans* and most times *Thiothrix* filaments, even when the feed lines were not regularly cleaned.

From the absence of *S.natans* and *Thiothrix* in N&P removal systems, it was hypothesized that the anaerobic reactor in these systems operates as a selector reactor against *S.natans* (and possibly *Thiothrix*) proliferation. This hypothesis finds support from the laboratory experiments of Wanner *et al.* (1987a,b) who calls this type of selection metabolic selection (as opposed to competitive or kinetic selection in aerobic selectors) which operates as follows: *S.natans* is an obligate aerobic (Mulder and Deinema, 1981); in the anoxic reactor, the RBCOD is utilized by denitrifiers; in the anaerobic reactor, RBCOD is converted to volatile fatty acids (VFA) which together with the VFA from the influent, is taken up by polyphosphate accumulating organisms such as *Acinetobacter spp.* (Wentzel *et al.*, 1985). Consequently with anaerobic and/or 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-formers 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, 1985, van Niekerk *et al*, 1987).

From the above discussion it can be seen that with respect to the filaments *S.natans*, *Thiothrix* and 021N there is consistency of behaviour in 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 and 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 the low F/M filaments 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.

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 (20 d) 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 16 h, and finally settling for 2 h. The other intermittently fed system, and continuously fed system, were maintained fully aerobic for 24 h. In the two fully aerobic systems, the DSVI declined steadily from a start up value of around 200 m*l*/g to below 60 m*l*/g over a period of 2 to 3 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 m*l*/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 6 h 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 which 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 conclusion 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.

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 10 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 with a concomitant reduction in low F/M filaments over less than a sludge age; switching back to intermittent aeration caused slow regrowth 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.

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 Zoogleae 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.

2.5 CONCLUSIONS FROM THE PHASE 1 INVESTIGATION

1. 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 competitive 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. From this 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. 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, is exposed to purely aerobic conditions by continuous aeration, the low F/M filament bulking is ameliorated and sludge settleability improved (DSVI < 80 m*l*/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. At present such an environmental condition is not known.

3. 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 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.

2.6 RECOMMENDATIONS FOR PHASE 2 RESEARCH

A number of questions emerge from the investigation and conclusions of Gabb *et al.* (1989a) discussed above, which serve as a useful guide for further research into specific control of 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 hydrolyze 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 reaction 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 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 or 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 modified UCT 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 or 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 for nitrification while the suspended sludge has a sludge age sufficiently short to suppress low F/M filament proliferation.

2.7 UNIVERSITY OF CAPE TOWN INVESTIGATION - PHASE 2

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 2 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.

(1) The development of an artificial sewage feed supporting low F/M filament growth by Gabb *et al.*(1989a)(but not reported by them – see Gabb, 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 the 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 the artificial sewage. From this information and measured principal constituents of Mitchell's Plain raw sewage (COD, Organic N, NH_4^+, 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 two experimental laboratory systems were operated receiving the artificial sewage, both with control systems receiving Mitchell's Plain raw sewage. It was found that an unaerated - aerated (6 hrs unaerated, 16 hrs aeration, 2 hrs settling) intermittently fed fill and draw (IFFD) system receiving artificial sewage feed promoted the abundant growth of the following filaments; types 0092, 0914, 0041, 0675, 0803, *Haliscomenobacter hydrossis* and *Nostocoida limicola II*. In the surveys of Blackbeard *et al.* (1986,1988), all of these filaments had been observed in bulking sludges 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) The work of Casey *et al.* (1990) with the 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. During these experiments in which continuously fed long sludge age single completely mixed reactor intermittent aeration (2 min on, 20 min off) systems were operated, it was found that the fats and oils (part of the PBCOD component), thought to be important for the growth of low F/M filament *M.parvicella* (Slijkhuis, 1983), did not cause *M.parvicella* to grow in the systems and had no observable effect on the filament populations which developed in the systems. Consequently Casey *et al.* (1990) removed the fats and oils from the artificial sewage constituents used in the remainder of the investigation. To compensate for the COD removed by the exclusion of the fats and oils the PBCOD concentration of the artificial sewage was increased. The constituents of the final artificial sewage fed to the systems operated in the investigation reported in this thesis is given in Appendix A.

Observations made by Casey *et al.* (1990) in the intermittently aerated single completely mixed reactor systems receiving the artificial sewage feed were

(1) Low F/M filaments, in particular *H.hydrossis* and 1851 but also 0092, 0041 and 0675, proliferated to exceptionally high DSVI's (>600 m*l*/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 m*l*/g to 150 m*l*/g) and a reduction in the growth of low F/M filaments, specifically *H.hydrossis*.

(6) 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 m*l*/g to 83 m*l*/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 bulking sludges 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 conclusion was arrived at by Gabb (1988).

(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 m*l*/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 m*l*/g down to 120-150 m*l*/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 m*l*/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 m*l*/g was continuous aeration.

(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 SCOPE OF THIS THESIS

In the phase 2 research programme outlined above, only single reactor intermittently aerated anoxic aerobic systems were operated, no separately compartmentalized anoxic aerobic systems. The research presented in this thesis examines the response of the low F/M filaments in anoxic-aerobic systems of a different type to single reactor intermittent aeration systems - i.e. systems with anoxic and aerobic reactors in separate compartments with inter-reactor recycle streams to expose the sludge to alternating anoxic and aerobic conditions.

As in earlier investigations, because all the indications point to the low F/M filament bulking problem lying in the continual interchange of the sludge between anoxic and aerobic reactors, the complicating feature of biological excess P removal on the bulking problem was obviated by not incorporating an anaerobic reactor into the laboratory systems. Consequently only simple 2 reactor in series anoxic-aerobic Modified Ludzack-Ettinger (MLE) (pre-denitrification) and Wuhrmann (post-denitrification) systems were operated. Both system types were operated at long sludge ages (15 days) and 20°C.

The experimental investigation presented in this thesis on the MLE and Wuhrmann N removal systems is divided into 2 parts;

(1) systems fed artificial sewage and
(2) systems fed real sewage

The research done in the 1st part of the investigation evaluated 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 Ditch type anoxic-aerobic reactor,
(2) the size of the anoxic mass fraction and
(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) or as a secondary anoxic reactor receiving effluent from the aerobic reactor (post-denitrification).

Research done in the 2nd part of the investigation repeated the objectives set-out in the 1st part of the investigation and additionally evaluated the effect of

(1) the frequency of anoxic-aerobic alternation per day and
(2) the system MLVSS concentration

on low F/M filament proliferation.

In the next chapter the experimental investigation and results of the above research are described.

CHAPTER THREE

EXPERIMENTAL INVESTIGATION

3.1 THE NATURE OF THE ANOXIC-AEROBIC INTERCHANGE IN N AND N&P REMOVAL SYSTEMS

Experimental evidence discussed in the literature review showed that the exposure of the sludge to alternating anoxic and aerobic conditions is a major contributing factor to the proliferation of the low F/M filaments: These filaments were suppressed under both fully aerobic conditions (Gabb *et al.*,1989a, Warburton *et al.*,1991) and fully anoxic conditions (Ketley *et al.*,1991) in systems fed real or artificial sewage.

Close scrutiny of the dominant filaments identified in various types of N and N&P removal systems reveal that these differ in different types of system; e.g. filament type 0092 is repeatedly dominant in MUCT systems, while *M.parvicella* is repeatedly dominant in single reactor completely mixed intermittently aerated systems, both fed real sewage. With artificial sewage fed to the intermittent aerated systems the dominant filament was *H.hydrossis* while in some MUCT systems fed artificial sewage, low F/M filaments could not be induced to proliferate. It is hypothesized that the observed differences in dominant filament type is due to the differences in the nature of the various types of anoxic zones. These different types of anoxic zone are discussed below.

3.1.1 MUCT N&P removal system

In this system (see Fig.3.1.a) the anoxic zone is compartmentilized into individual reactors in series immediately after the anaerobic zone. The anaerobic zone is designed in such a way that practically all the influent RBCOD is removed and therefore only influent PBCOD and PBCOD generated internally by the sludge via organism death and lysis (comparable to endogenous respiration, see Dold *et al.*, 1980, Van Haandel *et al.*, 1981) is discharged to the anoxic zone. At any time only a fraction of the sludge population resides in the anoxic zone. When the sludge is discharged to the anoxic zone from either the anaerobic or the aerobic zone, a sudden environmental change is experienced by the organisms. Sludge discharged to the anoxic zone from the aerobic zone, which has a high redox potential, has to adjust to a zone of lower redox potential, while sludge coming from the anaerobic zone, which has a very low redox potential, has to adjust to an environment of higher redox potential. A sudden reverse change in redox potential takes place when the sludge leaves the anoxic zone and enters the anaerobic and aerobic zones.

3.1.2 Completely mixed intermittently aerated N removal system

In this system (see Fig.3.1.b) both the influent RBCOD and PBCOD fractions are continually fed to the entire sludge population throughout the aerobic and anoxic periods.

The aeration pattern is maintained by intermittently sparging air into the mixed liquor to raise the dissolved oxygen (DO) concentration to a preset level (usually 2 mgO/*l*); thereafter sparging ceases and the DO progressively decreases through biological oxygen utilization. When the DO drops to zero mgO/*l* aerobic conditions terminate and anoxic conditions commence and nitrate, nitrified during the aerobic period, is denitrified due to it serving as the terminal electron acceptor for substrate utilization. The transition from aerobic to anoxic conditions is progressive and a prolonged period (several minutes) of low DO (< 0,2 mgO/*l*) exists in the mixed liquor. When the conditions again become aerobic i.e. when air sparging recommences, a period of low DO also exists although this transition is of much shorter duration than the reverse.

In the above discussion, the differences in the transition from anoxic to aerobic conditions and *vice versa* of multi-reactor N&P and single reactor intermittently aerated N removal systems are outlined. As a starting point for this investigation it was hypothesized that the differences in low F/M filament population structure arise from these differences. Should there be substance to this hypothesis, then if different types of anoxic zones are incorporated in activated sludge systems, then different low F/M filaments may dominate the activated sludge in these systems. In order to explore this avenue and gather more information on the effect of the different alternating anoxic-aerobic conditions, two other types of anoxic zone are investigated in this thesis. These are the anoxic zones in (1) the Modified Ludzack-Ettinger (MLE) (after Barnard 1973,1975) (see Fig.3.1.c) and (2) the Wuhrmann (1964) (see Fig.3.1.d). Both these systems are nitrification/denitrification systems i.e. only anoxic/aerobic and do not incorporate biological phosphorous (P) removal. Unlike the single reactor intermittent aeration N removal system, but similar to the MUCT N&P removal system, the anoxic and aerobic reactors of the MLE and Wuhrmann systems are separated completely mixed reactors. The characteristics of the anoxic-aerobic conditions of these two systems are described below.

3.1.3 Modified Ludzack-Ettinger (MLE) N removal system

In this system (see Fig.3.1.c) the anoxic reactor precedes the aerobic reactor (called predenitrification in a primary anoxic reactor). Both the RBCOD and PBCOD fractions of the influent sewage are continually fed to the sludge fraction residing in the anoxic reactor. No influent feed is discharged to the aerobic reactor and the feed to this reactor is the effluent from the anoxic reactor. As the anoxic reactor is large enough to remove all the influent RBCOD, only influent PBCOD and PBCOD generated internally by the sludge via organism death and lysis, is available to the organisms in the aerobic reactor. The sludge discharged to the aerobic reactor from the anoxic reactor via the underflow and mixed liquor recycles experiences a sudden drop in redox potential. This quick change in redox implies that no extended low DO concentration zones exist in the MLE system. The frequency of

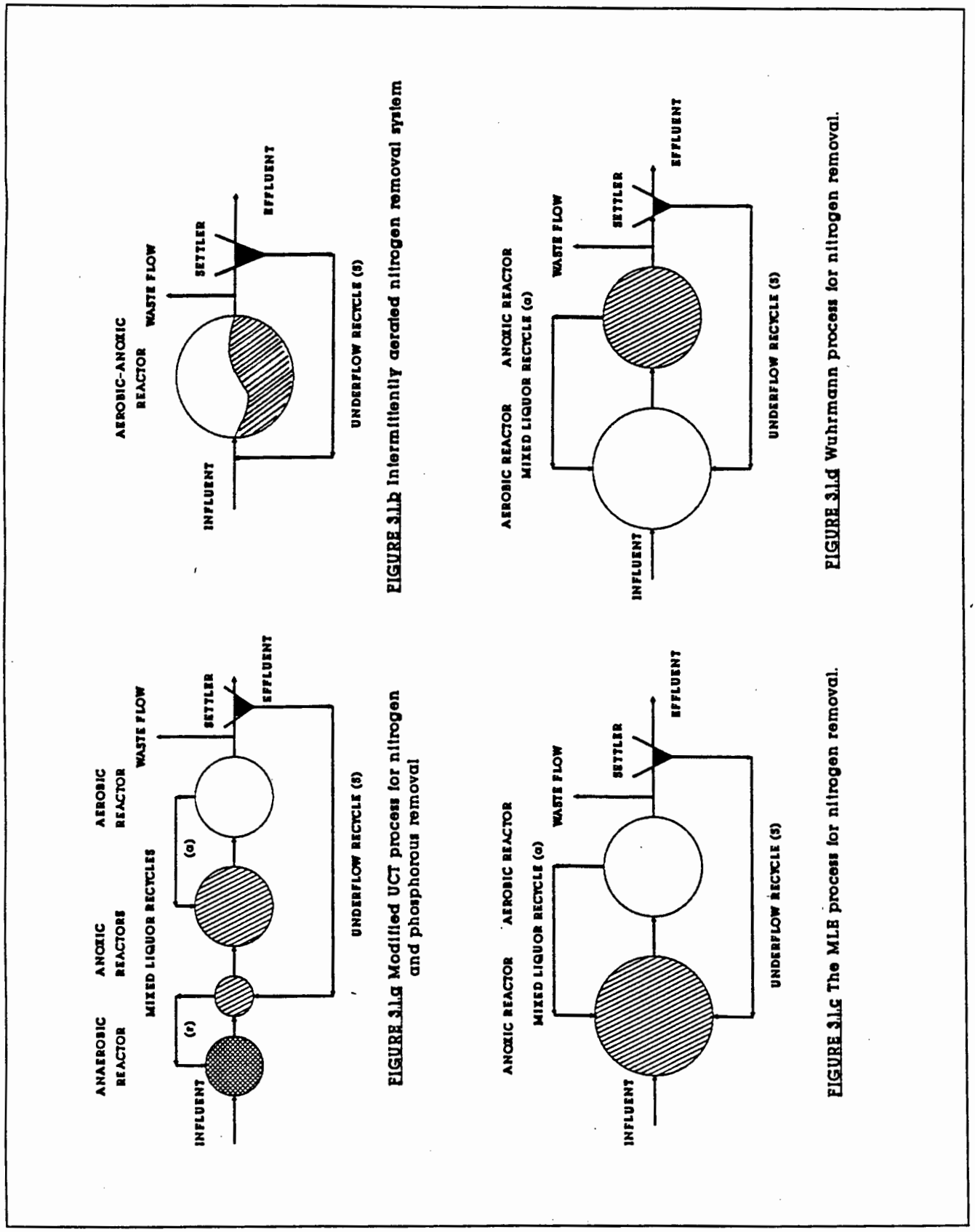


FIGURE 3.1a Modified UCT process for nitrogen and phosphorous removal

FIGURE 3.1b Intermittently aerated nitrogen removal system

FIGURE 3.1c The MLE process for nitrogen removal.

FIGURE 3.1d Wuhrmann process for nitrogen removal.

Figure 3.1 Schematic diagrams of the MUCT, intermittently aerated, MLE and Wuhrmann systems.

alternation between anoxic and aerobic reactors is controlled by the mixed liquor and underflow recycle ratios.

3.1.4 Wuhrmann N removal system

In this system (see Fig.3.1.d) the anoxic zone follows the aerobic reactor (called post denitrification in a secondary anoxic reactor) and the influent RBCOD and PBCOD is discharged to the aerobic reactor only. Because the influent sewage is fed to the aerobic reactor, where the biological degradation rates are 2 to 3 times higher than in anoxic reactors (van Haandel *et al.*,1981), all the influent RBCOD and most of the influent PBCOD is utilized in the aerobic zone. Therefore the only substrate available to the organisms in the anoxic zone is that self-generated internally by the organisms' death and lysis. Like in the MLE system, as the sludge flows between the anoxic and aerobic zones the redox changes are sudden.

From the above discussion it can be seen that the principle difference in the anoxic zones of the MLE and Wuhrmann systems is the substrate for denitrification - in the former it is principally the influent RBCOD and PBCOD and in the latter it is principally PBCOD generated by organism death and lysis. Comparing the anoxic zone of the MLE and Wuhrmann systems with that of the MUCT/UCT N&P removal systems, it is evident that influent to the anoxic zone of the MUCT/UCT systems is not the same as that to the anoxic zones of the MLE or Wuhrmann; in the MUCT/UCT system this is principally the influent PBCOD and the PBCOD self-generated internally by organism death and lysis (because the influent RBCOD is virtually completely removed in the preceding anaerobic reactor); in the MLE this is both influent RBCOD, PBCOD and self generated PBCOD and in the Wuhrmann this is only self-generated PBCOD. However the anoxic zones of the Wuhrmann, MLE and MUCT/UCT systems are similar in that the transition from one zone to the other is sudden. In this regard the anoxic zones of these three systems are different to that of the completely mixed intermittently aerated systems, where the transition from aerobic to anoxic conditions and *vice versa* is gradual due to the progressive reduction in DO concentration as the system moves from aerobic to anoxic or anoxic to aerobic conditions.

There is one further difference that needs to be considered when comparing the anoxic zones of the 4 systems mentioned above, that is the frequency of alternation between anoxic and aerobic conditions to which the sludge is exposed in the system. In the intermittent aeration system, this frequency is the number of aeration cycles in a day i.e. if the aeration cycle is 1 minute aeration in every 20, then the sludge is exposed to 72 changes from aerobic to anoxic and concomitantly 72 changes from anoxic to aerobic conditions per day. In the MUCT/UCT, MLE and Wuhrmann systems, the frequency of alternation is a function of the underflow and mixed liquor recycles in the system. Research on frequency of alternation

between anoxic and aerobic conditions in intermittently aeration systems fed real sewage has shown that reducing this frequency, from 48/d to 1 in 3 days, does not ameliorate low F/M filament bulking (Ketley *et al.*,1991). The effect of the frequency of alternation between anoxic and aerobic conditions on low F/M filament growth in the MLE and Wuhrmann systems is evaluated in this investigation but from Ketley's work it is expected that this will not have a significant effect on low F/M filament growth.

From the above discussion it is clear that the interchange between anoxic and aerobic conditions in various types of N&P and N removal systems differ in the following ways

(1) the proportions of the influent RBCOD and PBCOD that is discharged to the anoxic zone
(2) rapidity of transition from aerobic to anoxic conditions and *vice versa* and
(3) the frequency of alternation between anoxic and aerobic conditions.

In the first part of the research presented in this thesis, the effect of the anoxic-aerobic interchange between separate anoxic and aerobic reactors on low F/M filament proliferation in MLE and Wuhrmann systems fed artificial sewage is examined; in the second part the same experiments are repeated with systems fed real sewage and additionally the effect of frequency of alternation between anoxic and aerobic conditions is examined.

3.2 EXPERIMENTAL INVESTIGATION PART 1: OBSERVATION OF LOW F/M FILAMENT PROLIFERATION IN MLE AND WUHRMANN SYSTEMS FED ARTIFICIAL SEWAGE.

In this part of the investigation two systems were set up: A Modified Ludzack-Ettinger, MLE (see Fig.3.1.c) and a Wuhrmann system (see Fig.3.1.d) Initially, only the MLE system was operated and the initial design and operating features of this system are given in Table 3.1.a. The anoxic mass fraction was selected large because, previous research with intermittently aerated systems fed artificial sewage has shown that large anoxic mass fractions (50-70%) promote low F/M filament proliferation. The artificial sewage fed to the MLE system was identical to that fed to the intermittently aerated systems discussed in the literature review and its composition is summarized in Table 3.2 and detailed in Appendix A.

The MLE system was operated for 259 days. Daily, during this period the following parameters were measured and plotted graphically.

1 Influent and unfiltered effluent COD (see Fig.3.2)
2 Influent and unfiltered effluent TKN (see Fig.3.3)
3 Total and volatile mixed liquor suspended solids, MLSS and MLVSS concentration (see Fig.3.4)
4 Sludge settleability, DSVI (see Fig.3.5)

Table 3.1.a: Operating parameters of MLE system days 1 to 259

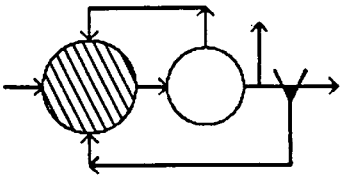
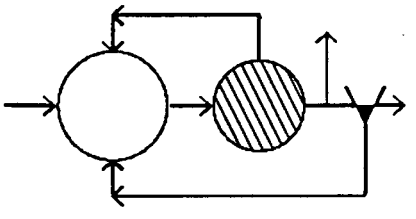
System Conditions		Operating parameters
Operating conditions		continuously fed, 2 reactors in series both completely mixed
Graphical representation		
Aeration		Reactor 1 Anoxic Reactor 2 Aerobic
		Reactor 1 / Reactor 2
Volumes (l)	Days 1 to 27	4.5 / 2.0
	Days 28 to 259	3.5 / 3.0
Unaerated mass fraction (%)		
	Days 1 to 27	70
	Days 28 to 259	55
(a) recycle ratio		0:1
(s) recycle ratio		1:1
System hydraulic retention time (hours)		15.6
Sewage		Artificial
Volume of feed (l/d)		10
Concentration of feed (mgCOD/l)		600
Influent TKN (mgN/l)		50 – 70
Sludge age (days)		15
Temperature (degrees ^{o}C)		20
MLVSS concentration (mgVSS/l)		1800
pH		7,4 – 8,0

Table 3.1.b: Operating parameters of Wuhrmann system days 219 to 259

System Conditions	Operating parameters
Operating conditions	continuously fed, 2 reactors in series both completely mixed
Graphical representation	
Aeration	Reactor 1 Aerobic Reactor 2 Anoxic
Volumes (l)	Reactor 1 3.0 Reactor 2 3.5
Unaerated mass fraction (%)	55
(a) recycle ratio (s) recycle ratio	0:1 1:1
System hydraulic retention time (hours)	15.6
Sewage	Artificial
Volume of feed (l/d)	10
Concentration of feed (mgCOD/l) Influent TKN (mgN/l)	600 50 – 70
Sludge age (days)	15
Temperature (degrees°C) MLVSS concentration (mgVSS/l) pH	20 1800 7.4 – 8.0

5 Filtered effluent nitrate + nitrite concentration (see Fig.3.6)
6 Filtered (0.45μm) anoxic and aerobic nitrate + nitrate concentration (see Fig.3.7)
7 Oxygen utilization rate in the aerobic reactor (see Fig.3.8)

The COD/VSS ratio (f_{cv}) and TKN/VSS ratio (f_n) of the sludge VSS in the aerobic reactor was measured regularly the former 102 times and the latter 54 times during the 259 day period.

The methods whereby these parameters were measured are detailed in Appendix B and all the measured data are listed in Appendix D.

Table 3.2: Ingredients of artificial sewage comprising proportions of RBCOD and PBCOD fed to the MLE and Wuhrmann systems during the 1st part of the investigation i.e. days 1 to 252. Values given in the Table are ml per 10*l*. (for details - see Appendix A)

	Final concentrations in feed			
	mg/*l*	mgCOD/*l*	mgN/*l*	
Vitamins	7.68			30
Micro Inorganic Nutrients	9.25	10		30
S_{bsi}		60		200
Additional Micro Nutrients	0.26			50
Organic Nitrogen		85	22	140
Macro Inorganic Nutrients	532.1	70	38	170
Complex Carbohydrates		375		350
Tap water				9250
TOTAL TKN			60	
TOTAL COD		600		

During the 259 days of operation a number of changes were made to the design and operating features of the MLE system. The days on which these changes were made and the reasons for the changes are given in Table 3.3. Two important changes were made to the MLE system during the 259 day period viz (1) on day 27 the unaerated anoxic sludge mass fraction was reduced from 70% to 55% by increasing the volume of the aerobic reactor at the expense of the anoxic reactor i.e. total system volume remained unchanged. This was done to see whether any decrease in low F/M filament population could be effected by decreasing the the anoxic mass fraction and (2) on day 252 the PBCOD component of the influent artificial sewage was removed and replaced with RBCOD so that from day 252 the influent comprised only RBCOD.

On day 182 a second system was started up. The purpose of this system was to investigate the effect of the position of the anoxic reactor in the configuration, and therefore this system was operated as a Wuhrmann system (see Fig.3.1.d) the low F/M filament behaviour of which could be compared with the behaviour of the MLE system already in operation.

Table 3.3: Operational and configurational changes made to the MLE and Wuhrmann systems during the 1st part of the investigation.

Day	System	Change	Reason
1	MLE	Start up with bulking sludge harvested from intermittent aeration system. Sludge age = 15 days and 70% anoxic mass fraction. Dosed 50 mg nitrate per liter influent to anoxic reactor	Intiate investigation into effect of low F/M filament growth in MLE systems fed artificial sewage.
25		Reduced nitrate dosage to anoxic reactor from 50 to 25 mgN per litre influent	Effluent nitrate concentrations high (> 50 mgN/*l*).
27	1st MLE	Decreased anoxic volume to 3,5 *l* and increased aerobic volume to 3,0 *l*.	To decrease anoxic mass fraction from 70 to 55%
39	1st MLE	Reduced nitrate dosage to anoxic reactor from 25 to 20 mgN per litre influent.	20 mgN more convenient to pipette than 25 mgN.
143	1st MLE	Increased nitrate dosage to anoxic reactor from 20 to 40 mgN per litre influent.	To avoid nitrate depletion in the anoxic reactor.
148	1st MLE	Added 2nd clarifier in series with 1st clarifier	Attempt to contain rising sludge in clarifier.
161	1st MLE	Removed 2nd clarifier.	2nd clarifier did not contain rising sludge.
163	1st MLE	Reduced nitrate dosage to anoxic reactor from 40 to 20 mgN per litre influent.	To stop rising sludge in the clarifier caused by denitrification of high NO_3 effluent concentrations.
171	1st MLE	Raised stirrer blade in anoxic reactor to 1mm below surface level.	Break up scum formation on surface of anoxic reactor.
182	2nd MLE	Set up 2nd MLE system with same design and operating parameters as 1st MLE system.	Compare kinetic and low F/M filament behaviour between 2 MLE systems.
219	Wuhrmann	Interchanged anoxic and aerobic reactors of 2nd MLE system, but retaining same reactor volumes.	Change 2nd MLE system to Wuhrmann configuration.

Table 3.3: continued

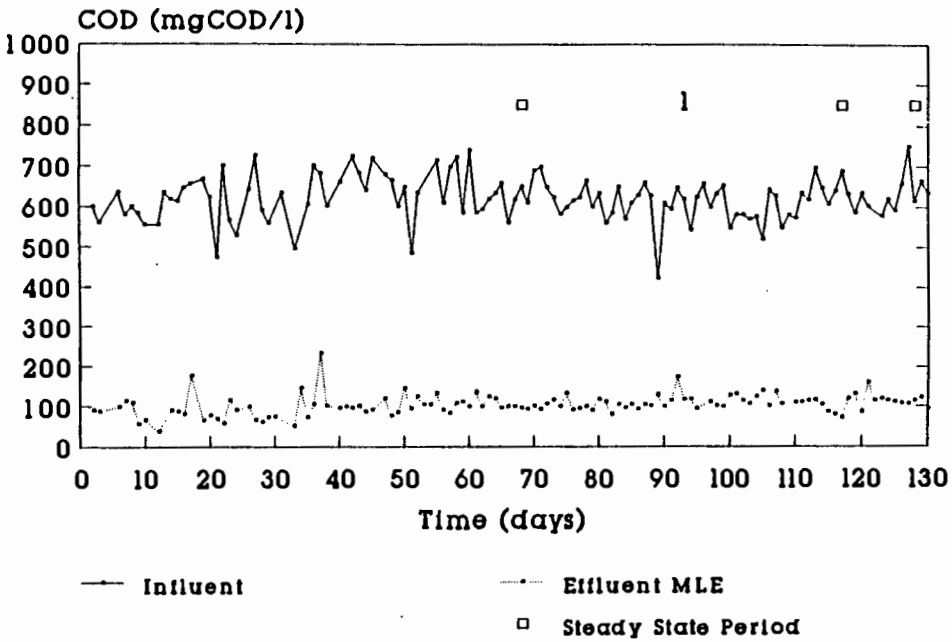
Day	System	Change	Reason
253	1st MLE Wuhrmann	Removed PBCOD component of influent artificial sewage leaving only RBCOD influent.	Attempt to decrease glutinous production and accumulation in sludge.
259	1st MLE Wuhrmann	Commenced feeding real sewage.	Terminated artificial sewage experiments.

Initially (day 182 to 218) this second system was started up as an MLE system identical to the first MLE system (see Table 3.1.a for design and operating parameters). This was done in order to ensure that the start up conditions for the Wuhrmann would be the same as the MLE, in particular, regarding the low F/M filament populations. When the DSVI and filament population in the second system was similar to the first, which was found to be the case after 37 days after start up i.e. on day 219, the second system was changed to the Wuhrmann configuration by interchanging only the position (not the sizes) of the anoxic and aerobic reactors. The design and operating parameters of the second system operating as a Wuhrmann system (day 219-259) are given in Table 3.1.b.

From day 219 to 259 the Wuhrmann system was operated in parallel to the first MLE system. During this period, the operational changes made to the MLE system were also made to the Wuhrmann system. These changes are listed for the MLE and Wuhrmann systems in Table 3.3. above. Also the same parameters that were measured for the first MLE system were measured for the second system both initially as an MLE and subsequently as a Wuhrmann system. The results are plotted on the same graphs as those already presented for the first MLE system except that because operation of the second system commenced on day 182, the plotted data also commenced on day 182 (see Fig.3.2 to 3.8). All the data obtained from the second system are listed in Appendix D.

3.2.1 Mass balances

In order to test the validity of the measured data nitrogenous material (N) and carbonaceous material (COD) balances were performed on the systems. These balances operate on the principle that the N and COD which goes into the system should be accounted for by the N and COD that leaves the system. When more than 90% of the influent N and COD mass can be accounted for in the N and COD leaving the system then good N and COD mass balances



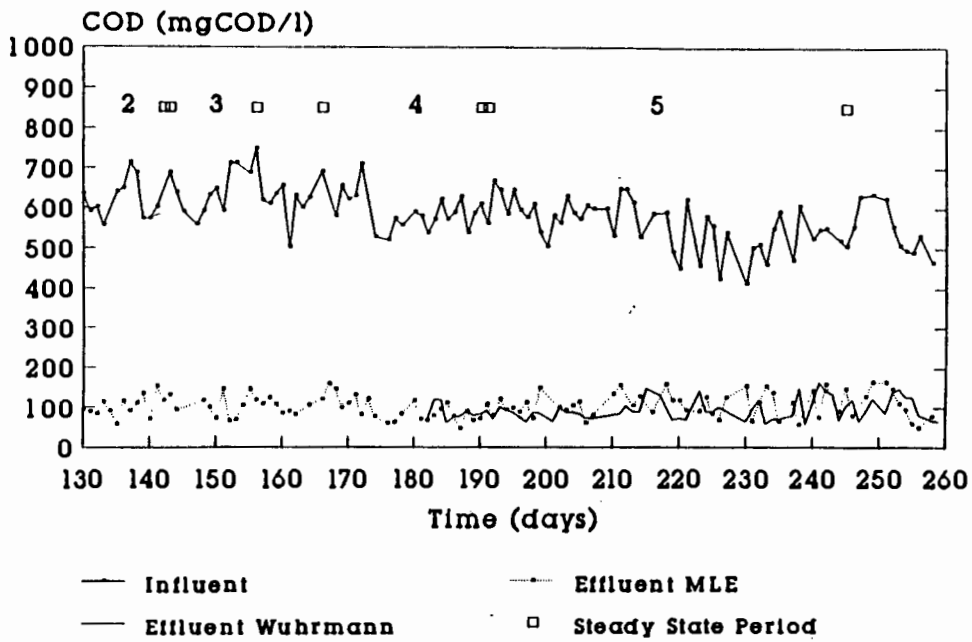
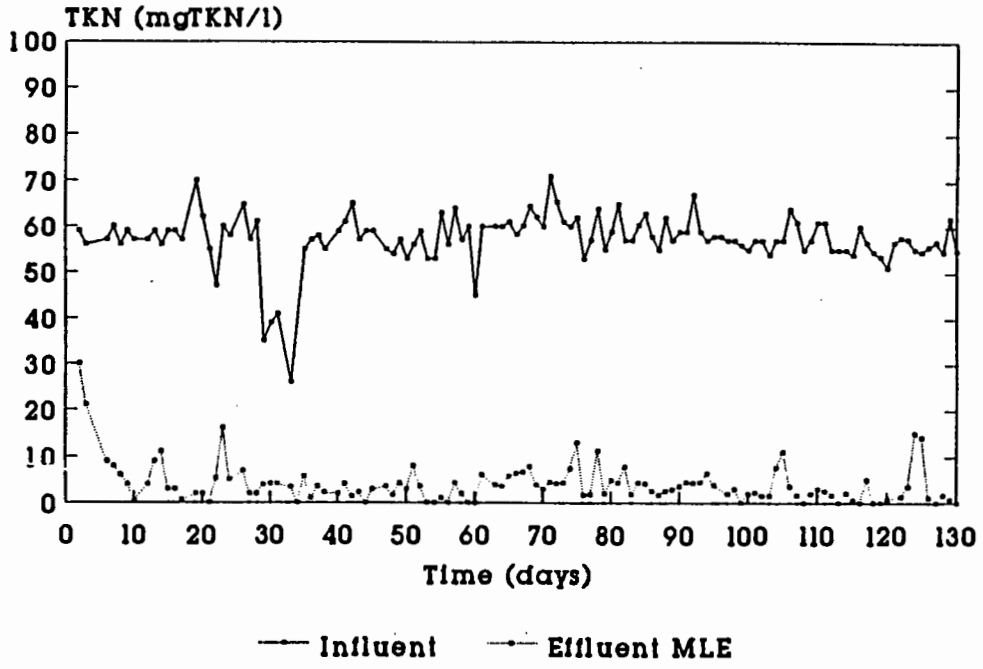


Fig 3.2 Daily influent and effluent COD concentrations measured for the MLE and Wuhrmann systems during the 1st part of the investigation (days 1 to 259).



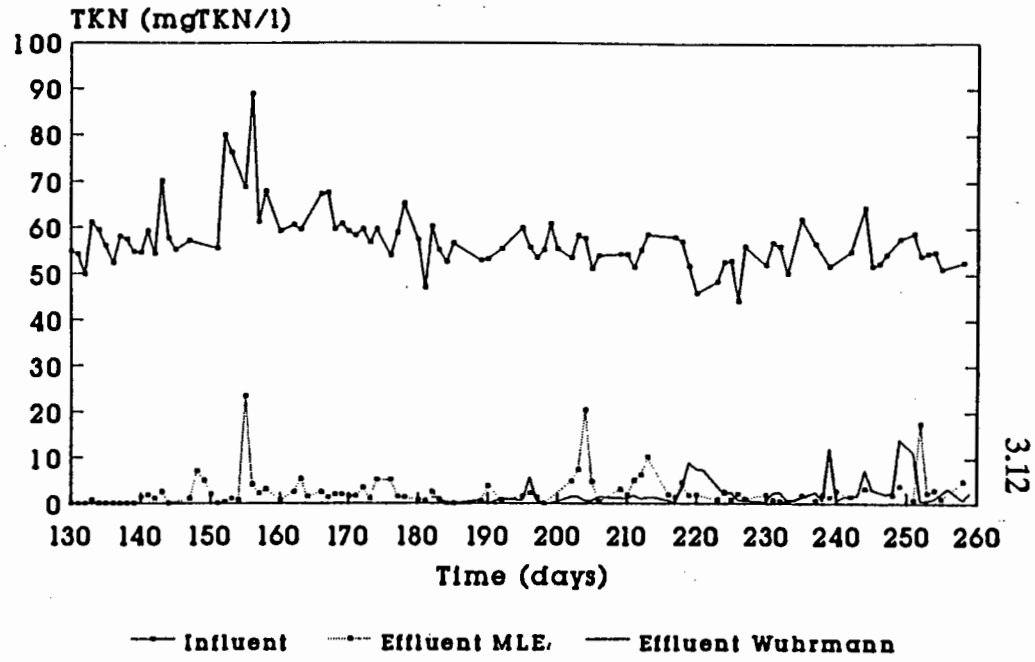
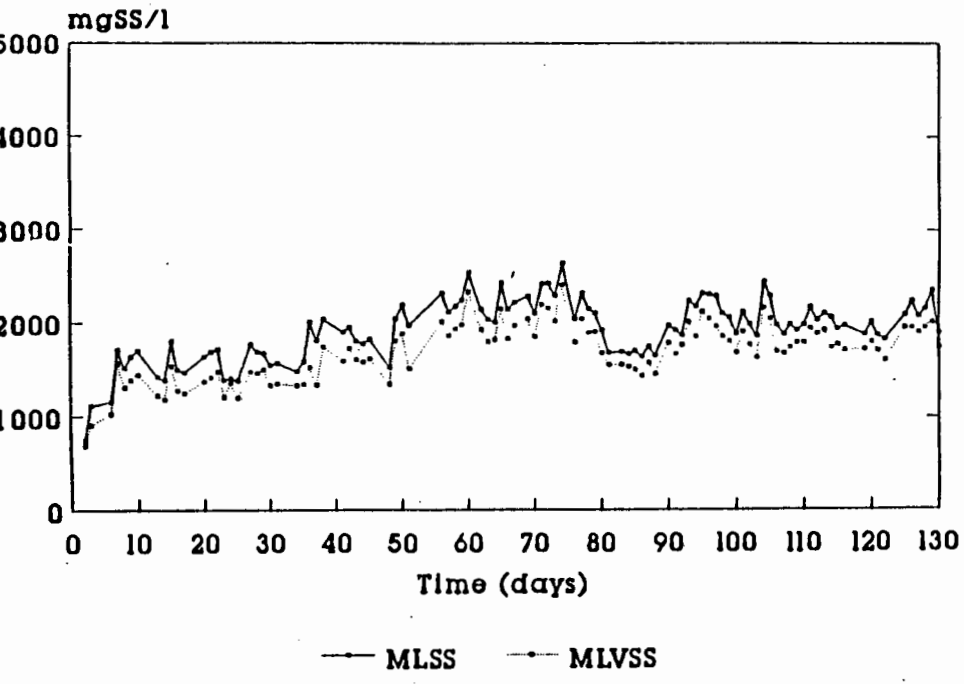


Fig 3.3 Daily influent and effluent TKN concentrations measured for the MLE and Wuhrmann systems during the 1st part of the investigation (days 1 to 259).



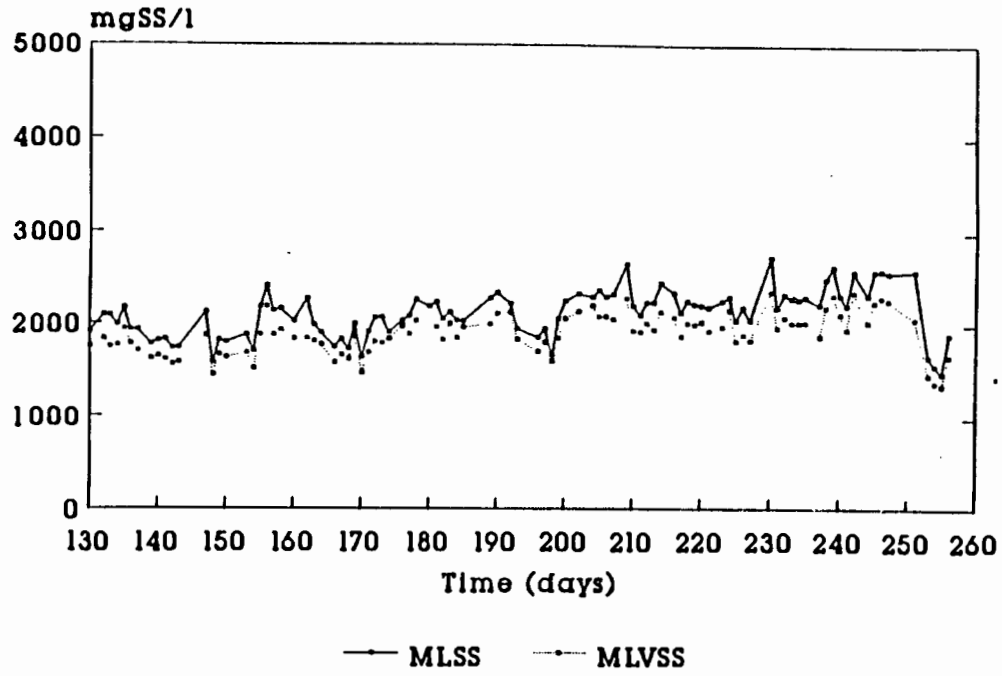


Fig 3.4.a Daily total and volatile mixed liquor suspended solids concentrations measured for the MLE system during the 1st part of the investigation (days 1 to 259).

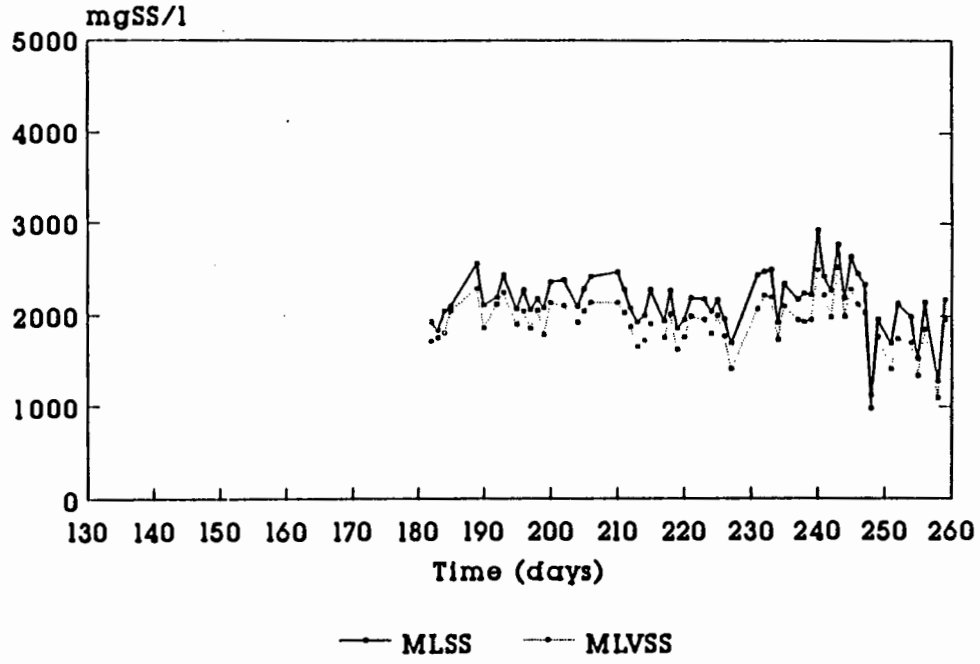
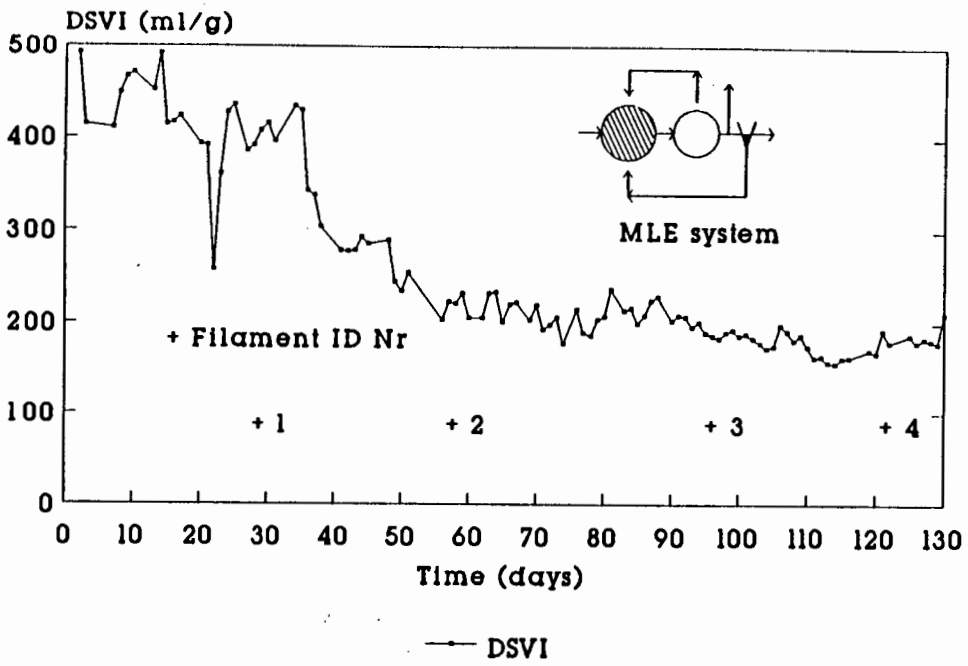


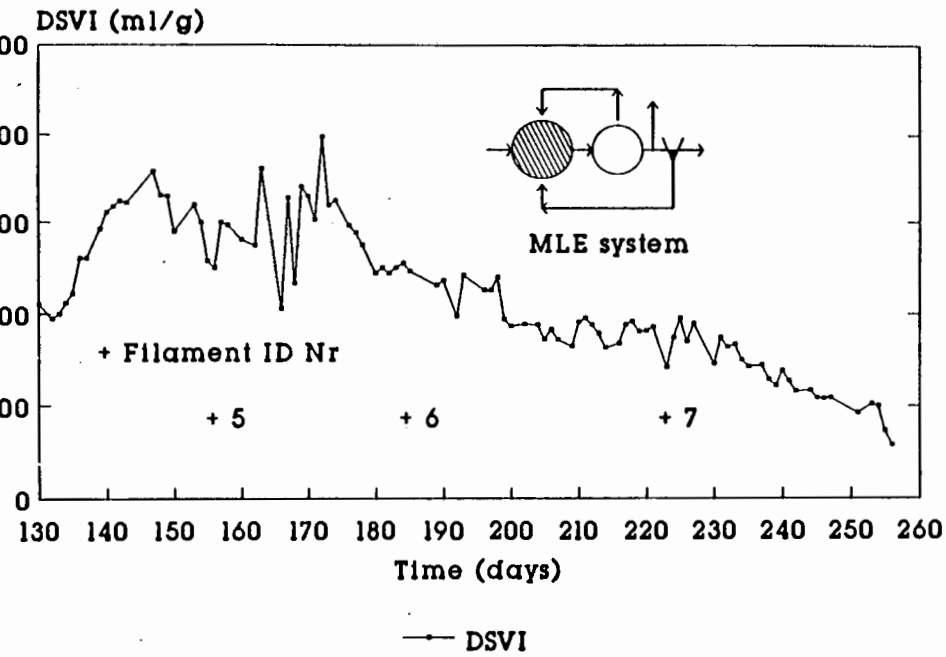
Fig 3.4.b Daily total and volatile mixed liquor suspended solids concentrations measured for the 2nd system initially as an MLE system (days 182 - 218) and later as a Wuhrmann system (days 219- 259) during the 1st part of the investigation.



FILAMENT IDENTIFICATION
SYSTEM 1

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
1	28	1851	*H.hydrossis*	0092	common to very common
2	57	1851	*H.hydrossis*	0803, 0041, *Flexibacter*	very common to abundant
3	94	*H.hydrossis*	0041	*N.limicola II* 0092, 1851	very common to abundant
4	125	1851	*H.hydrossis*	0041, 0092	very common

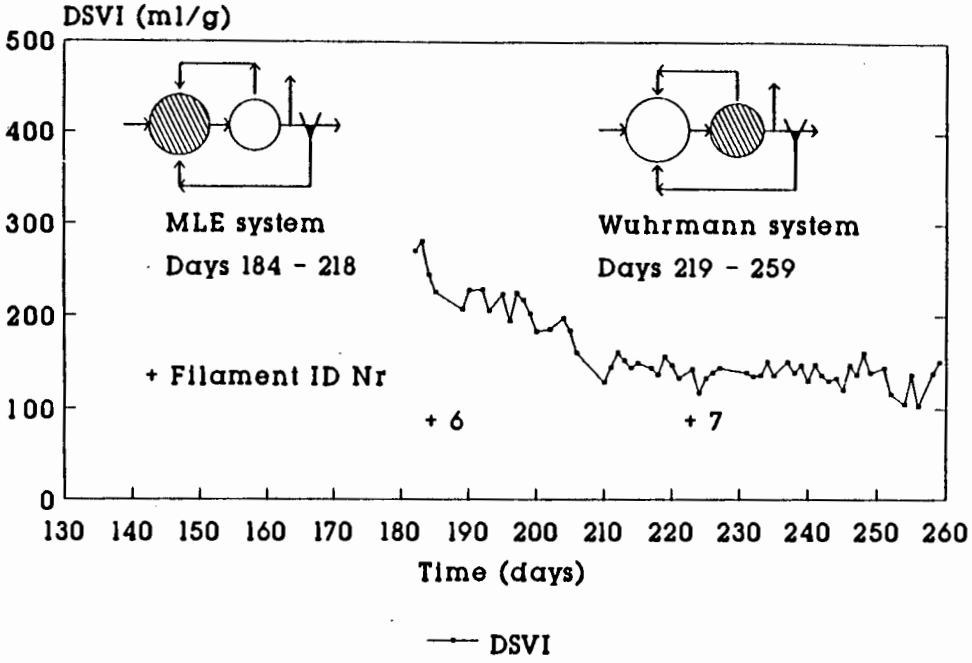
Fig 3.5.a Daily DSVI measured for the MLE system during the 1st part of the investigation (days 1 to 130). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION
SYSTEM 1

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
5	155	*H.hydrossis*	0803	*Thiothrix*, 0041, 0092	very common
6	184	*H.hydrossis*	1851	0803, 0041, 0092, *Nocardia*	abundant
7	223	1851	*H.hydrossis*	0803, 021N	common
8	267	1851	*H.hydrossis*	0041	very common

Fig 3.5.b Daily DSVI measured for the MLE system during the 1st part of the investigation (days 130 to 259). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION
SYSTEM 2

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
6	184	*H.hydrossis*	1851	0803, 0041, *Nocardia*	abundant
7	223	1851	*H.hydrossis*	0803, 021N	very common
8	267	1851	*H.hydrossis*	0041	very common

Fig 3.5.c Daily DSVI measured for the 2nd system initially as an MLE (days 182 to 218) and later as a Wuhrmann system (days 219 to 259) during the 1st part of the investigation. Also shown on this figure are the filament identifications performed approximately once per month.

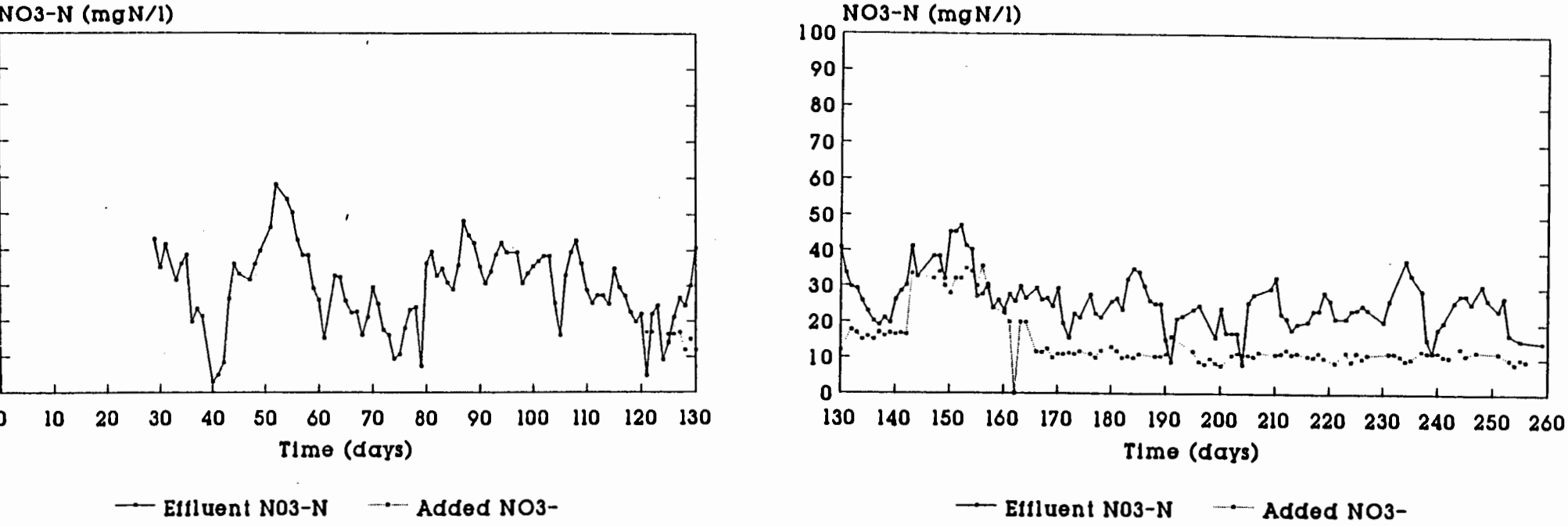


Fig 3.6.a Daily NO_3^- concentration dosed to the anoxic reactor and filtered effluent NO_3^- + NO_2^- concentration for the MLE system during the 1st part of the investigation (days 1 to 259).

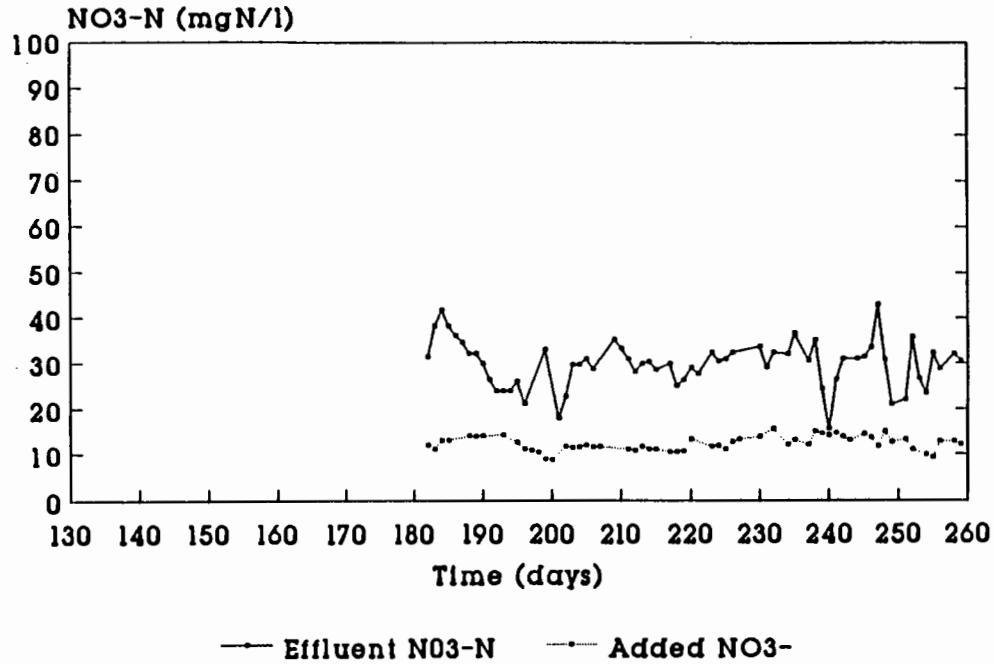
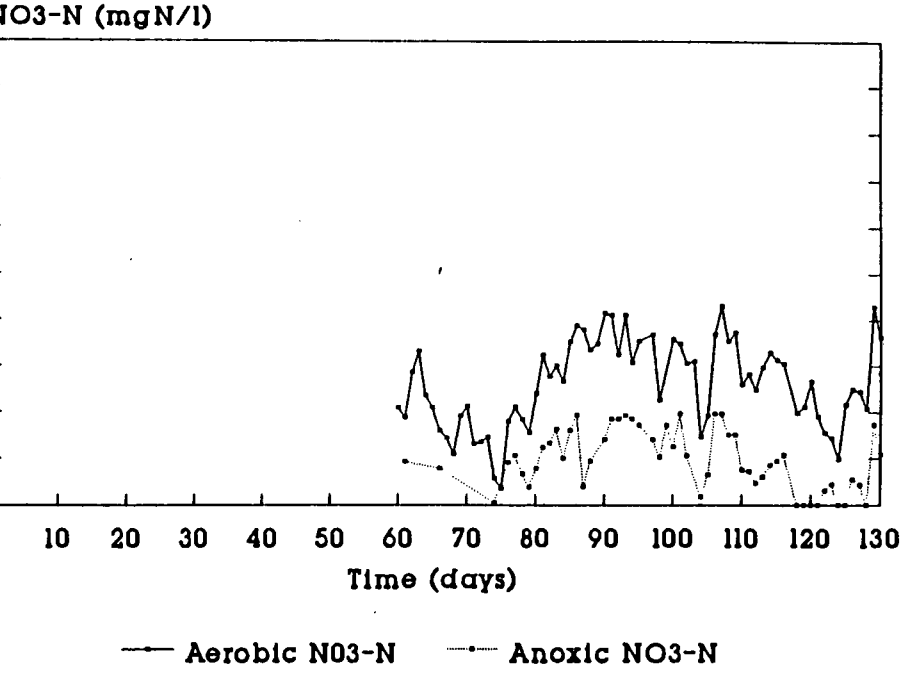


Fig 3.6.b Daily NO_3^- concentration dosed to the anoxic reactor and filtered effluent NO_3^- + NO_2^- concentration for the 2nd system initially as an MLE (days 182 to 218) and later as a Wuhrmann system (days 219 to 259) during the 1st part of the investigation.



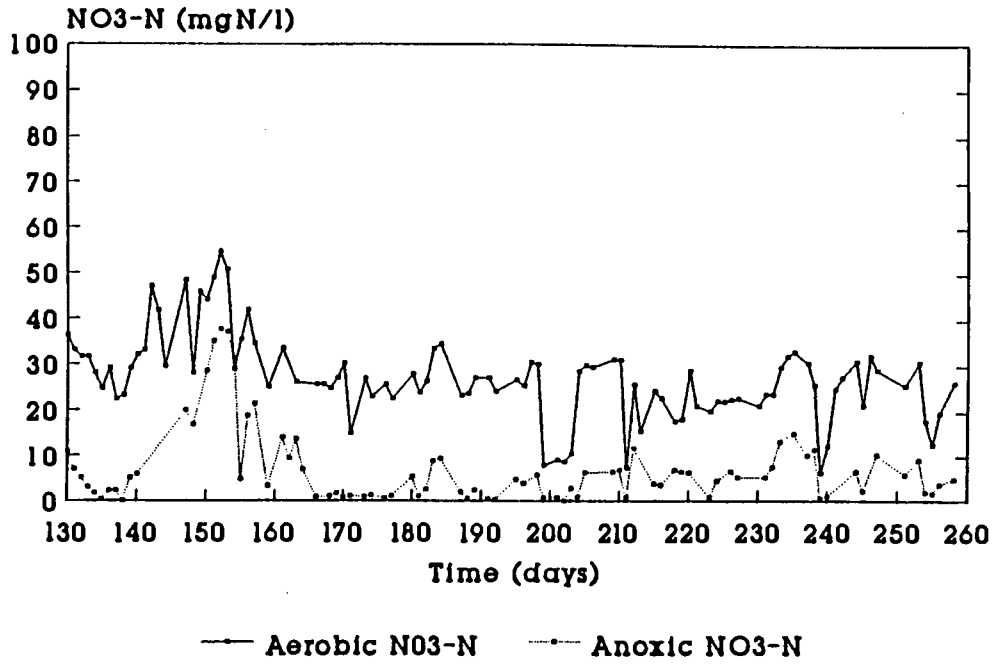


Fig 3.7.a Daily 0,45μm filtered anoxic and aerobic reactor NO_3^- + NO_2^- concentrations for the MLE system during the 1st part of the investigation (days 1 to 259).

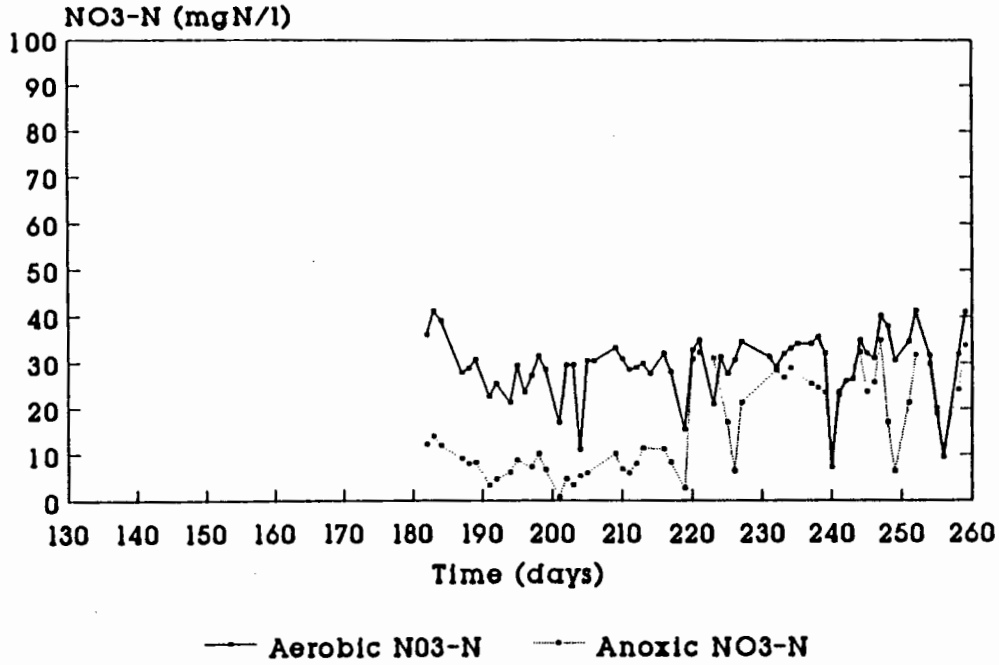
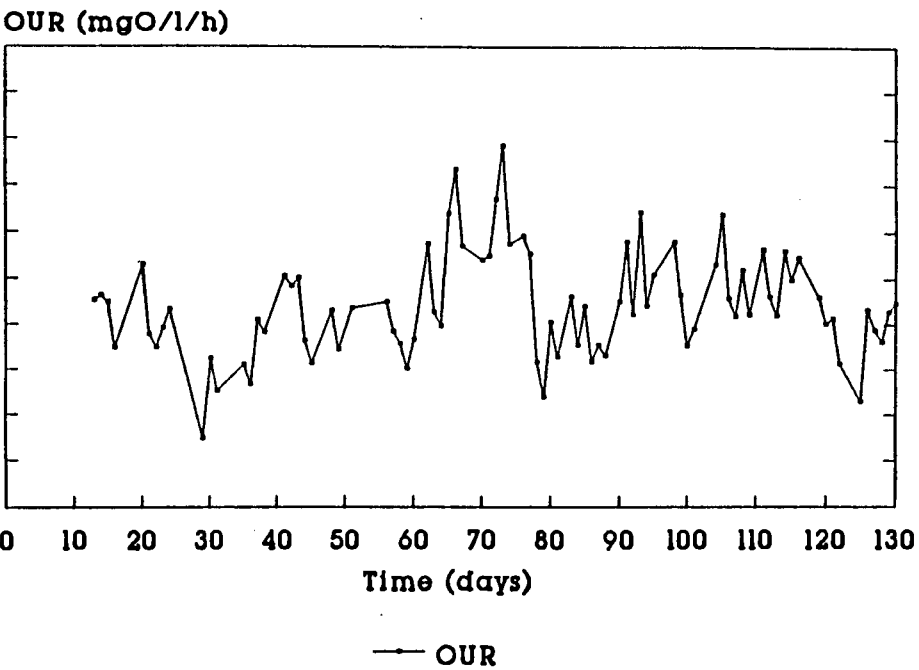


Fig 3.7.b Daily 0,45μm filtered anoxic and aerobic reactor NO_3^- + NO_2^- concentrations for the 2nd system initially as an MLE (days 182 to 218) and later as a Wuhrmann system (days 219 to 259) during the 1st part of the investigation.



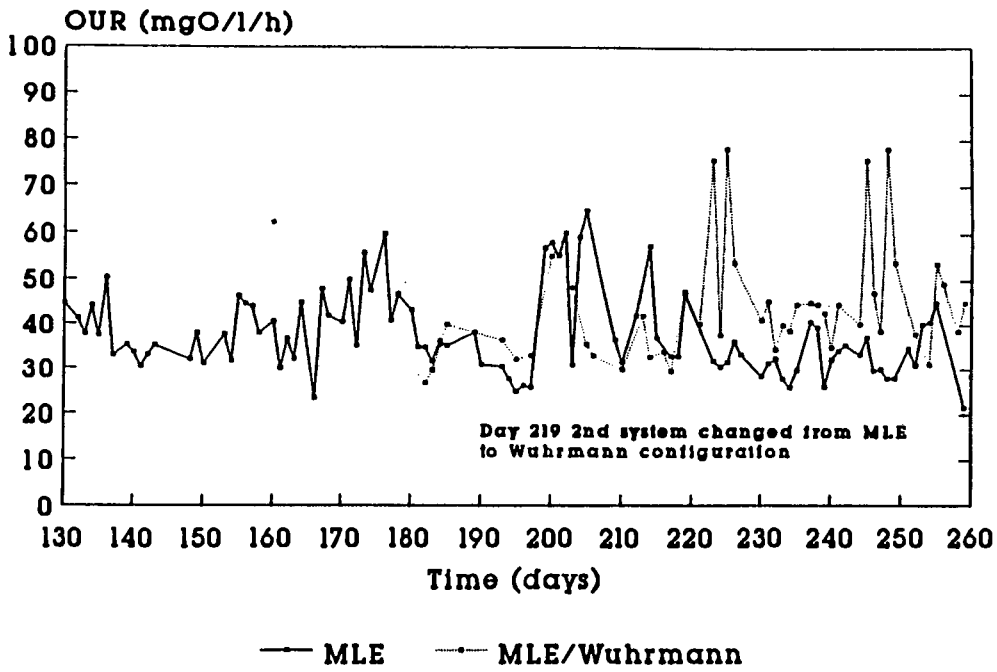


Fig 3.8 Daily oxygen utilization rates measured in the aerobic reactors of the MLE and Wuhrmann systems during the 1st part of the investigation (days 1 to 259).

have been obtained.

Mass balances are most reliable when a prolonged period of steady state is achieved in the systems. Steady state conditions develop over periods when no intentional configurational or operational changes are made to the system. The procedure to determine the N and COD balances is outlined below (details are given in Appendix C).

3.2.1.a The nitrogen (N) balance

The only sources of influent nitrogenous material are free and saline ammonia (±75%), and organically bound nitrogen, both measured by the TKN test. This quantity of influent N leaves the anoxic/aerobic activated sludge process in a total of 3 ways:

(1) TKN and nitrate + nitrite in the effluent flow. This mass of nitrogen is found from the product of the measured concentrations (effluent TKN and nitrate + nitrite) and the daily flow rate (l/d).

(2) Nitrate + nitrite denitrified to nitrogen gas in the anoxic reactor. This mass of nitrogen is found by performing a nitrate + nitrite mass balance on the anoxic reactor. The difference between the mass of nitrate entering and leaving the anoxic reactor per day is the nitrate + nitrite mass denitrified to nitrogen gas per day.

(3) Nitrogen built into the heterotrophic sludge mass leaving the system via the daily sludge wastage. This mass of nitrogen is found from the product of the mass of VSS wasted per day and the measured TKN/VSS ratio (f_n) of the sludge.

The sum of these 3 masses of nitrogen leaving the system as a percentage of the mass of N entering the system gives the proportion of N recovered i.e. the N mass balance.

3.2.1.b Carbonaceous material (COD) balance

Like with the N balance, so with the COD balance, the COD leaving the system daily is calculated as a percentage of the COD entering the system daily. The daily COD mass entering the system is the product of the influent COD concentration and the influent flow rate (l/d). This daily COD mass leaves the system in the following ways:

(1) COD in the effluent flow. This daily mass of COD is the product of the measured unfiltered effluent COD concentration and the flow rate (l/d).

(2) Nitrate and oxygen utilized for COD degradation. The nitrate mass utilized per day for COD degradation is simply the mass of nitrate denitrified per day. The mass of nitrate denitrified per day is found from the N balance above. As the oxygen equivalent of nitrate is 2,86 mgO/mgNO_3-N, the equivalent mass of oxygen utilized in denitrification is 2,86 times the mass of nitrate denitrified per day. The oxygen utilized per day for

COD degradation is obtained from the measured aerobic reactor oxygen utilization rate (mgO/d). This rate is the sum of the oxygen utilization rates for nitrification and COD degradation. The oxygen utilization rate for nitrification is found from the mass of nitrate generated per day by nitrification. The mass of nitrate generated per day is calculated from the N balance above and 4,57 times this mass of nitrate is the oxygen utilization rate for nitrification. The total oxygen utilization rate for COD degradation therefore is the measured rate of oxygen utilization minus the oxygen utilization rate for nitrification plus the equivalent oxygen utilization rate for denitrification.

(3) COD incorporated in the sludge leaving the system via the daily sludge wastage. This mass of COD is found from the product of the mass of VSS wasted per day and the measured COD/VSS ratio (f_{CV}) of the sludge.

The sum of the masses per day of COD in (1) the effluent and (2) the total oxygen utilization rate for COD degradation and (3) sludge wastage flows, as a fraction of the influent COD mass per day gives the fraction of COD recovered that is, the COD mass balance (see Appendix C for details).

3.2.2 Substrate utilization rates

In addition to performing COD and N mass balances over both systems, RBCOD and PBCOD utilization rates in the anoxic and aerobic zones were calculated. This was done to assess the kinetic behaviour of the systems. Because of the direct link through basic biological metabolic behaviour (see Chapter 1, WRC 1984), between COD degraded and oxygen (under aerobic conditions) and nitrate (under anoxic conditions) utilized, the RBCOD and PBCOD utilization rates can be calculated from the mass of oxygen utilized for COD degradation in the aerobic zone and the nitrate mass utilized for COD degradation in the anoxic zone.

Because influent is fed to the first reactor of the MLE and Wuhrmann systems, influent COD utilization in the anoxic zone of the MLE system and in the aerobic zone of the Wuhrmann system takes place by two simultaneous processes (1) the rapid utilization of influent RBCOD and (2) a slower utilization of influent PBCOD (i.e. PBCOD from the influent and self generated by organism death and lysis). The PBCOD internally generated by the sludge through organism death and lysis adds to the influent PBCOD and is used concomitantly with the influent PBCOD. When the influent PBCOD is completely utilized, the only COD remaining for utilization is that internally generated. The rates at which influent RBCOD, and the influent and internally generated PBCOD are utilized in the reactors receiving the influent flows, i.e. in the anoxic zone of the MLE and in the aerobic zone of the Wuhrmann, is directly proportional to the nitrate utilization rate in the MLE and the carbonaceous (COD degradation) oxygen utilization rate in the Wuhrmann. Also the

utilization rate of the part of the influent PBCOD that remains and the PBCOD generated internally in the reactor following the one receiving the influent, which is the aerobic reactor in the MLE and the anoxic in the Wuhrmann system, is directly proportional to the carbonaceous oxygen demand in the aerobic reactor of the MLE and the nitrate utilization rate in the anoxic reactor of the Wuhrmann.

The procedures whereby the RBCOD and PBCOD utilization rates in the anoxic and aerobic reactors of the MLE and of the Wuhrmann systems were calculated are explained below.

3.2.2.a RBCOD utilization rates in first reactor (receiving influent)

(1) Anoxic zone - MLE

The maximum RBCOD utilization rate in this reactor is related to the initial rapid rate of denitrification K_1 (see van Haandel *et al.*, 1981). This maximum rate is so much greater than the loading rate of the RBCOD on the anoxic reactor via the influent flow ($RBCODLR_{anx}$), that the RBCOD utilization rate ($RBCODUR_{anx}$) is substrate limited and therefore equal to the RBCOD loading rate i.e.

$$RBCODUR_{anx} = RBCODLR_{anx}$$

$$= \frac{f_{bs}.MS_{bi}}{MX_a.\text{anoxic mass fraction}} \qquad \text{mgCOD/(mgAVSS.d)} \qquad (3.1)$$

where

$RBCODUR_{anx}$ = RBCOD utilization rate in the primary anoxic reactor of the MLE. (mgCOD/d)

$RBCODLR_{anx}$ = RBCOD loading rate on the anoxic reactor of the MLE by the influent flow. (mgCOD/d)

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

MS_{bi} = daily mass load of biodegradable COD in the influent sewage

$$= MS_{ti}.(1-f_{us}-f_{up}) \qquad \text{(mgCOD/d)} \qquad (3.2)$$

where

MS_{ti} = daily mass load of influent COD

$$= Q.S_{ti} \qquad \text{(mgCOD/d)}$$

where

Q = influent flow rate (l/d)
S_{ti} = influent COD concentration (mgCOD/l)
f_{us} = soluble unbiodegradable fraction of the influent COD
f_{up} = particulate unbiodegradable fraction of influent COD
MX_a = mass of active volatile solids in the system

$$= \frac{MS_{bi}.Y_h.R_s}{(1+b_h.R_s)} \quad \text{(mgAVSS)} \qquad (3.3)$$

where

Y_h = yield coefficient (mgVSS/mgCOD)
= 0.45 (mgVSS/mgCOD)
b_h = endogenous respiration rate (/d)
R_s = sludge age (d)

(2) Aerobic zone - Wuhrmann

The aerobic zone of the Wuhrmann system is similar to the anoxic zone of the MLE system in that the maximum RBCOD utilization rate in this reactor is much greater than the RBCOD loading rate on the reactor by the influent flow. Therefore the RBCOD utilization rate in this aerobic reactor ($RBCODUR_{aer}$) is substrate limited and equal to the RBCOD loading rate on this reactor ($RBCODLR_{aer}$) by the influent flow i.e.

$$RBCODUR_{aer} = RBCODLR_{aer}$$

$$= \frac{f_{bs}.MS_{bi}}{MX_a.\text{aerobic mass fraction}} \quad \text{mgCOD/(mgAVSS.d)} \qquad (3.4)$$

$$= RBCODUR_{anx}$$

It is evident that when the influent is fed at some fixed rate which is much lower than the maximum RBCODUR under anoxic or aerobic conditions, then the RBCOD utilization rate is the same in the anoxic zone of the MLE system as in the aerobic zone of the Wuhrmann system and equal to the loading rate of RBCOD.

3.2.2.b PBCOD utilization rates in first reactor (receiving influent)

(1) Anoxic zone - MLE

Influent RBCOD and PBCOD is utilized simultaneously in the anoxic zone, but at different rates. The sum of these two rates is directly proportional to the rate at which nitrate is denitrified; the constant of proportionality being the mgCOD utilized per mg of nitrate denitrified i.e. $2{,}86/(1-f_{cv}.Y_h) = 8{,}6$ mgCOD/mgNO_3-N for $f_{cv} = 1.48$

mgCOD/mgVSS[1]. Using the measured value of 1.34 instead of the usual value of 1.48 changes slightly the mgCOD utilized/mgNO_3-N denitrified from 8.6 to 7.2. By subtracting the anoxic RBCOD utilization rate (from 3.2.2.a above) from the combined RBCOD and PBCOD utilization rate obtained from the measured nitrate reduction rate, the PBCOD utilization rate in the anoxic reactor ($PBCODUR_{anx}$) can be calculated, i.e.

$$PBCODUR_{anx} = CODUR_{anx} - RBCODUR_{anx} \text{ mgCOD/(mgAVSS.d)} \quad (3.5)$$

where

$$CODUR_{anx} = \text{RBCOD + PBCOD utilization rates}$$

$$= \frac{2{,}86.\text{mass of } NO_3\text{-N denitrified per day.}}{MX_a.\text{anoxic mass fraction.}(1-f_{cv}.Y_h)} \quad (3.6)$$

where

2,86	=	oxygen equivalent of nitrate (mgO/mgNO_3-N)
$(1-f_{cv}.Y_h)$	=	mass of oxygen required to degrade 1 mgCOD (mgO/mgCOD)
f_{cv}	=	measured COD/VSS ratio of the sludge.

(2) Aerobic zone - Wuhrmann

The PBCOD utilization rate in the aerobic zone ($PBCODUR_{aer}$) of the Wuhrmann system is determined in the same way as the $PBCODUR_{anx}$ in the anoxic reactor of the MLE was determined. The only differences are that in the Wuhrmann system the combined RBCOD and PBCOD utilization rates ($CODUR_{aer}$) is proportional to the carbonaceous oxygen demand rather than the denitrification rate and the constant of proportionality with oxygen is $1{,}0/(1-f_{cv}.Y_h)$. Therefore

$$PBCODUR_{aer} = CODUR_{aer} - RBCODUR_{aer} \text{ mgCOD/(mgAVSS.d)} \quad (3.7)$$

where

$$CODUR_{aer} = \text{RBCOD + PBCOD utilization rates}$$

$$= \frac{MO_c}{MX_a.\text{aerobic mass fraction.}(1-f_{cv}.Y_h)} \text{ mgCOD/(mgAVSS.d)} \quad (3.8)$$

---

1 In this investigation the f_{cv} ratio of the VSS was measured and in the calculations the measured value was used.

where

MO_c = carbonaceous oxygen demand per day found from the COD mass balance (mgO/d).

3.2.2.c RBCOD utilization in second reactor

By definition, the RBCOD is completely utilized in the first reactor irrespective of whether the reactor is aerobic or anoxic and consequently no RBCOD enters the second reactor with the result that the RBCOD utilization rate in the second reactor, whether anoxic or aerobic, is zero.

3.2.2.d PBCOD utilization rate in second reactor

Because all the influent RBCOD is utilized in the first reactor (the mass fraction of the first reactors of the MLE and Wuhrmann systems were such that this would have certainly been the case), the second reactor receives whatever influent PBCOD was not utilized in the first reactor as well as that internally generated by organism death and lysis. Now for the aerobic and anoxic mass fractions of the first reactor of the MLE and Wuhrmann systems, it is reasonable to accept that the influent PBCOD remaining and discharged to the second reactor is small compared to the mass of PBCOD generated internally by organism death and lysis. The reason for this is as follows: From the general activated sludge nitrification/denitrification kinetic model (van Haandel *et al.*, 1981) irrespective of the origin of the PBCOD, i.e. influent or generated internally, the $PBCODUR_{anx}$ = neta.$PBCODUR_{aer}$, where neta was found to be about 0,38. This means that the $PBCODUR_{anx}$ in both the primary anoxic, as in the MLE, and the secondary anoxic, as in the Wuhrmann, is reduced by neta relative to the PBCODUR that would take place if these reactors were aerobic i.e. relative to $PBCODUR_{aer}$ in the same reactor. With the MLE system, which receives both the influent RBCOD and PBCOD into the anoxic reactor, even though $PBCODUR_{anx}$ is reduced compared to $PBCODUR_{aer}$, the large anoxic mass fraction (55-70%) compensates for this reduction. With the Wuhrmann system which receives the influent RBCOD and PBCOD into the aerobic reactor, even though the aerobic mass fraction is relatively small (30-45%) the high $PBCODUR_{aer}$ compensates for this. Therefore it is reasonable to accept that the influent PBCOD is virtually completely utilized in the first reactor of the MLE and Wuhrmann systems. Consequently the PBCOD available in the second reactor is virtually completely generated internally by organism death and lysis.

(1) Aerobic zone - MLE.

The PBCOD utilization rate in this reactor under aerobic conditions ($PBCODUR_{aer}$) is proportional to the carbonaceous oxygen demand in this reactor, MO_c, which is the difference between the measured oxygen demand, MO_t, and that required for nitrification, MO_n, found from the N and COD mass balances i.e.

$$PBCODUR_{aer} = \frac{MO_c}{MX\bar{a}.\text{aerobic mass fraction}.(1-f_{cv}.Y_h)}$$

mgCOD/(mgAVSS.d)

(3.9)

where

MO_c = carbonaceous oxygen demand per day found from the COD mass balance (mgO/d).

(2) Anoxic zone - Wuhrmann

The PBCOD utilization rate in this reactor under anoxic conditions ($PBCODUR_{anx}$) is directly proportional to the measured denitrification rate, i.e.

$$PBCODUR_{anx} = \frac{2{,}86.\text{mass of } NO_3\text{-N denitrified per day}}{MX_a.\text{anoxic mass fraction}.(1-f_{cv}.Y_h)}$$

mgCOD/(mgAVSS.d)

(3.10)

The calculation procedures for the N and COD mass balances and substrate utilization rates described above were coded into into a Turbo Pascal computer program for ease of repeated calculations. A listing of the particular procedure which performs the calculations is given in Appendix F. The program structure and a double density floppy disk with the complete source code and compiled program are also given in Appendix F.

3.2.3 Mass balances, substrate utilization rates and denitrification in the MLE and Wuhrmann systems

For both systems the 259 day time period constituting the first part of the investigation, was divided into a number of steady state periods. The periods were identified by the days during which no intentional operational changes were made to the systems. For the 1st system 5, and for the 2nd system 2 steady state periods were identified. For each of the steady state periods (see Table 3.4) of both systems during this part of the investigation N and COD mass balances as well as PBCOD and RBCOD utilization rates were calculated. The results of these calculations are given in Table 3.5 and are discussed below.

3.2.3.a COD mass balances

Examining Table 3.5 it can be seen that unacceptably low COD recoveries (60-70%) were recorded for all the steady state periods for both systems. COD recoveries as low as these indicate in all likelihood some inadvertant errors were made in the measurement and/or operation of the two systems. With regard to measurement errors, the same procedures for measuring the COD and VSS

Table 3.4: Steady state periods observed in system 1 (MLE) and system 2 initially as an MLE (days 182 - 218) and subsequentially as a Wuhrmann (days 219 - 259) during the 1st part of the investigation.

System	Steady State Period Days and Number				
	1	2	3	4	5
1st MLE	60 - 109	120 - 142	143 - 156	166 - 190	191 - 245
2nd MLE	182 - 219				
Wuhrmann		222 - 245			

Steady state periods were chosen such that during each period no intentional or operational changes were made to the systems and system response during the steady state period looked stable. For the 1st MLE system the steady state periods were selected as follows; (1) no anoxic or aerobic NO_3^- + NO_2^- concentrations available, (2) constant DSVI (± 200 ml/g), (3) increasing DSVI and constant anoxic and aerobic NO_3^- + NO_2^- concentrations, (4) high NO_3^- concentration dosed to the anoxic reactor and erratic DSVI, (5) lowered NO_3^- concentration to anoxic reactor and (6) smooth steadily decreasing DSVI with constant NO_3^- + NO_2^- concentrations in the effluent and anoxic and aerobic reactors. For the 2nd system as both an MLE and Wuhrmann only one steady state period was selected for each and in both cases these represented the complete duration of operation.

concentrations and oxygen utilization rates used on other systems which did yield good N and COD balances were used on the two systems in this investigation. Consequently, the poor COD mass balance problem is not likely to be in incorrect measurement techniques but rather in some operational problem. After careful consideration it was thought that the most likely cause of COD loss in the experimental set-up was loss of COD between the feed bucket and the biological reactor.

The influent COD concentration fed to the two systems was measured by taking a sample of the prepared artificial sewage influent before pouring the influent into the influent feed bucket. The volume of feed in the bucket was measured to be that required for 1 day: At 10 *l*/d influent flow, 10 *l* is poured into the feed bucket and this would be fed over the subsequent 24h period. This procedure allowed checking that all the feed volume was fed to the systems daily. The daily mass of COD fed to the two systems was calculated as the product of the flow i.e. 10 *l*/d and the measured influent COD concentration of the sample. At the end of the 24h period, any particulate COD accumulated in the feed bucket was collected with the last 200 to 300 ml of feed and poured directly into the first reactor

Table 3.5: N & COD mass balances and substrate utilization rates calculated for both systems during part 1 of the investigation.

System Nr	System Type	Period Days	Mass Balances		COD Utilization Rates[1]		
			COD	N	RBCOD[2]	PBCOD[3]	PBCOD[4]
1	MLE	60 - 109	74	87	0.354	0.453	1.222
		120 - 142	65	92	0.354	0.446	0.719
		143 - 156	58	84	0.354	0.314	0.519
		166 - 190	62	97	0.354	0.379	0.640
		191 - 245	73	89	0.354	0.433	0.821
		AVERAGE[7]	66	90	0.354	0.447	0.843
2	MLE	182 - 219	63	77	0.354	0.310	0.730
	Wuhrmann	222 - 245	84	108	0.413	1.326[5]	0.619[6]

1 Units in mgCOD/(mgAVSS.d)
2 RBCOD utilization under anoxic (MLE) and aerobic (Wuhrmann) conditions and limited by RBCOD loading rate.
3 PBCOD utilization rate in anoxic (first) reactor of MLE i.e. $PBCODUR_{anx}$ with influent and self generated PBCOD.
4 PBCOD utilization rate in aerobic (second) reactor of MLE i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD
5 PBCOD utilization rate in aerobic (first) reactor of Wuhrmann i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD.
6 PBCOD utilization rate in anoxic (second) reactor of Wuhrmann i.e. $PBCODUR_{anx}$ with self generated PBCOD only.
7 Average weighted by number of days in steady state period relative to the total number of days in the 1st part of the investigation.

to minimize COD losses. Also to reduce loss of COD the influent feed buckets were refrigerated and kept at 4°C. However, the feed buckets were not covered with a floating disc to prevent air entrainment and also the artificial sewage in the feed bucket needed to be fairly well mixed to keep the particulate COD fraction in suspension. As a result, oxygen could have been entrained from the air and dissolved into the feed volume through the open surface of the influent feed bucket. Also the dissolved oxygen in the feed could lead to loss of COD in the influent bucket and feed lines through utilization and slime accumulation on the feed bucket and feed line walls. These sources of COD loss were evaluated as possible causes for the poor COD mass balances.

The influent feed lines were about 2½ m long and 6 mm diameter transparent plastic tubing. It was found that significant growths of glutinous material accumulated daily in the feed supply line and bucket walls. To limit the COD loss through this and to prevent this material blocking feed lines, the bucket and the feed lines were cleaned out daily. The COD which had accumulated on the walls was not retained and represented COD not received by the two systems. This loss, including that lost through biodegradation in the feed bucket itself over the 24h period, resulted in the COD discharged to the biological reactor being less than that measured at the feed bucket at the start of the 24h period. To check the extent to which this was happening, a number of samples of influent were taken at the feed bucket and the discharge point into the reactor at different times of the day (see Fig 3.9). The data in Fig.3.9 shows that COD was lost both in the bucket and in the feed lines. From the data, it was estimated that only about 82% of the mass of COD poured into the feed bucket, was actually discharged into the biological reactor.

The magnitude of the reduction in COD concentration between the feed bucket and the biological reactor found experimentally can be confirmed from the lower than expected MLVSS concentration accumulated in the biological reactors at the set sludge age. To do this two assumptions need to be made:

(1) The unbiodegradable particulate (f_{up}) and soluble (f_{us}) fractions of the artificial sewage discharged into the reactor were constant throughout the investigation; this assumption is valid as the components and concentration of the artificial sewage was not changed for either system during the period day 1 to day 252 and

(2) The fraction of influent COD R_f received by the biological reactors was constant throughout the investigation.

The method employed to calculate the value of R_f from the measured MLVSS concentrations is outlined below.

The mass of volatile solids that accumulate in the biological reactor is a function of *inter alia* sludge age, the sewage characteristics f_{us} and f_{up} and the mass of COD received by the biological reactor daily. Accepting that the mass COD received daily by the MLE and Wuhrmann systems is given by $R_f.MS_{ti}$ where MS_{ti} is the product of the daily influent flow and the experimentally measured influent COD concentration in the feed bucket at the start of the 24h period. The mass of MLVSS in the system as a function of $R_f.MS_{ti}$ is then given by

$$MX_v = R_f.MS_{ti}.R_s\left[\frac{(1-f_{us}-f_{up}).Y_h.(1+f.b_h.R_s)}{(1+b_h.R_s)} + f_{up}/f_{cv}\right] \quad \text{(mgAVSS)} \qquad (3.11)$$

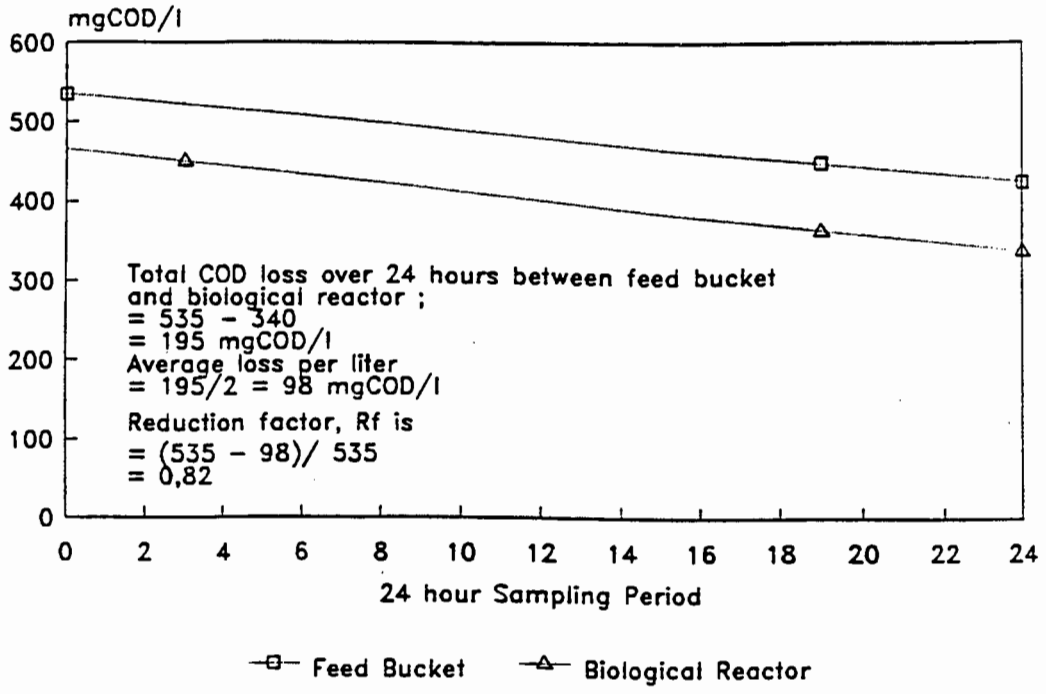


Fig 3.9 Artificial COD concentration gradient measured between the influent feed bucket and biological reactor over a 24 hour period. Approximately 82% of the COD in the feed bucket reached the biological reactor at the end of the 24 hour period.

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where

MX_v	=	mass of VSS in the system (mgVSS)
MS_{ti}	=	mass of COD measured in the feed bucket at the start of the 24h period (mgCOD/d)
$R_f.MS_{ti}$	=	mass of COD entering the system per day (mgCOD/d)
R_s	=	sludge age (d)
Y_h	=	specific heterotrophic yield (mgVSS/mgCOD)
b_h	=	endogenous respiration rate (/d)
f_{cv}	=	sludge VSS/COD ratio (mgVSS/mgCOD)
f	=	endogenous residue (mgVSS/mgVSS)
f_{us}	=	unbiodegradable soluble fraction of influent COD
f_{up}	=	unbiodegradable particulate fraction of influent COD

In Equ. (3.11) above values for the different parameters are required and were established as follows;

(1) sludge age R_S - set at 15 days.

(2) f, b_h, and Y_h - accepted from the steady state activated sludge theory i.e. 0.2, 0.24/d and 0.45 mgAVSS/mgCOD respectively.

(3) f_{us} and f_{up} - as the parameters f_{us} and f_{up} are sewage characteristics, these values vary from sewage to sewage and are required to be known for the artificial sewage to enable calculation of R_f. The unbiodegradable soluble COD fraction f_{us} is found from the filtered effluent COD concentration S_{use} and is given by the ratio of this concentration and the total COD concentration discharged to the reactor $R_f.S_{ti}$ i.e. $f_{us} = S_{use}/R_f.S_{ti}$. The particulate unbiodegradable COD fraction f_{up} cannot be directly determined like f_{us}; it is obtained from the measured VSS that accumulates in the biological reactor, MX_v. Because MX_v is a function not only of f_{up} but also the mass of COD discharged to the reactor $R_f.MS_{ti}$, an additional source of data was required to enable calculation of both f_{up} and R_f. This source of data (see Table 3.6) was obtained from another system in the laboratory receiving the same artificial sewage and operated at 3.75 days sludge age. The feed bucket and feed line arrangement, operation and maintenance of this system was similar to that of the MLE and Wuhrmann systems and so it could be assumed that the 3.75 day sludge age system had a similar loss of influent COD with the result that the same COD reduction factor R_f as applied to the MLE and Wuhrmann systems could be applied to this system . With this additional data f_{up} and R_f could be determined simultaneously for the 3.75 day sludge age system and the MLE and Wuhrmann systems.

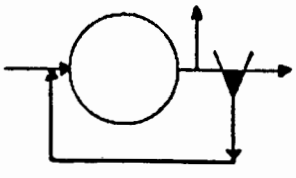
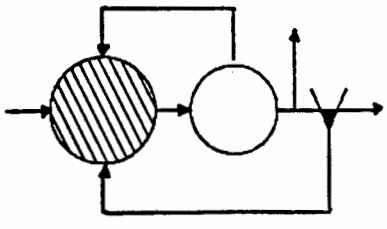
Following this procedure, R_f was found to be 0.78 i.e. 78% of the measured influent COD was received by the biological systems and 22% lost in the feed bucket and feed lines. This fraction compares favourably with the observed value of 82% measured experimentally. The associated f_{up} value was found to be 0.07. This value also compares very well with the 0.08 Mitchell's Plain raw sewage value which the artificial sewage was designed to simulate.

3.2.3.b N mass balance

In all of the steady state periods it was found that the N balance was generally somewhat below a 100% i.e. 90% The likely cause of this low order of recovery is given below.

Influent TKN concentrations, like COD concentrations, were measured from feed samples taken from the feed bucket at the start of each 24h period. As was discussed above, influent COD was lost through oxygen utilization and slime accumulation on the feed bucket and feed line walls. It is reasonable to assume that a portion of the influent TKN was lost in the same fashion. Free and saline ammonia (measured to be 74% of influent TKN) is readily assimilable by the sludge

Table 3.6: Design and operating parameters of 2 systems used to calculate fup and influent COD reduction factor Rf

System	Unit 1	Unit 2
Operating conditions	continuously fed completely mixed	
Graphical representation		
Sludge age (d)	3.75	15
Volume (l)	3.75	6.5
Sewage type	Artificial	Artificial
Mass COD fed/d (mgCOD/d)	5600	5600
Influent Flow (l/d)	10	10
MLVSS (mgVSS/l)	1191	1872
Effluent COD (mgCOD/l)	95	95
Temperature (°C)	20	20
pH of mixed liquor	7.2 - 8.2	7.2 - 8.2

accumulated on the feed bucket and feed line walls. The amount of TKN lost, N_{tl}, through unaccounted sludge growth as a function of the influent COD concentration measured at the feed bucket is given by

$$N_{tl} = f_n.(R_f).S_{ti}.Y_h \quad (mgN/l) \qquad (3.12)$$

where

N_{tl} = influent TKN assimilated by sludge growth on feed bucket and feed lines (mgN/l).

f_n = sludge TKN/VSS ratio measured to be 0.08 mgTKN/mgVSS.

R_f = influent COD reduction factor.

S_{ti} = influent COD concentration measured from the feed bucket at the start of the 24h period (mgCOD/l).

Y_h = specific heterotrophic yield (mgVSS/mgCOD).

The actual concentration of influent TKN received by the biological reactors is the measured influent TKN concentration less the TKN assimilated by sludge growth on the feed bucket and feed line walls (N_{tl}). Typically N_{tl} ranged from 3.0 to 4.0 mgN/l.

Accepting that 82% of the influent COD mass was received by the biological systems and that 3 to 4 mgN/l of influent TKN was assimilated by sludge growth on the feed bucket and feed line walls, the N and COD mass balances and substrate utilization rate calculations were repeated and are given in Table 3.7. With this reduced influent COD and TKN mass, the N and COD mass balances on the two systems are now much improved i.e. between 80 and 100%. The COD balances obtained in the different steady state periods of the MLE and Wuhrmann systems are discussed in greater detail in section 3.2.3.d below.

3.2.3.c Denitrification in the MLE and Wuhrmann systems

The mass of nitrate denitrified per day in the MLE and Wuhrmann systems is found by evaluating the nitrate mass balance on the anoxic reactor. In the MLE system the mass of nitrate entering the anoxic reactor is the sum of the mass of nitrate (1) dosed to the anoxic reactor, (2) in the underflow s-recycle and (3) in the mixed liquor a-recycle from the aerobic reactor. The mass of nitrate leaving the anoxic reactor is the product of the anoxic nitrate concentration and the anoxic-aerobic flow rate i.e. Q.(1 + a + s) (l/d). The mass of nitrate denitrified per day is the difference between the daily mass of nitrate entering and leaving the anoxic reactor.

For the MLE system the mass nitrate denitrified, $M(N)_d$, per day is found from

$$M(N)_d = Q.(s.N_{ne} + a.N_{naer} + N_{ndos} - (1 + s + a).N_{nanx}) \quad (mgN/d) \quad (3.13)$$

where

$M(N)_d$ = mass of nitrate denitrified per day (mgN/d)
Q = daily influent feed volume (l/d)
s = underflow recycle ratio
a = mixed liquor recycle ratio
N_{ne} = system effluent nitrate concentration (mgN/l)
N_{naer} = aerobic effluent nitrate concentration (mgN/l)
N_{ndos} = nitrate concentration dosed to anoxic reactor with respect to the influent flow (mgN/l)
N_{nanx} = anoxic effluent nitrate concentration (mgN/l)

In the Wuhrmann system the mass of nitrate denitrified per day, $M(N)_d$, is the difference between the nitrate concentrations entering and leaving the anoxic reactor times the flow rate through the anoxic reactor plus the nitrate mass dosed daily. The mass of nitrate denitrified per day is found from

$$M(N)_d = Q.[\, N_{ndos} + (1 + a + s\,).(N_{naer} - N_{nanx})] \quad (mgN/d) \quad (3.14)$$

with symbols as described above for Equ.3.13 above.

For each of the steady state periods, for each system, the daily masses of nitrate denitrified were calculated using measured values and are given in Table 3.8.a.

In order to gain a better insight into the role of the anoxic reactor in the MLE and Wuhrmann systems on low F/M filament growth, the nitrate load and nitrate denitrified were compared and the anoxic reactor effluent nitrate + nitrite concentration examined (see Table 3.8.a). Nitrate depletion and possibly temporary anaerobic conditions can arise in the anoxic reactor when the concentration of nitrate in the outflow of the anoxic reactor is less than about 3 mgN/l and when this happens, the nitrate load on the anoxic reactor is closely equal the nitrate denitrified.

Examining Table 3.8.a it can be seen that nitrate depletion in the anoxic reactor occurred possibly only once throughout the 1st part of the investigation. This was for system 1 (MLE) during the period days 166 to 252 and the impact of this nitrate depletion on low F/M filament proliferation is discussed below in section 3.2.4.

3.2.3.d Discussion of mass balances, substrate utilization rates and denitrification in the MLE and Wuhrmann systems

During the 259 day period, 5 steady state periods (see Table 3.4) were identified for the first MLE system and 2 steady state periods for the second system, 1 for each as MLE and Wuhrmann. These steady state periods were chosen such that, during each period, no operational or configurational changes were made (see Table 3.3) and response of the systems looked relatively stable. Mass balances and substrate utilization rates were calculated for each period, applying the influent COD daily mass reduction factor R_f discussed above and are listed in Table 3.7.

From Table 3.7 it can be seen that the improved COD mass balances are still low - the average of 5 mass balances for system 1 being 86% and for system 2 as MLE and Wuhrmann 76% and 106% respectively. This is not seen as an indication of poor experimental procedure, but rather corroborates the tendencies noted by Ketley *et al.* (1991) and Warburton *et al.* (1991) that systems (in their case intermittently aerated) with large anoxic (50 - 70%) mass fractions do not yield the high order of COD recovery that fully aerobic systems do. The reason for lower COD recoveries i.e. lower COD mass balances, in systems incorporating large anoxic zones is at this stage unclear. It was concluded that COD balances calculated for both systems were acceptable and that any unusual behavioural pattern of low F/M filaments in these systems could not be attributed to poor operation and analysis of the systems.

With regard to the substrate utilization rates calculated for each steady state period for each system, the following can be observed from Table 3.7:

(1) The RBCODUR in the first reactor (anoxic in the MLE and aerobic in the Wuhrmann) was limited by the rate of addition of influent RBCOD received by the system. Under anoxic conditions, in the absence of RBCOD supply limitation the $RBCODUR_{anx}$ is 5.20 mgCOD/(mgAVSS.d) [obtained from the K_1 denitrification rate 0.72 $mgNO_3$-N/(mgAVSS.d) * $2.86/(1-f_{cv}.Y_h)$ mgCOD utilized/$mgNO_3$-N denitrified]. This rate is 15 times greater than the rate at which RBCOD was loaded on the anoxic reactor (i.e. 0.354 vs 5.2). The same factor 15 also applies to the aerobic reactor of the Wuhrmann system. This is because with RBCOD, it has been observed that RBCOD is utilized under anoxic conditions at approximately the same rate as under aerobic conditions (Gabb *et al.* 1989a).

(2) The PBCODUR in the first reactor (aerobic) of the Wuhrmann system was calculated to be 1.860 mgCOD/(mgAVSS.d). Converting this aerobic value to an equivalent anoxic value to allow comparison with the established K_2 denitrification rate

Table 3.7: N & COD mass balances and substrate utilization rates calculated for both systems during part 1 of the investigation using the influent artificial COD reduction factor R_f.

System Nr	System Type	Period Days	Mass Balances COD	Mass Balances N	COD Utilization Rates[1] RBCOD[2]	COD Utilization Rates[1] PBCOD[3]	COD Utilization Rates[1] PBCOD[4]
1	MLE	60 - 109	95	89	0.354	0.282	1.965
		120 - 142	73	96	0.354	0.437	0.737
		143 - 156	78	81	0.354	0.095	1.461
		166 - 190	77	103	0.354	0.449	0.852
		191 - 245	88	94	0.354	0.348	1.253
		AVERAGE[7]	86	93	0.354	0.353	1.356
2	MLE	182 - 219	76	104	0.354	0.252	0.976
	Wuhrmann	222 - 245	106	95	0.413	1.860[5]	0.535[6]

1 Units in mgCOD/(mgAVSS.d)
2 RBCOD utilization under anoxic and aerobic conditions and limited by RBCOD loading rate.
3 PBCOD utilization rate in anoxic (first) reactor of MLE i.e. $PBCODUR_{anx}$ with influent and self generated PBCOD.
4 PBCOD utilization rate in aerobic (second) reactor of MLE i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD
5 PBCOD utilization rate in aerobic (first) reactor of Wuhrmann i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD.
6 PBCOD utilization rate in anoxic (second) reactor of Wuhrmann i.e. $PBCODUR_{anx}$ with self generated PBCOD only.
7 Average weighted by number of days in steady state period relative to the total number of days in the 1st part of the investigation.

measured in primary anoxic reactors yields: 1.860 mgCOD/(mgAVSS.d) / 7.2[1] mgCOD utilized/mgNO_3-N denitrified * 0.38 = 0.098 mgNO_3-N/(mgAVSS.d), where 0,38 is neta which is the aerobic PBCODUR reduction factor for anoxic conditions (see van Haandel *et al.*,1981). The equivalent K_2 rate for the Wuhrmann system is therefore 0.098 which compares favourably with the established K_2 rate in the primary anoxic reactor (WRC, 1984) of 0.101 mgNO_3-N/(mgAVSS.d) (see Table 3.8.b).

1 Obtained from $2.86/(1-f_{cv}.Y_h)$ where Y_h was accepted at the usual value, of 0.45 mgVSS/mgCOD and f_{cv} at the measured value of 1.34 mgCOD/mgVSS

Table 3.8.a: Mass NO_3^- + NO_2^- denitrified per day in the primary anoxic reactor of the MLE and the secondary anoxic reactors of the Wuhrmann systems during the 1st part of the investigation. Also given are the masses of NO_3^- + NO_2^- loading and leaving the anoxic reactor per day.

System Type	Steady State Period	Nr	Anox[1] Dose	Anox[2] Outfl	Denitrification (mgN/d) Act[3]	Load[4]	Effl[5]
1st MLE	60 - 109	1	20.0	12.5	249	499	250
	120 - 142	2	15.9	3.7	320	396	74
	143 - 156	3	32.4	25.6	192	704	512
	166 - 190	4	11.1	2.4	318	366	48
	191 - 245	5	12.2	5.1	245	347	102
2nd MLE	182 - 218	1	11.6	8.4	238	406	168
Wuhrmann	222 - 245	1	13.5	28.0	171	731	560

1 NO_3^- concentration with respect to influent dosed to the anoxic reactor.
2 Anoxic outflow NO_3^- + NO_2^- concentration (mgN/*l*).
3 Actual denitrification (mgN/d) in system calculated using measured data. Found from the difference between 4 and 5.
4 Daily mass NO_3^- + NO_2^- (mgN/d) entering anoxic reactor.
5 Daily mass NO_3^- + NO_2^- (mgN/d) leaving anoxic reactor. To find NO_3^- + NO_2^- concentration of anoxic reactor i.e. column 2, divide effluent mass by 10 *l*/d and (1 + a + s) where a and s are the mixed liquor and underflow recycle ratios respectively.

(3) The average PBCODUR in the first reactor (anoxic) of the 1st MLE system (associated to the K_2 rate = 0.101 mgNO_3-N/(mgAVSS.d) above) was calculated to be 0.353 mgCOD/(mgAVSS.d). The equivalent denitrification rate is 0.353/7.2 = 0.049 mgNO_3-N/(mgAVSS.d) which is significantly less than established K_2 rate of 0.101 mgNO_3-N/(mgAVSS.d). This observation is taken into account when commenting on low F/M filament growth in this system.

(4) The above comparison of the PBCODUR for the first reactor of the MLE and Wuhrmann is now applied to the second reactor of these systems. Converting the aerobic PBCODUR in the MLE i.e. 1.356 mgCOD/(mgAVSS.d) to the equivalent denitrification rate K_3 yields 1.356/7.2 * 0.38 = 0.072 mgNO_3-N/(mgAVSS.d) (see Table 3.8.b). Converting the anoxic PBCODUR (Wuhrmann) i.e. 0.535 mgCOD/(mgAVSS.d) to the equivalent denitrification rate yields 0.535/7.2 = 0.074 mgNO_3-N/(mgAVSS.d). Both these rates compare very favourably with the established K_3 rate of 0.072 mgNO_3-N/(mgAVSS.d) (van Haandel *et al.*,1981, WRC,1984) (see Table 3.8.b).

Table 3.8.b: Equivalent denitrification rates determined for the MLE and Wuhrmann systems during the 1st part of the investigation with artificial sewage used as influent feed.

			Denitrification rates[1]		
System Nr	System Type[2]	Operating Period	Reactor 1 K_1	K_2	2 K_3
1	MLE	1 - 252	0.049	0.049	0.072
2	MLE	182 - 218	0.049	0.035	0.052
2	Wuhrmann	219 - 252	0.057	0.098	0.074
-	Accepted Values[3]		0.720	0.101	0.072

1 Units are mgNO_3-N/(mgAVSS.d).

2 MLE K_2 obtained directly from denitrification rate
K_3 obtained from carbonaceous oxygen utilization rate times neta where neta = 0,38.
Wuhrmann K_2 obtained from carbonaceous oxygen utilization rate times neta where neta = 0,38.
K_3 obtained directly from denitrification rate.

3 From WRC (1984) at 20°C.

K_1 Determined directly from the RBCOD loading rate in the 1st reactor (anoxic in the MLE, aerobic in the Wuhrmann).

K_2 Determined from the PBCOD utilization rate in the 1st reactor, where PBCODUR = CODUR - RBCODUR. In the 1st reactor CODUR is the rate at which influent RBCOD and PBCOD, both in the influent and internally generated through organism death and lysis, is utilized. In the MLE system this is under anoxic conditions i.e. through denitrification and in the Wuhrmann system this is under aerobic conditions. The equivalent denitrification rate for aerobic conditions was determined using neta, the PBCODUR aerobic reduction factor for anoxic conditions where neta = 0,38.

K_3 Determined from the PBCOD utilization rate in the 2nd reactor. The PBCOD is generated internally through organism death and lysis only. For the MLE system this is utilized under aerobic conditions and for the Wuhrmann system this is utilized under aerobic conditions.

(5) The neta value i.e. the aerobic PBCODUR reduction factor for anoxic conditions for the MLE and Wuhrmann systems also can be calculated. The neta value is given by the ratio of the Wuhrmann anoxic PBCODUR and the MLE aerobic PBCODUR the former determined at 0.535 and the latter average at 1.356 mgCOD/(mgAVSS.d). Hence neta = 0.535/1.356 = 0.39. This value is very close to that established by van Haandel *et al.* (1981) and therefore is suitable for artificial sewage systems of this investigation. This supports the use of 0.38 for neta in the PBCODUR calculations in (2) and (4) above.

From the above calculations and comparisons it can be seen that the kinetic rates observed in the MLE and Wuhrmann systems fed artificial sewage in most instances compare very favourably with rates established in earlier research with real sewage. Consequently it can be accepted that kinetically the MLE and Wuhrmann systems performed in accordance with expectation and any unusual observation regarding the behaviour of the filamentous organisms cannot be attributed to unusual kinetic performance.

3.2.4 Low F/M filament growth in MLE and Wuhrmann systems

System 1 - MLE (see Fig.3.1.c)

Start up sludge for this system (70% anoxic, 30% aerobic) was taken from an intermittent aeration system fed artificial sewage with a large anoxic fraction (70%) and a DSVI of 400 m*l*/g. Initially, the additional nitrate dosed to the anoxic reactor was 40 mgN/*l* influent feed. On day 25 the additional nitrate was lowered to 25 mgN/*l* influent feed and on day 28 the anoxic mass fraction was lowered from 70 to 54% with a concomitant rise in aerobic mass fraction from 30 to 46% (see Table 3.3). Sludge settleability and filament identification on day 28 showed the DSVI was still ±400 m*l*/g and filament type 1851 to be dominant, *H.hydrossis* secondary and type 0092 tertiary. The overall filament abundance was common to very common (see Fig.3.5.a).

It was observed that from start up i.e. day 1 to day 35 the measured DSVI fluctuated erratically around the 400 m*l*/g level. From day 35 the DSVI (400 m*l*/g) started to decrease and the daily fluctuation in DSVI became less noticeable. Also the system response e.g. effluent COD, TKN and nitrate + nitrite concentrations stabilized. On day 40 the nitrate dosed to the anoxic reactor was reduced to 20 mgN/*l* influent. On day 60 the DSVI reached 200 m*l*/g. Filament identification on day 57 showed that the dominant and secondary filaments remained unchanged i.e. type 1851 and *H.hydrossis* respectively. Type 0092 was not present but types 0803 and 0041 were. The overall filament abundance was very common[1] (see Fig.3.5.a).

From day 60 to day 130 the DSVI remained unchanged at the 200 m*l*/g level. This period was notable for the occurrence of rising sludge in the secondary clarifier, caused by denitrification of the effluent nitrate in the clarifier. Filament identification on day 94 showed that *H.hydrossis* replaced type 1851 as the dominant filament, with type 0041 moving to secondary. Type 1851 was present at the tertiary level as also were *N.limicola II* and type 0092. Overall filament abundance was very common to abundant. A second filament identification on day 125 showed that type 1851 had moved up to dominant and *H.hydrossis*

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1 Overall filament abundance is a semi-quantitative assessment of the amount of filaments present in the sludge sample.

down to secondary. Types 0041 and 0092 remained at the tertiary level. Overall filament abundance was very common.

From day 130 to day 170 the DSVI increased in an erratic fashion from 200 to 350 ml/g. On day 143, the additional nitrate dosed to the anoxic reactor was increased from 20 to 40 mgN/*l* influent (see Table 3.3). This was done to avoid nitrate depletion in the anoxic reactor (see section 3.2.3.c above). During this period rising sludge due to denitrification in the clarifier was a frequent occurrence. In an attempt to limit the sludge loss through denitrification in the clarifier, a second clarifier, in series with the first, was added to the system on day 148. This did not have the desired effect and it was removed on day 160. It was speculated that the increased nitrate concentration added to the anoxic reactor was exacerbating the occurrence of rising sludge in the clarifier because higher nitrate dosing caused higher effluent nitrate concentrations and so on day 163 the additional nitrate was reduced from its former level of 40 mgN/*l* to 20 mgN/*l* influent. This action did not completely eliminate the rising sludge problem but at least reduced it to manageable proportions.

Also during this period (day 130 to 170) a significant accumulation (2 - 3cm) of scum and foam on the anoxic reactor was observed; the aerobic reactor also accumulated some scum but much less so than the anoxic. On day 170 the stirrer blade of the anoxic reactor was raised to within 1mm of the surface, which resulted in a cessation of scum accumulation on the anoxic and aerobic reactors (see Table 3.3). Filament identification on day 155 showed that *H.hydrossis* replaced type 1851 as the dominant filament, with type 0803 secondary and with *Thiothrix* (a nutrient deficiency filament) and types 0041 and 0092 present at the tertiary level. Overall filament abundance was very common.

From day 170 to 190 the DSVI decreased rapidly from 350 to 200 ml/g. During this period no rising sludge in the clarifier and no scum and foam accumulation in the anoxic and aerobic reactors was noted. Filament identification on day 184 showed that *H.hydrossis* was still dominant, type 1851 replaced type 0803 as the secondary filament with types 0803 and 0041 as well as *Nocardia* at the tertiary level. Curiously *Nocardia*, which is known to cause foaming problems, was not identified during the period when foaming and scum accumulation occurred on the reactor surfaces, and now, when no foaming was observed, *Nocardia*, is noted at minor levels.

After day 190 and up till day 252, the DSVI gradually decreased from 200 to 100 ml/g. This period was associated with the presence of glutinous material in the sludge which caused blockage in the inter-reactor overflow pipes and consequent operational difficulties. Ketley *et al.* (1991) experienced similar blockages with single reactor fully anoxic systems fed

artificial sewage. Filament identification on day 223 showed that type 1851 and *H.hydrossis* were still dominant and secondary filaments respectively. Type 0803 was still present at the tertiary level. Type 021N, a nutrient deficiency filament, appeared for the first time also at the tertiary level. Overall filament abundance was common (see Fig.3.5.b).

On day 252 the PBCOD component of the influent feed was removed leaving RBCOD as the principal component of the artificial sewage. This was a temporary measure taken in an attempt to stop the development of glutinous material in the sludge which had been causing operational difficulties. It was thought that the glutinous material production was caused by extra-cellular growth promoted by the PBCOD component of the artificial sewage. It was later discovered, by Ketley *et al.* (1991), that glutinous production in the sludge increased when the nitrate + nitrite concentration leaving systems with single anoxic reactors, fed artificial sewage, decreased to below 5 mgN/*l*. Such low anoxic nitrate + nitrite concentrations were measured in the system from day 166 to day 252 (3,0 - 5,0 mgN/*l*) and lends support to Ketley's observation. From day 252 until the end of the 1st part of the investigation i.e. day 259, the DSVI dropped sharply from 100 to 60 ml/g. Associated with the drop in DSVI was the increase in inter-reactor blockages and continued glutinous material production. By day 259 the glutinous material production had become so excessive and the operational problems so serious that it was no longer possible to keep the system in operation with the expectation of obtaining reasonable results. So on day 259 operation of the system was stopped.

System 2 - MLE (see Fig.3.1.c)
The 2nd MLE system (54% anoxic, 46% aerobic) was set up on day 165 with start up sludge taken from the daily waste flow of the 1st MLE system. Both systems were identical in operation and configuration (see Table 3.1.a). By day 182, i.e. after 17 days, the MLVSS, DSVI and system response e.g. effluent COD, TKN, nitrate + nitrite was stable and acceptably close to that of the 1st MLE system.

Glutinous material produced in the sludge, which caused operational difficulties in the 1st MLE system, was also present in the 2nd MLE system causing similar operational difficulties. From day 182 to 218 the DSVI gradually declined from 250 to 150 ml/g. The same gradual decline and roughly the same DSVI values were observed in the 1st MLE system. This was seen as evidence that the low F/M filament populations of each system were similar. By day 218 it was established that this system could be operated to achieve similar results as the 1st MLE system and accordingly the 2nd MLE system was changed to a Wuhrmann system.

System 2 - Wuhrmann (see Fig.3.1.d)

On day 219 the positions of the anoxic and aerobic reactors of the 2nd MLE system were interchanged, to form the Wuhrmann configuration. The anoxic and aerobic mass fractions remained unchanged, i.e. 54 and 46% respectively. The design and operating parameters of the system are given in Table 3.1.b. The problems experienced with glutinous material production in the sludge continued unabated after the configuration change. Inter-reactor blockages were as frequent in the Wuhrmann as in the 1st MLE system.

From day 219 to day 252, the DSVI remained relatively unchanged from the level (150 m*l*/g) measured at the switch over to the Wuhrmann system. During the same period the DSVI of the 1st MLE system declined gradually from 180 to 100 m*l*/g. Filament identification on day 223 showed that filament type 1851 replaced *H.hydrossis* as dominant and *H.hydrossis* moved down to secondary. Types 0803, 0092 and 021N were present at the tertiary level. The filament type and frequency of occurrence, with the exception of type 0092, matched that of system 1 for the same period. Overall filament abundance was very common (see Fig.3.5.c).

On day 252 the PBCOD component of the artificial sewage was removed leaving only RBCOD in the influent feed. As with the 1st MLE system, this measure was taken in an attempt to prevent the production of glutinous material in the sludge which had been plaguing both systems.

From day 252 until day 259 (end of 1st part of the investigation) glutinous material production continued to cause inter-reactor blockages. During this period, filament abundance reflected by the DSVI test, remained unchanged with the measured DSVI being close to the 150 m*l*/g level.

At this point it should be noted that in both systems operating as either MLE or Wuhrmann, the DSVI did not reach the excessively high (>600 m*l*/g) levels observed in intermittent aeration systems fed artificial sewage with similar anoxic mass fractions (Casey *et al.*,1990); the filament populations in MLE, Wuhrmann and intermittent aeration systems were however the same in that *H.hydrossis* and type 1851 were consistently dominant. From this it was concluded that the overall filament abundance in the MLE and Wuhrmann systems was for some reason significantly lower than in the intermittent aeration systems fed the same artificial sewage and with the same anoxic mass fraction.

3.2.5 Conclusions for systems fed artificial sewage

With the operation of the MLE and Wuhrmann systems it became increasingly clear that the low F/M filaments present in bulking sludges fed artificial sewage (*H.hydrossis* and type 1851 in particular) were not the same as those found in similar systems fed real sewage in which *M.parvicella* and type 0092 tend to dominate. This observation, as well as the persistent

problem of the production of glutinous material with artificial sewage feed led to the decision to abandon further work with the artificial sewage and repeat the work with real sewage. Therefore in order to examine the impact on the nature of the anoxic zone i.e. its type, position, size and frequency of alternation with aerobic conditions, on filaments other than *H.hydrossis* it was decided to switch the influent feed to both systems from artificial to real sewage. The details and conclusions of the research with real sewage are given in section 3.3 of this chapter. At this juncture, the following conclusions can be drawn from the artificial sewage work presented above:

(1) Sludge bulking (DSVI > 150 m*l*/g) did occur in both systems operating as MLE systems, but not in system 2 when operating as as a Wuhrmann system. Even though bulking (DSVI > 150 m*l*/g) did occur in the MLE systems it was never as excessive as in similar intermittent aeration systems fed artificial sewage (DSVI > 600 m*l*/g).

(2) Changing the position of the anoxic reactor, without altering its size, by switching from an MLE to Wuhrmann configuration did not affect the filament population type but did affect the overall filament abundance. i.e. generally the Wuhrmann system had a consistently lower DSVI than the MLE system.

(3) A marked drop in DSVI was observed (400 to 200 m*l*/g) when the anoxic mass fraction of the 1st MLE system was reduced from 70% to 54% . This observation is confounded by the concomitant reduction of nitrate dosage to the anoxic reactor (50 to 25 mgN/*l*). However, as the system effluent nitrate + nitrite concentration (see Fig.3.6) was high (>10 mgN/*l*) it is most probable that the decrease in DSVI was not induced by the reduction of nitrate dosed to the anoxic reactor. Because of the erratic fluctuation in DSVI measured during the period when the anoxic mass fraction of the 1st MLE system was 70% (start up till day 35), it is reasonable to assume that the initial high DSVI (400 m*l*/g) was attributable to the high filament content of the start up sludge; this was harvested from an intermittent aeration system fed artificial sewage shown to promote bulking sludges (Casey *et al.*, 1990).

(4) Low F/M filaments *H.hydrossis* and type 1851 were frequently identified as dominant or secondary in the MLE and Wuhrmann systems. This also was the case in intermittently aerated and MUCT systems fed artificial sewage. In contrast *M.parvicella* and types 0041 and 0092, usually are dominant filaments in bulking sludges fed real sewage. These real sewage filaments were identified only at minor levels in the systems fed artificial sewage or as in the case of *M.parvicella*, not at all.

(5) Glutinous material production, not observed in systems fed real sewage, was observed in the MLE and Wuhrmann systems fed artificial sewage and is possibly stimulated by low nitrate and/or nitrite concentrations in the anoxic reactor. Ketley *et al.* (1991) subsequently observed similar glutinous material production in single reactor fully anoxic systems with low anoxic reactor and hence also in the effluent, nitrate + nitrate concentrations, fed artificial sewage.

(6) Feeding the MLE and Wuhrmann systems artificial sewage comprising proportions of (i) PBCOD and RBCOD and (ii) only RBCOD did not stimulate low F/M filament proliferation to the levels expected from earlier observations in intermittently aerated systems fed artificial sewage (see Casey *et al.* 1990). So by contrast for artificial sewage, the MLE and Wuhrmann systems cannot really be said to have developed bulking sludges.

3.3 EXPERIMENTAL INVESTIGATION PART 2: OBSERVATION OF LOW F/M FILAMENT PROLIFERATION IN MLE AND WUHRMANN SYSTEMS FED REAL SEWAGE.

In this part of the investigation three systems were set up: Initially the same two systems operated in the 1st part of the investigation (MLE and Wuhrmann) and later a 2nd MLE system. The design and operating features of the 1st MLE, Wuhrmann and 2nd MLE systems operated during this part of the investigation are given in Tables 3.9.a,b and c respectively.

The 1st MLE and Wuhrmann systems each were operated for 285 days, starting from day 260 to day 545. The 2nd MLE system was started up on day 508 and operated for 37 days up to day 545. On day 545 the investigation terminated. Daily during these periods of operation the following parameters were measured on each of the 3 systems and plotted graphically.

1 Influent and unfiltered effluent COD (see Fig.3.10).
2 Influent and unfiltered TKN (see Fig.3.11).
3 Total and volatile mixed liquor suspended solids, MLSS and MLVSS concentrations (see Fig.3.12).
4 Sludge settleability, DSVI (see Fig.3.13).
5 Filtered effluent nitrate + nitrite concentration (see Fig.3.14).
6 Filtered (0.45$_\mu$m) anoxic and aerobic nitrate + nitrite concentration (see Fig.3.15).
7 Oxygen utilization rate in the aerobic reactor (see Fig.3.16).

The COD/VSS ratio (f_{cv}) and TKN/VSS ratio (f_n) were measured regularly on each of the 1st MLE and Wuhrmann systems; the COD/VSS ratio 70 times and the TKN/VSS ratio 55

times. The methods whereby these parameters were measured are detailed in Appendix B and all the measured data on the 3 systems are listed in Appendix E.

The 285 day period over which the 1st MLE and Wuhrmann systems were operated was divided into 17 steady state periods for each system and the 37 day period over which the 2nd MLE system was operated was divided in to 3 steady state periods. The steady state periods coincided with new sewage batches fed to the systems (new influent sewage collection and storage is outlined in Appendix B). The first steady state period of the 1st MLE and Wuhrmann systems were regarded as transition periods in switching from artificial to real sewage.

Towards the end of the 1st part of the investigation in which the 1st MLE and Wuhrmann systems were fed artificial sewage these systems were beset with operational difficulties caused by excessive production of glutinous material in the sludge. On day 260, when the artificial feed to the 1st MLE and Wuhrmann systems was replaced with real sewage, the underflow recycle ratio was increased, in both systems, from a ratio of 1:1 with respect to the influent flow to 2:1. This step was taken in an attempt to alleviate inter-reactor blockages by increasing the inter-reactor flow rate. In all other respects both systems were operated in the same way and with the same design parameters as during the 1st part of the investigation (see Tables 3.9.a and b).

The 2nd part of the investigation, in which the nature of the anoxic zone on low F/M filament proliferation in MLE and Wuhrmann systems is examined, differs from the 1st part not only in feeding real sewage rather than artificial sewage but also in exploring the effect of the frequency of alternation between anoxic and aerobic conditions on low F/M filament proliferation. Accordingly, the 285 day period was divided into 7 phases with different configurational and operational conditions for each phase in both the 1st MLE and Wuhrmann systems. The days on which these changes were made and the motivating reasons for these changes are given in Table 3.10 for the 1st MLE and Wuhrmann systems respectively. Operation of the 2nd MLE system (design and operating parameters are given in Table 3.9.c) was commenced to investigate the effect of the MLVSS concentration on low F/M filament proliferation. This was done by keeping all the parameters of this system the same as that of the 1st MLE system, except the volume of the anoxic and aerobic reactors, which were each enlarged by 54%. With the same raw wastewater, COD load and sludge age, the 1st and 2nd MLE systems accumulate the same mass of MLVSS in the reactors. Because the reactor volumes of the 2nd MLE system were 54% larger, the MLVSS concentration was about 35% lower in the 2nd MLE system than the 1st MLE system.

The commencement and termination days of the operational phases and steady state periods are given in Table 3.11 This Table also shows the daily frequency of alternation between anoxic and aerobic conditions in operation of the 1st MLE, Wuhrmann and 2nd MLE systems during the different phases. The frequency of alternation between anoxic and aerobic conditions per day is given by the inverse of the actual retention time i.e.

$$\frac{Q(1 + a + s)}{Vp} \quad (/d) \qquad (3.15)$$

Where

Q = influent flow rate (l/d)
a = mixed liquor recycle ratio
s = underflow recycle ratio
Vp = process volume (l)

3.3.1 Discussion of mass balance and substrate utilization rates

For each steady state period identified, N and COD mass balances and COD utilization rates were calculated. The methods employed to calculate the N and COD mass balances and substrate utilization rates were the same as those described in sections 3.2.1 and 3.2.2 above, with one exception. In section 3.2.3.a above the artificial sewage influent COD reduction factor (R_f) was described to quantify the mass of influent COD lost through slime production and accumulation on the feed bucket and feed line walls. Associated with the loss of influent COD was a loss of influent TKN (see Equ.3.12). These losses were attributed to the mechanical stirring in the feed bucket required to keep all the components (see Table 3.2) of the artificial sewage in suspension. The components of real sewage separate far more slowly than those of artificial sewage, thereby requiring much gentler mechanical stirring in the feed bucket. Accordingly the slime growth and accumulation on the feed bucket and feed line walls was observed to be far less significant in the systems fed real sewage compared to the same systems fed artificial sewage. Therefore the influent COD and TKN values used to calculate the N and COD mass balances and substrate utilization rates were the same as those measured from the sample taken from the influent feed bucket at the start of each 24 hour period.

The results of the steady state mass balance and substrate utilization calculations are shown in Table 3.12 and are discussed below.

3.3.1.a N mass balances

In the 1st and 2nd MLE systems good average N balances were obtained of 94% and 96% respectively. In the Wuhrmann system an average N balance of 106% was obtained.

Table 3.9.a: Operating parameters of 1st MLE system days 260 to 545

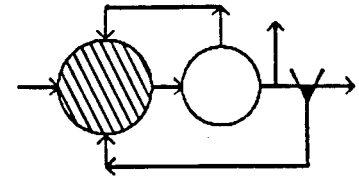
System Conditions	Operating parameters
Operating conditions	continuously fed, 2 reactors in series both completely mixed
Graphical representation	
Aeration	Reactor 1 Anoxic Reactor 2 Aerobic
Volumes (l)	Reactor 1 3.5 Reactor 2 3.0
Unaerated mass fraction (%)	55
	Days 260 –343 344 – 351 352 – 545
(a) recycle ratio	0:1 0:1 4:1
(s) recycle ratio	2:1 1:1 1:1
Hydraulic retention time (hours)	15.6
Sewage	Real
Volume of feed (l/d)	10
Concentration of feed (mgCOD/l)	500
Influent TKN (mgN/l)	40 – 60
Sludge age (days)	15
Temperature (degrees°C)	20
MLVSS concentration (mgVSS/l)	2000
pH	7,4 – 8,0

Table 3.9.b: Operating parameters of Wuhrmann system days 260 to 545

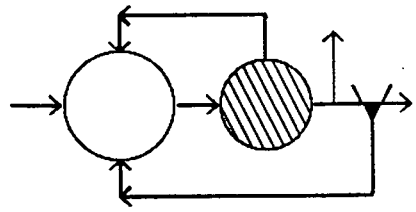
System Conditions	Operating parameters
Operating conditions	continuously fed, 2 reactors in series both completely mixed
Graphical representation	
Aeration	Reactor 1 Aerobic Reactor 2 Anoxic
Volumes (l)	Reactor 1 3.0 Reactor 2 3.5
Unaerated mass fraction (%)	55
	Days 260 –343 344 – 351 352 – 545
(a) recycle ratio	0:1 0:1 4:1
(s) recycle ratio	2:1 1:1 1:1
System hydraulic retention time (hours)	15.6
Sewage	Real
Volume of feed (l/d)	10
Concentration of feed (mgCOD/l)	500
Influent TKN (mgN/l)	40 – 60
Sludge age (days)	15
Temperature (degrees °C)	20
MLVSS concentration (mgVSS/l)	2000
pH	7,4 – 8,0

Table 3.9.c: Operating parameters of 2nd MLE system days 508 to 545

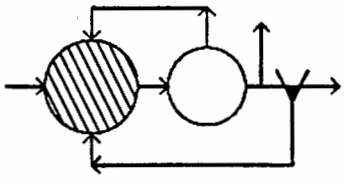
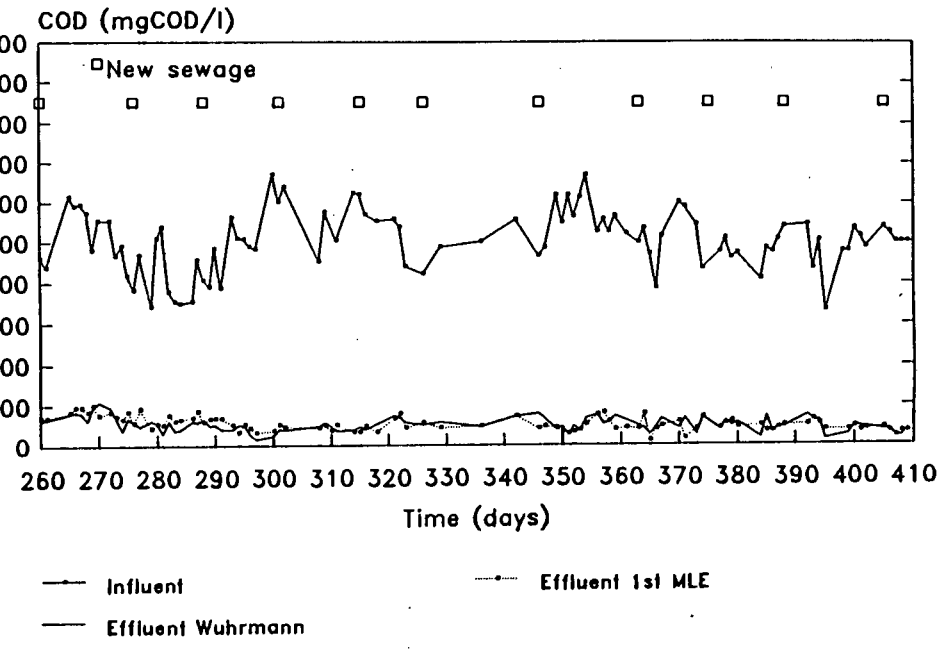
System Conditions	Operating parameters
Operating conditions	continuously fed, 2 reactors in series both completely mixed
Graphical representation	
Aeration	Reactor 1 Anoxic Reactor 2 Aerobic
Volumes (l)	Reactor 1 7.0 Reactor 2 3.0
Unaerated mass fraction (%)	70
(a) recycle ratio (s) recycle ratio	4:1 1:1
System hydraulic retention time (hours)	24.0
Sewage	Real
Volume of feed (l/d)	10
Concentration of feed (mgCOD/l) Influent TKN (mgN/l)	500 40 – 60
Sludge age (days)	15
Temperature (degrees °C) MLVSS concentration (mgVSS/l) pH	20 1600 7,4 – 8,0

Table 3.10: Operational and configurational changes made to the 2 MLE and Wuhrmann systems during the 2nd part of the investigation.

Day	System	Change	Reason
260	1st MLE Wuhrmann	Replaced artificial sewage with real sewage. Nitrate dosed to the anoxic reactor = ± 12 mgN per liter of influent.	Continue investigation into effect of anoxic zone on low F/M filament growth in systems fed real sewage.
260	1st MLE	Increased underflow s-recycle ratio to 2:1.	To speed up inter reactor flow rate in an attempt to reduce inter-reactor blockages caused by glutinous material production in the sludge.
344	1st MLE	Reduced s-recycle to 1:1.	Inter-reactor blockages had ceased.
352	Wuhrmann	Reduced s-recycle to 1:1.	Inter-reactor blockages had ceased.
352	1st MLE	Increased mixed liquor a-recycle ratio from 0:1 to 4:1.	To increase anoxic/aerobic frequency of alternation.
385	1st MLE	Increased anoxic reactor volume to 4,5 *l* and reduced aerobic volume to 2,0 *l*.	To increase anoxic mass fraction from 54 to 70%
385	Wuhrmann	Increased mixed liquor a-recycle ratio from 0:1 to 4:1.	To increase anoxic/aerobic frequency of alternation.
430	1st MLE	Increased nitrate dosed to the anoxic reactor from 12 to 20 mgN liter influent.	Avoid nitrate depletion in the anoxic reactor.
447	1st MLE	Increased a-recycle ratio from 4:1 to 6:1.	To increase anoxic/aerobic frequency of alternation.
447	Wuhrmann	Increased a-recycle ratio from 4:1 to 7:1 and increase s-recycle ratio from 1:1 to 2:1.	To increase anoxic/aerobic frequency of alternation.

Table 3.10: continued

472	Wuhrmann	Seeded bulking sludge harvested from intermittently aerated system.	To confirm that Wuhrmann system slows low F/M filament growth.
479	1st MLE	Reduced nitrate dosed to the anoxic reactor from 20 to 12 mgN per liter influent.	To contain rising sludge in the clarifier
495	1st MLE	Increased a-recycle ratio from 6:1 to 31:1.	To increase anoxic/aerobic frequency of alternation.
499	1st MLE	Reduced a-recycle ratio from 31:1 to 17:1.	To decrease anoxic/aerobic frequency of alternation.
500	1st MLE	Seeded sludge from Wuhrmann system.	To restore sludge VSS after tube split.
508	2nd MLE	Start up system with sludge harvested from MLE and Wuhrmann systems.	Investigate the effect of sludge concentration on low F/M filament growth.
508	1st MLE	Reduced a-recycle ratio from 6:1 to 4:1.	To decrease anoxic/aerobic frequency of alternation.
508	Wuhrmann	Reduced a-recycle ratio from 7:1 to 4:1 and s-recycle ratio from 2:1 to 1:1.	To decrease anoxic/aerobic frequency of alternation.
524	1st MLE 2nd MLE	Blended together sludges from both systems.	To aquire identical starting conditions for comparison of low F/M filament growth in 2 MLE systems.
524	Wuhrmann	Increased anoxic reactor volume to 4,5 *l* and reduced aerobic volume to 2,0 *l*.	To increase anoxic mass fraction from 54 to 70%
545		Stopped investigation.	



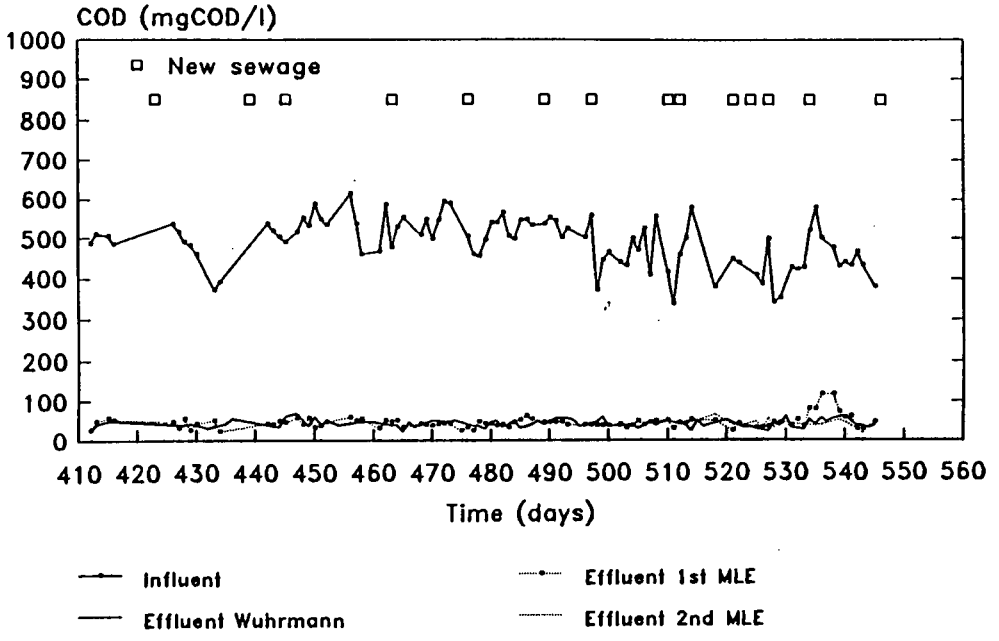
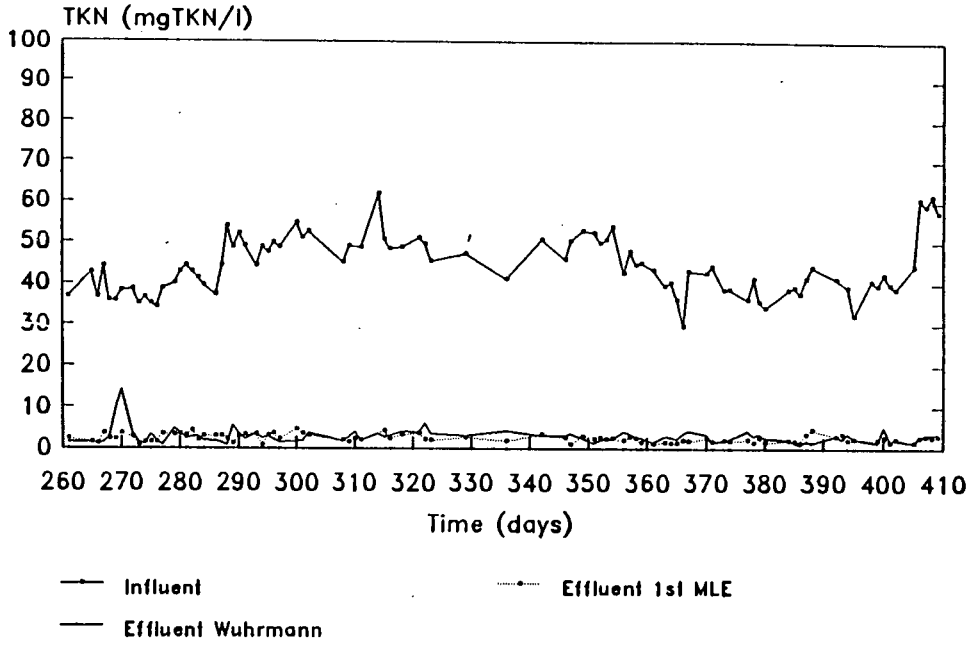


Fig 3.10 Daily influent and effluent COD concentrations measured for the 2 MLE and Wuhrmann systems during the 2nd part of the investigation (days 260 to 545)



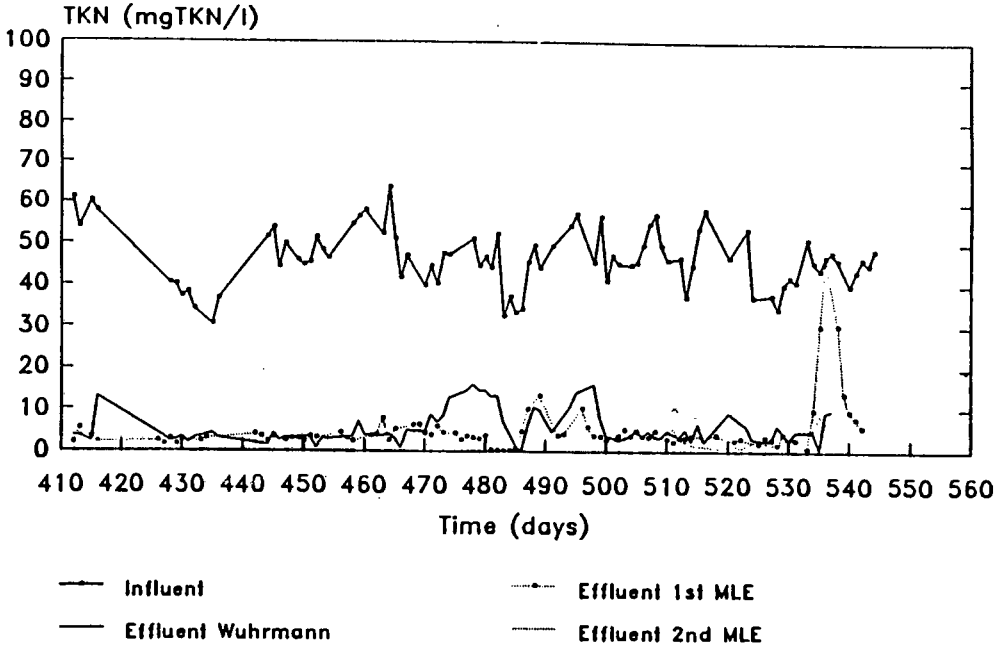
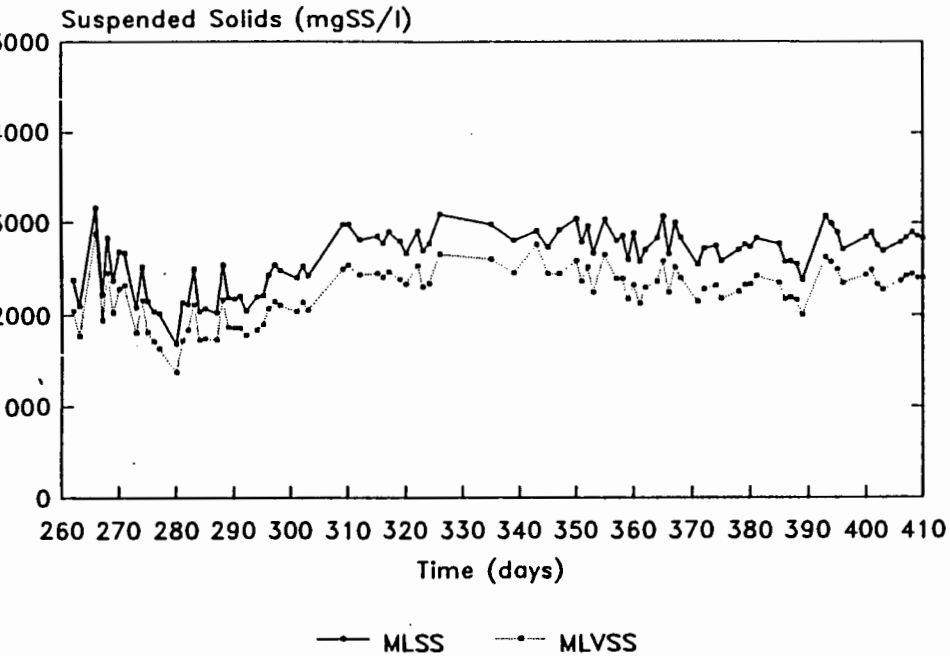


Fig 3.11 Daily influent and effluent TKN concentrations measured for the 2 MLE and Wuhrmann systems during the 2nd part of the investigation (days 260 to 545)



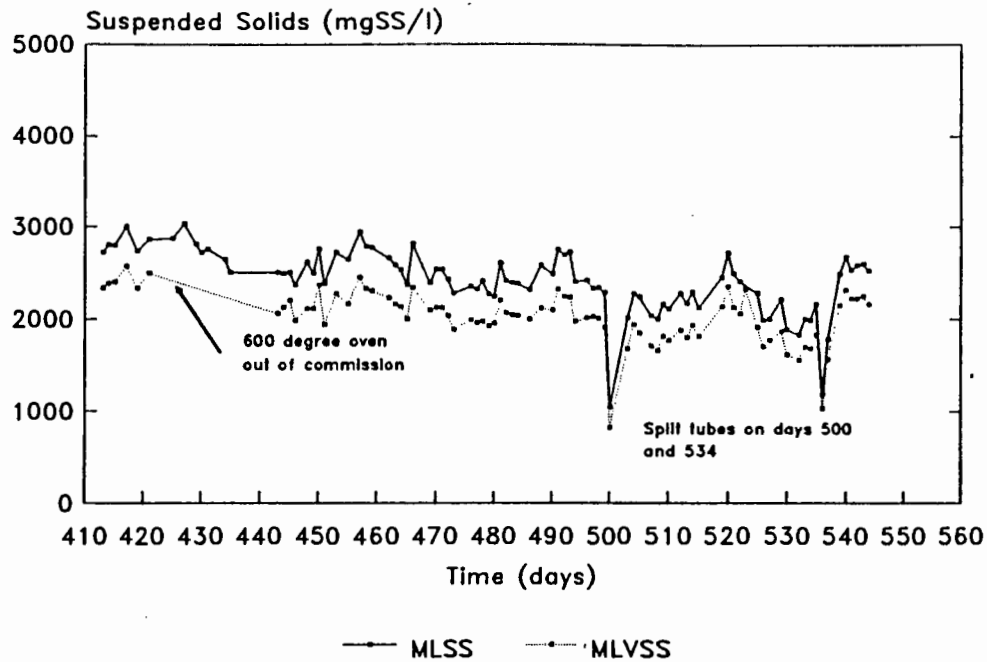
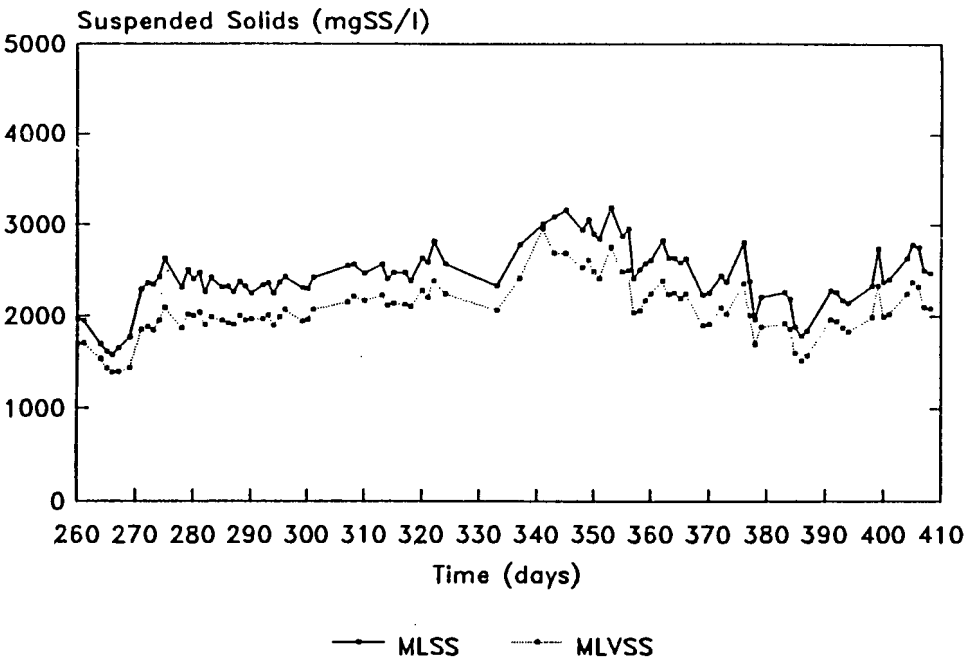


Fig 3.12.a Daily total and volatile mixed liquor suspended solids concentrations measured for the 1st MLE system during the 2nd part of the investigation (days 260 to 545)



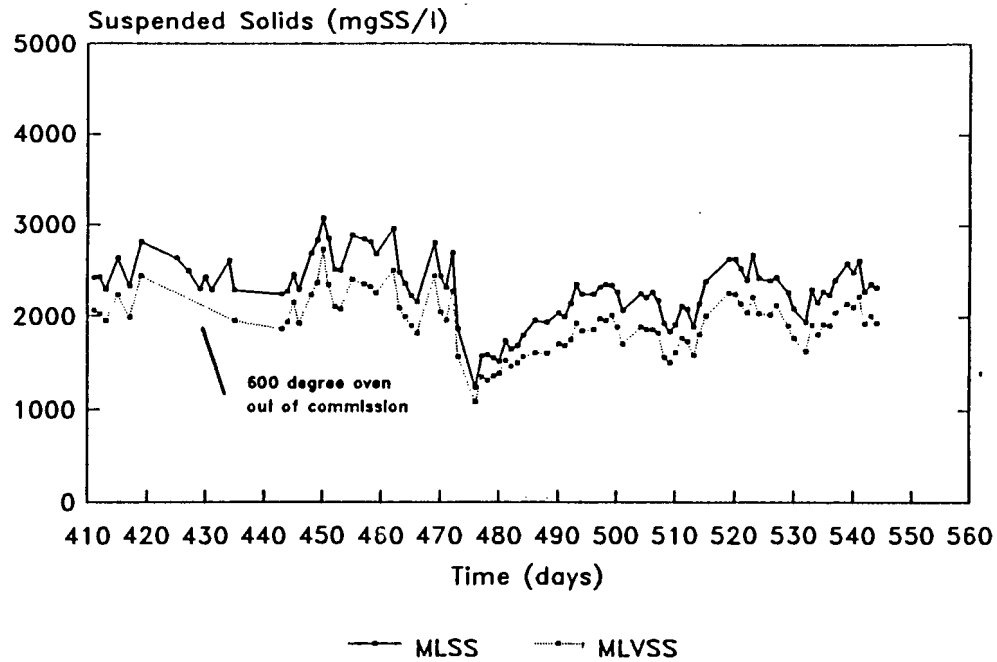


Fig 3.12.b Daily total and volatile mixed liquor suspended solids concentrations measured for the Wuhrmann system during the 2nd part of the investigation (days 260 to 545)

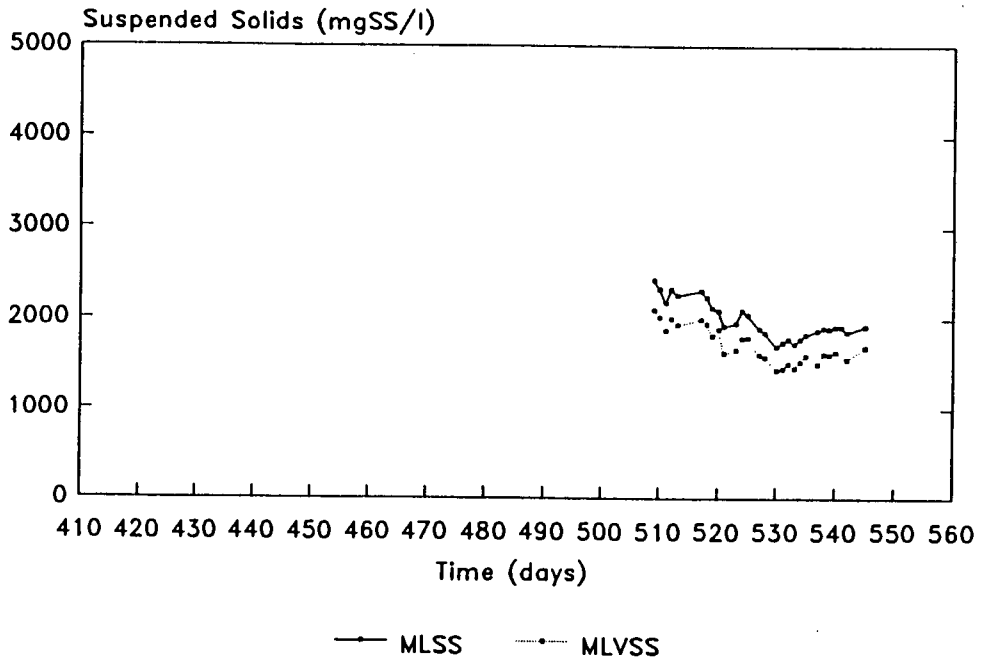
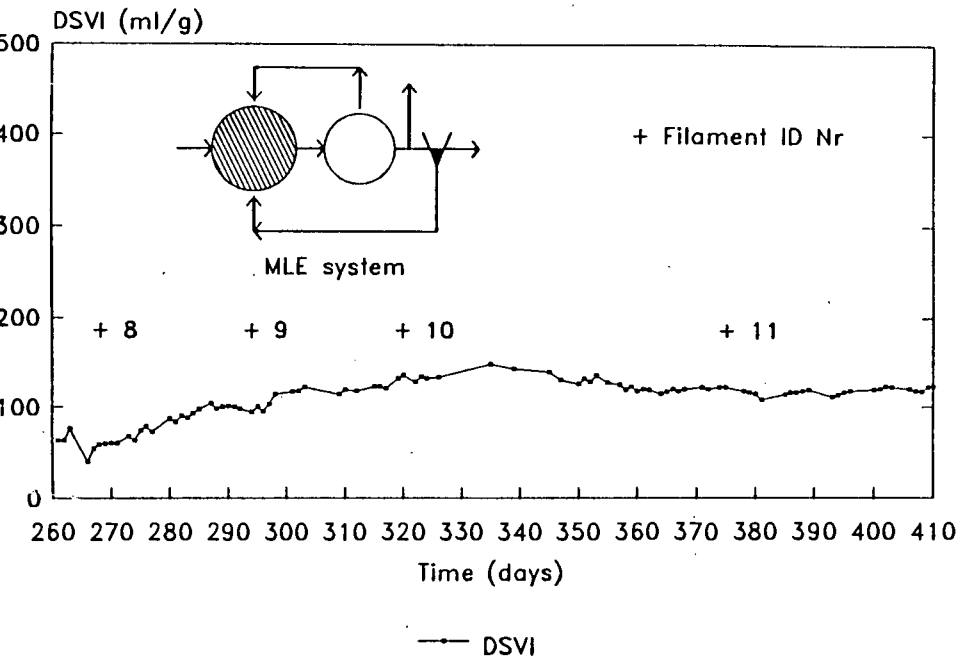


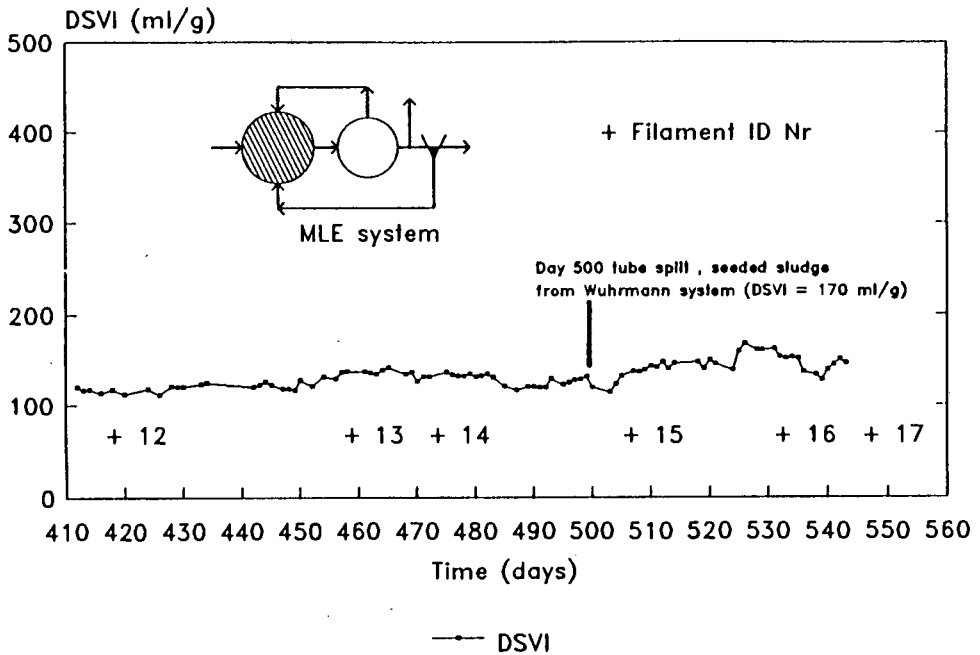
Fig 3.12.c Daily total and volatile mixed liquor suspended solids concentrations measured for the 2nd MLE system during the 2nd part of the investigation (days 508 to 545)



FILAMENT IDENTIFICATION
SYSTEM 1

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
8	267	1851	*H.hydrossis*	0041	very common
9	293	0092	*H.hydrossis*	0041, 1851, *Beggiatoa sp.*	common to very common
10	317	0092	*H.hydrossis*	0041, 1851, *Beggiatoa sp.*	very common
11	374	*H.hydrossis*	0092	0041, 021N	very common to abundant

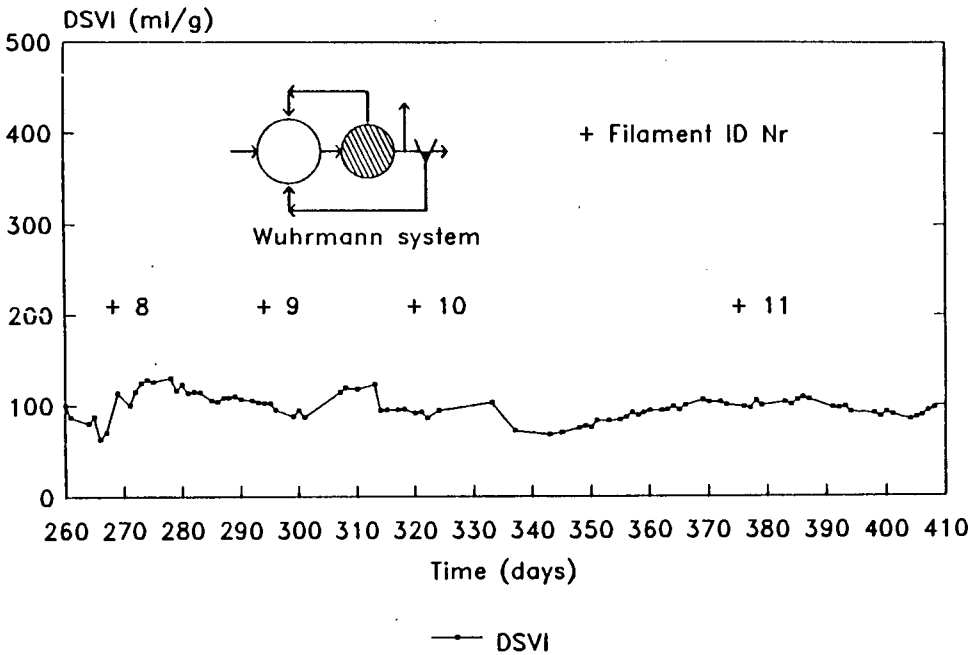
Fig 3.13.a Daily DSVI measured for the 1st MLE system during the 2nd part of the investigation (days 260 to 410). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION
SYSTEM 1

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
12	419	0092	*Beggiatoa sp.*	*M.parvicella*, *H.hydrossis*, 021N, 0041	common
13	457	*H.hydrossis*	0041	*Beggiatoa sp.* 0092, 021N	very common
14	472	021N	0092	0041, 1851 *H.hydrossis*	common
15	504	021N	0092	*H.hydrossis*, *M.parvicella*, 0041	very common to abundant
16	531	021N	0092	*H.hydrossis*, *M.parvicella*, 0041	common to very common
17	545	021N	0092	*H.hydrossis*, *M.parvicella*, 0041	very common

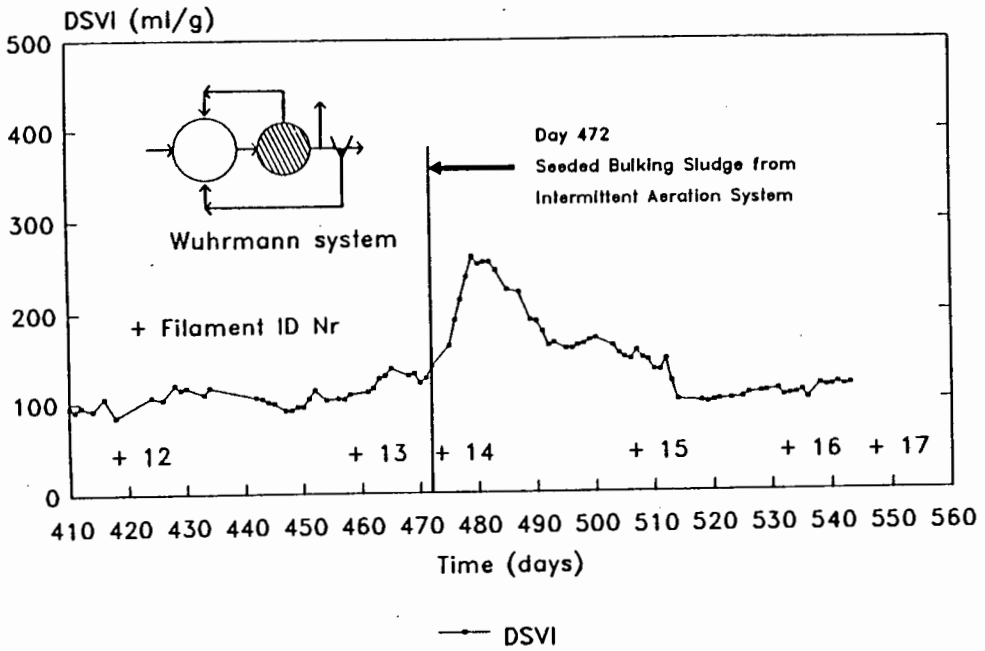
Fig 3.13.b Daily DSVI measured for the 1st MLE system during the 2nd part of the investigation (days 410 to 545). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION SYSTEM 2

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
8	267	1851	*H.hydrossis*	0041	very common
9	293	0092	*H.hydrossis*	0041, 1851, *Beggiatoa sp.*	common to very common
10	317	0092	*H.hydrossis*	0041, 1851, *Beggiatoa sp.*	very common
11	374	*H.hydrossis*	0092	0041, 021N	very common to abundant

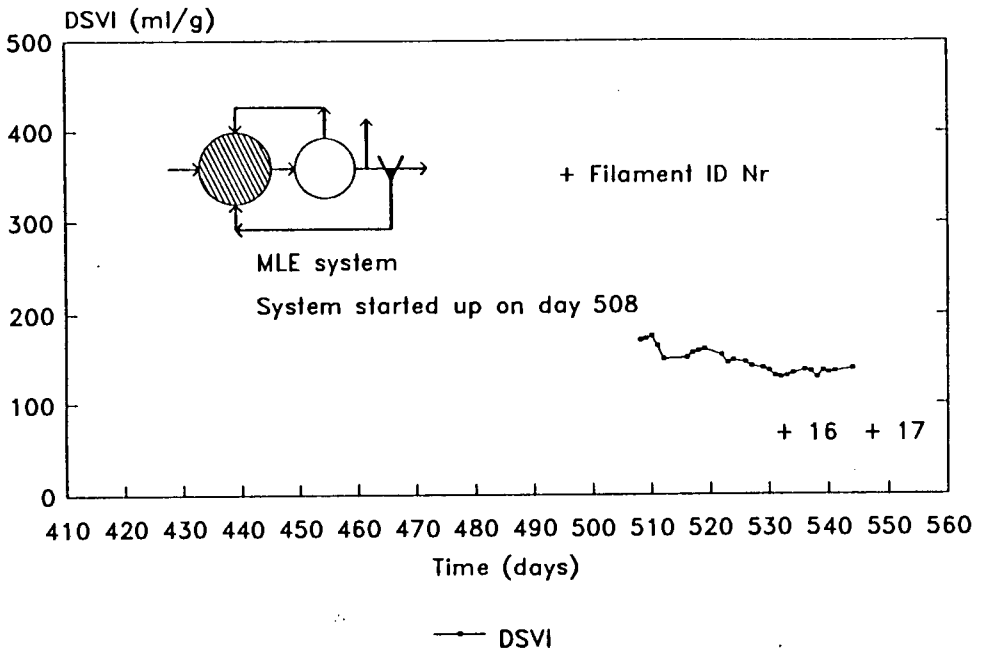
Fig 3.13.c Daily DSVI measured for the Wuhrmann system during the 2nd part of the investigation (days 260 to 410). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION
SYSTEM 2

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
12	419	0041	0092	*H.hydrossis*, 021N	very common
13	457	0041	0092	*H.hydrossis*, *M.parvicella*, 021N, 1851	common
14	472	0041	0092	*H.hydrossis* *M.parvicella*, 021N	some
15	504	0041	--------	*H.hydrossis*, *M.parvicella*, 1701, 0041 021N	very common
16	531	0041	*H.hydrossis*	0092, 021N, *M.parvicella*,	common to very common
17	545	*H.hydrossis*	0041	0092, 021N, *M.parvicella*,	very common to abundant

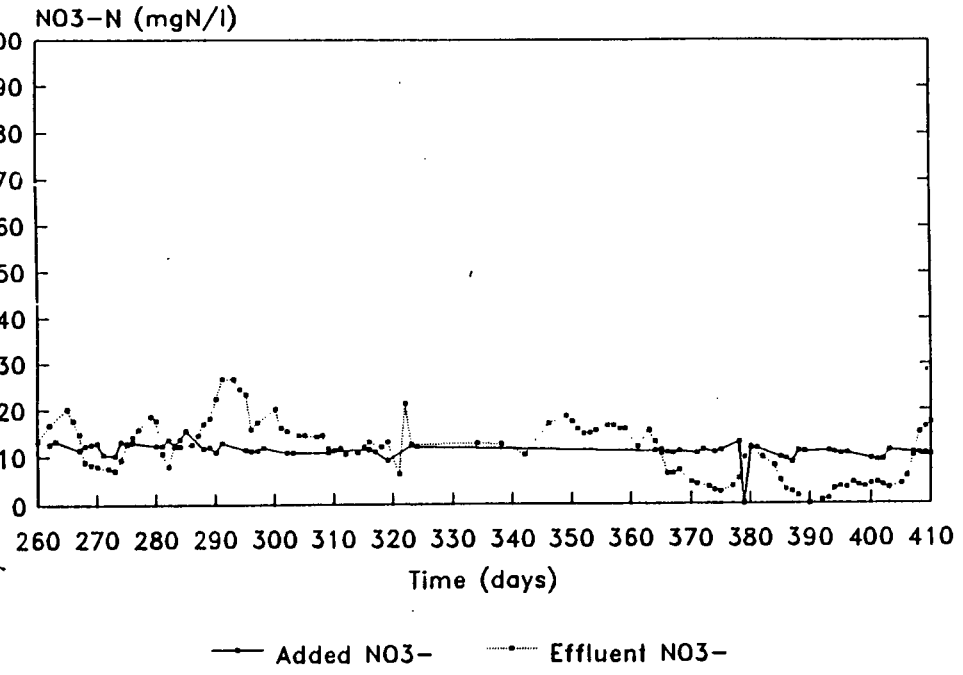
Fig 3.13.d Daily DSVI measured for the Wuhrmann system during the 2nd part of the investigation (days 410 to 545). Also shown on this figure are the filament identifications performed approximately once per month.



FILAMENT IDENTIFICATION
SYSTEM 3

ID Nr	Day	Dominant	Secondary	Tertiary	Abundance
16	531	021N	0092	*H.hydrossis*, *M.parvicella*, 0041	abundant
17	545	021N	0092	*H.hydrossis*, *M.parvicella*, 0041	common to very common

Fig 3.13.e Daily DSVI measured for the 2nd MLE system during the 2nd part of the investigation (days 508 to 545). Also shown on this figure are the filament identifications performed approximately once per month.



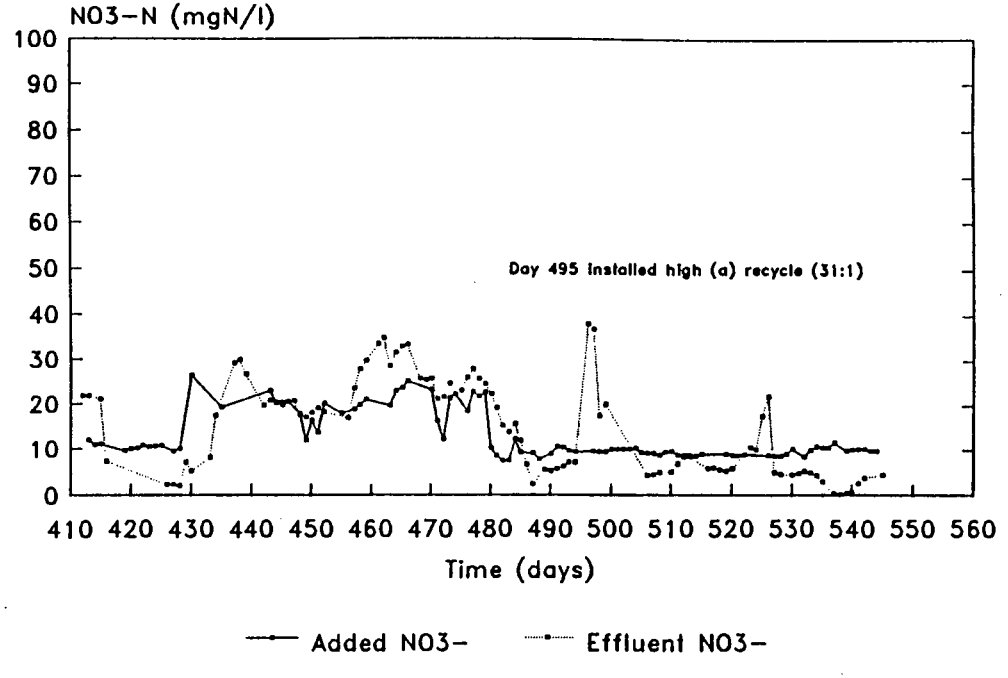
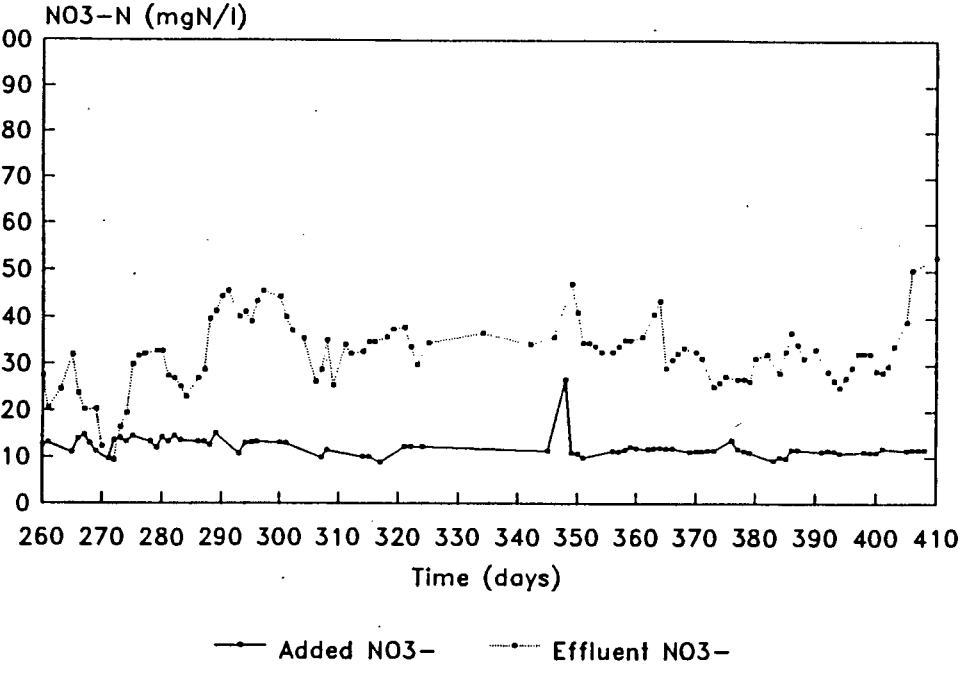
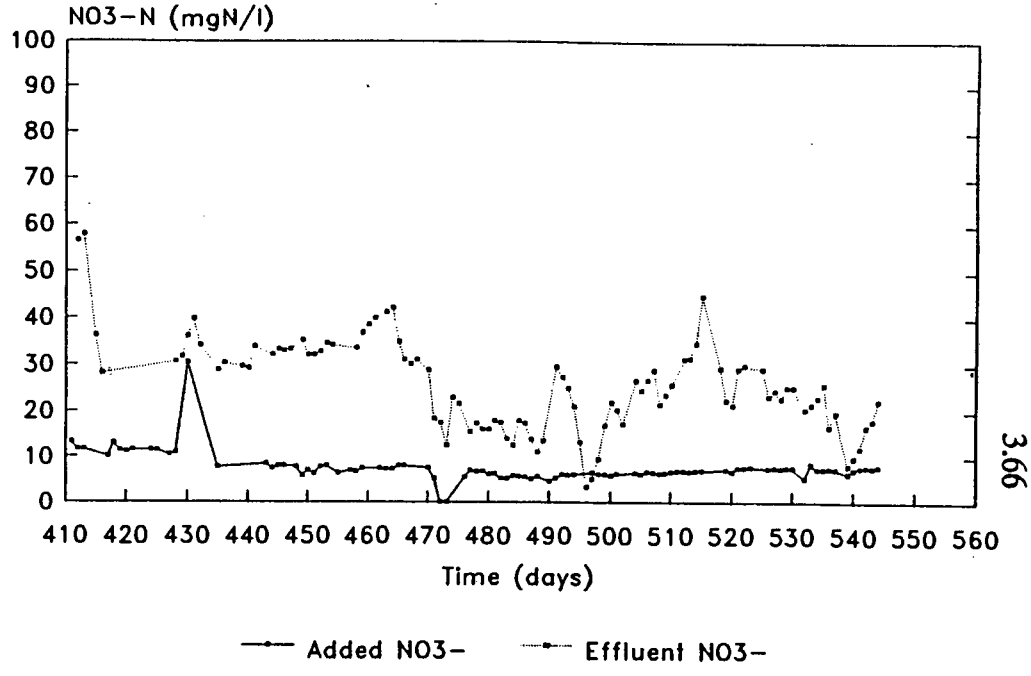


Fig 3.14.a Daily NO_3^- concentration dosed to the anoxic reactor and filtered effluent NO_3^- + NO_2^- concentration for the 1st MLE system during the 2nd part of the investigation (days 260 to 545).





3.66

Fig 3.14.b Daily NO_3^- concentration dosed to the anoxic reactor and filtered effluent NO_3^- + NO_2^- concentration for the Wuhrmann system during the 2nd part of the investigation (days 260 to 545).

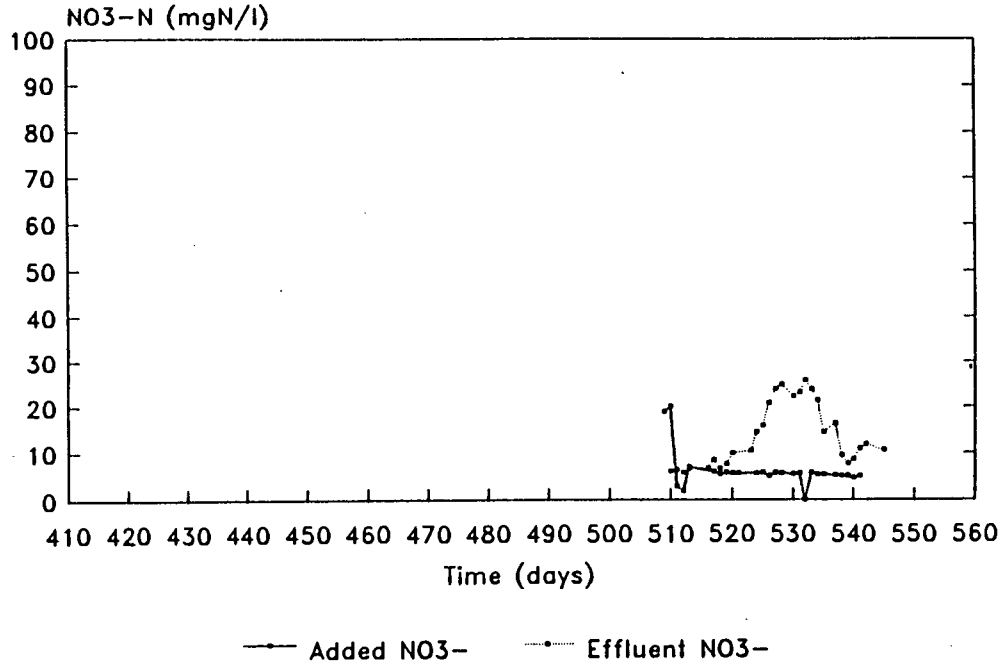


Fig 3.14.c Daily NO_3^- concentration dosed to the anoxic reactor and filtered effluent NO_3^- + NO_2^- concentration for the 2nd MLE system during the 2nd part of the investigation (days 508 to 545).

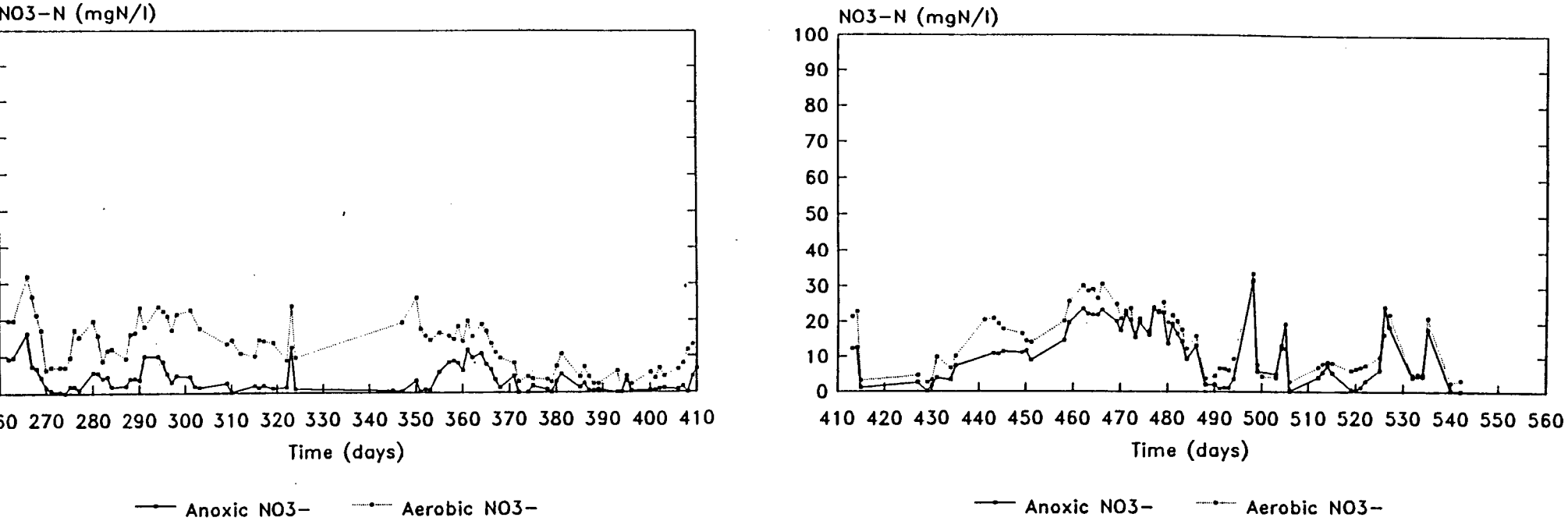
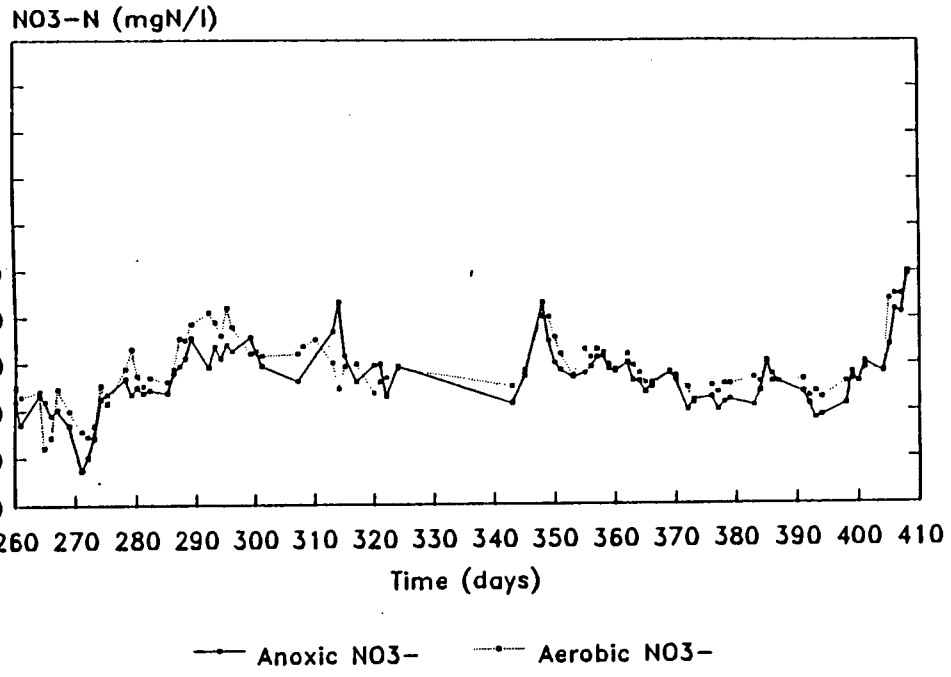


Fig 3.15.a Daily 0,45μm filtered anoxic and aerobic reactor NO_3^- + NO_2^- concentrations for the 1st MLE system during the 2nd part of the investigation (days 260 to 545)



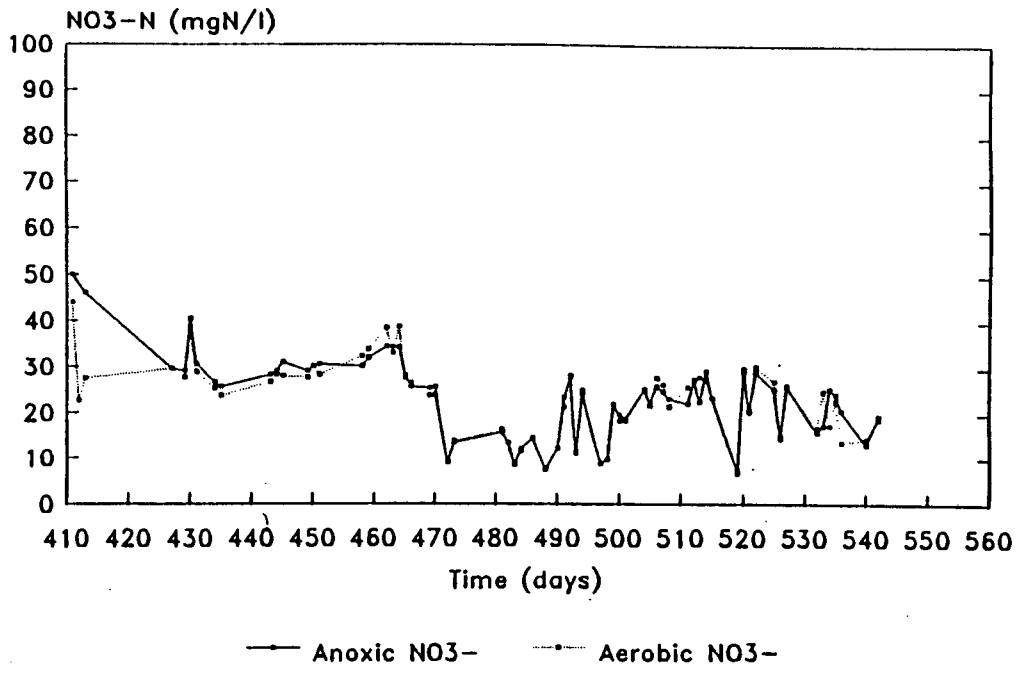


Fig 3.15.b Daily 0,45μm filtered anoxic and aerobic reactor NO_3^- + NO_2^- concentrations for the Wuhrmann system during the 2nd part of the investigation (days 260 to 545)

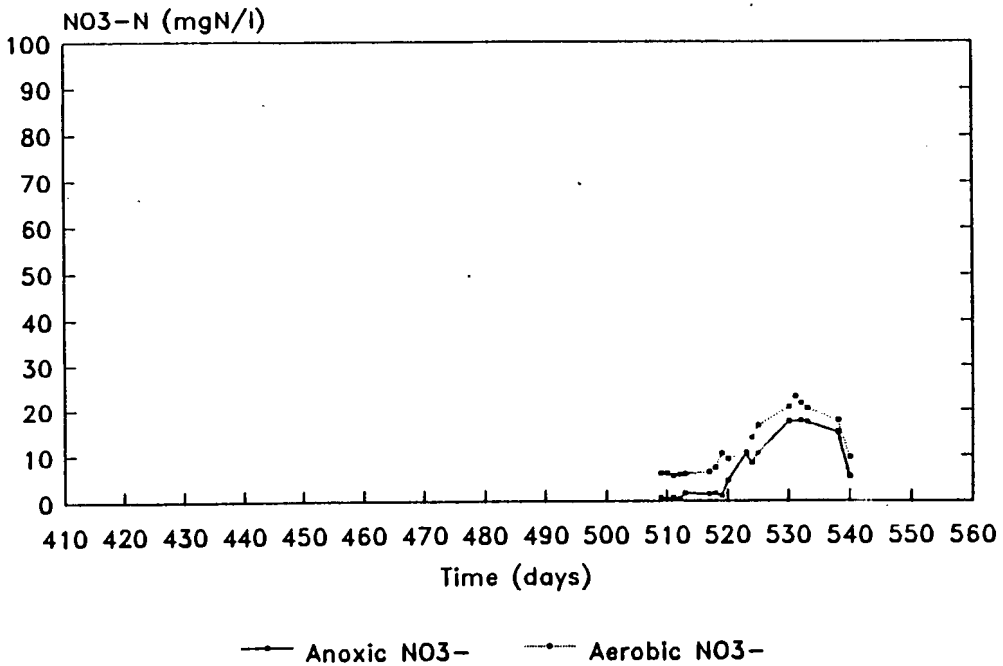
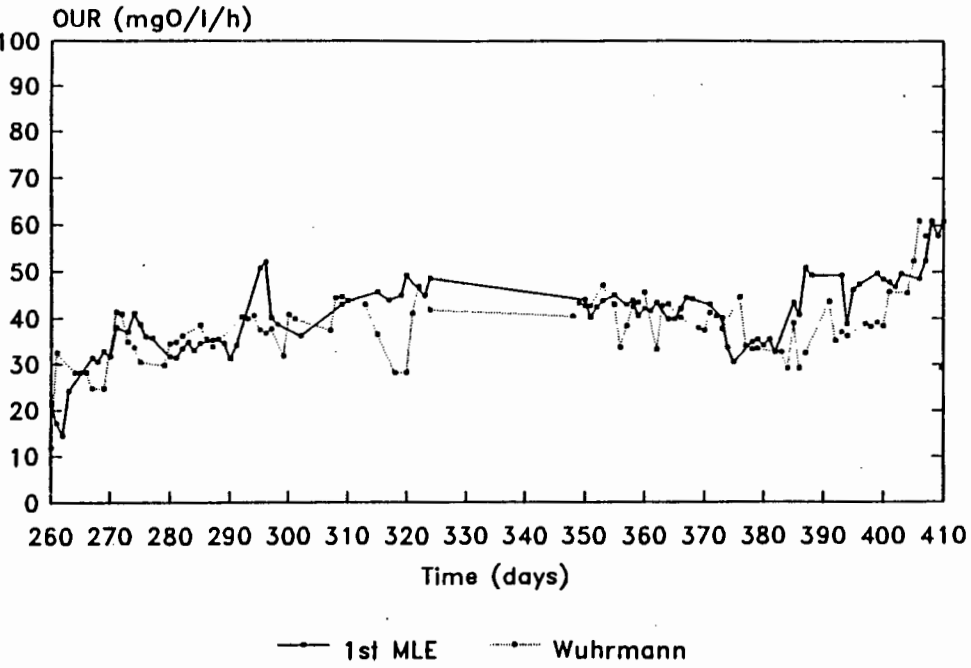


Fig 3.15.c Daily 0,45µm filtered anoxic and aerobic reactor NO_3^- + NO_2^- concentrations for the 2nd MLE system during the 2nd part of the investigation (days 508 to 545)



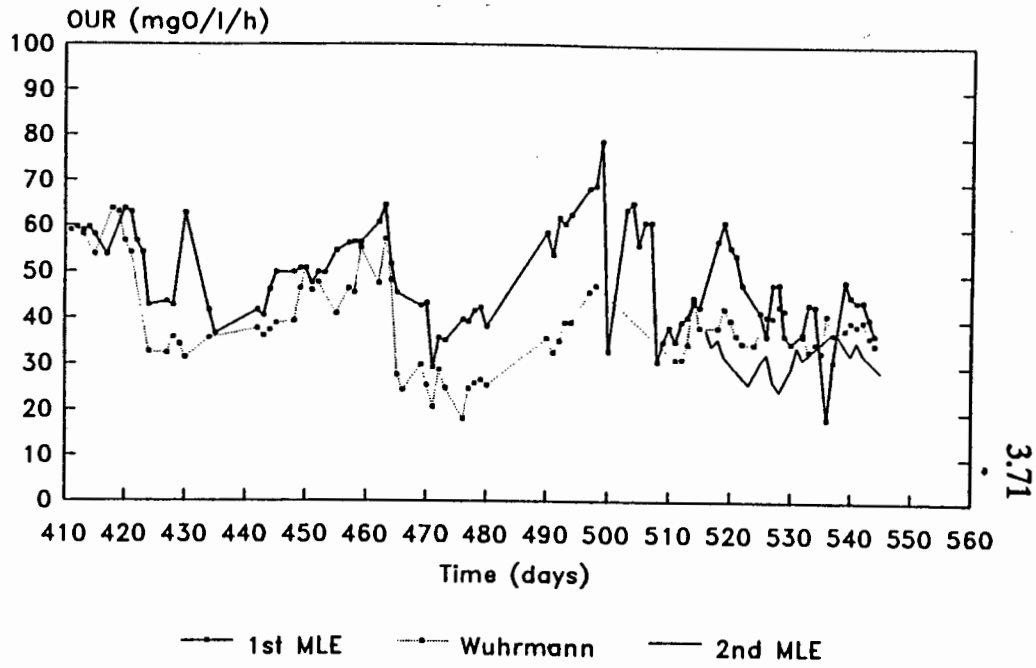


Fig 3.16 Daily oxygen utilization rates measured in the aerobic reactors of the 2 MLE and Wuhrmann systems during the 2nd part of the investigation (days 260 to 545)

The good N recovery in the 3 systems indicates that operational and testing procedures were accurately performed. Each system had varying mixed liquor recycle ratios, which directly effect the N mass balance (see Appendix C Equ.C1) yet consistently good N balances were achieved. Typically a 0.5 mgN/*l* measurement error in the anoxic reactor nitrate + nitrite concentration can effect a 5% N mass balance change in a system with a 4:1 mixed liquor recycle ratio.

3.3.1.b COD mass balances

The 1st MLE system obtained an average COD mass balance (17 steady state periods) of 77%. The 2nd MLE system obtained an average of 78%. From Table 3.12.a it can be seen that the COD mass balance deteriorated after the anoxic mass fraction of the 1st MLE system was increased from 54 to 70%. Typically the COD mass balance ranged from 72 to 88% with a 54% anoxic mass fraction and ranged from 64 to 73% with a 70% anoxic mass fraction. As the same system operation and test procedures were used throughout the investigation and yielded good N mass balances the lower COD mass balances calculated for the systems with high anoxic mass fractions cannot be ascribed to poor experimental procedure but rather confirms the tendency noted by Warburton *et al.* (1991) that, for some as yet unknown reason, systems with large anoxic mass fractions (50-70%) yield low COD mass balances. This tendency is confirmed by the 2nd MLE system which had the same anoxic mass fraction as the 1st MLE system and which obtained an average COD mass balance very close to that of the 1st MLE system.

For the Wuhrmann system 17 steady state periods were identified and an average COD mass balance of 68% was obtained. As the same test procedures were used to measure the parameters required to calculate the COD mass balances of the 1st and 2nd MLE systems, in which better COD mass balances were obtained it would appear that in the Wuhrmann system, generally lower COD mass balances were obtained.

3.3.1.c RBCOD utilization rates

The RBCODUR in the first reactor (anoxic in the MLE systems and aerobic in the Wuhrmann) was limited by the loading rate of RBCOD on the first reactor of the systems because the maximum potential RBCODUR was significantly greater than the loading rate (RBCODLR) i.e. 24 times greater than the RBCODLR on the anoxic reactor of the 1st and 2nd MLE systems (0.236 vs 5.6) and 11 times greater than the RBCODLR of the Wuhrmann system (0.534 vs 5.6) (see section 3.2.3.d above). Knowing the RBCODUR to be equal to the RBCODLR, the PBCODUR under anoxic and aerobic conditions could be calculated from the measured nitrate and carbonaceous oxygen utilization rates.

Table 3.11.a: Steady state periods (SSP) observed in system 1 (MLE) during the 2nd part of the investigation. Also given are the mass fractions (%), the mixed liquor a- and underflow s-recycle ratios and the frequency of alternation between anoxic and aerobic conditions per day.

Phase Nr	Period	SSP Nr	SSP	Days	Recycles (a)	Recycles (s)	Mass fractions Anoxic	Mass fractions Aerobic	Freq. Altn.
1	260 - 343	1	260 - 275	15	2	0	54	46	4.6
		2	276 - 287	11					
		3	288 - 300	12					
		4	301 - 314	13					
		5	315 - 325	10					
		6	326 - 343	17					
2	344 - 351	7	344 - 351	7	1	0	54	46	3.1
3	352 - 384	8	352 - 363	11	1	4	54	46	9.2
		9	364 - 374	10					
		10	375 - 384	9					
4	385 - 446	11	388 - 404	16	1	4	70	30	9.2
		12	405 - 422	17					
		13	423 - 438	15					
5	447 - 494	14	447 - 462	15	1	6	70	30	12.3
		15	463 - 475	12					
6	508 - 524	16	512 - 520	8	1	4	70	30	9.2
7	525 - 545	19	534 - 545	11	1	4	70	30	9.2

3.3.1.d PBCOD utilization rates

(1) PBCODUR in the anoxic reactor of the MLE systems

The PBCODUR in the first reactor (anoxic) of the 1st and 2nd MLE systems was calculated to be 0.375 and 0.373 mgCOD/(mgAVSS.d) respectively (see Table 3.14). These values can be converted to equivalent denitrification rates by dividing by $2.86/(1-f_{cv}.Y_h)$ giving 0.048 $mgNO_3$-N/(mgAVSS.d) for the 1st and 2nd MLE systems respectively. The equivalent K_2 denitrification rates are less than the accepted K_2 rate of 0.101 $mgNO_3$-N/(mgAVSS.d) established by van Haandel *et al.* (1981). There are 3 possible reasons why the observed K_2 rate is low.

(i) Nitrate depletion:

In the anoxic reactor nitrate serves as the terminal electron acceptor for substrate utilization and insufficient nitrate

Table 3.11.b: Steady state periods (SSP) observed in system 2 (Wuhrmann) during the 2nd part of the investigation. Also given are the mass fractions (%), the mixed liquor a- and underflow s-recycle ratios and the frequency of alternation between anoxic and aerobic conditions per day.

Phase Nr	Period	SSP Nr	SSP	Days	Recycles (s)	Recycles (a)	Mass fractions Anoxic	Mass fractions Aerobic	Freq. Altn.
1	260 - 351	1	260 - 275	15	2	0	54	46	4.6
		2	276 - 287	11					
		3	301 - 314	13					
		4	315 - 325	10					
		5	326 - 343	17					
2	352 - 384	6	352 - 363	11	1	0	54	46	3.1
		7	364 - 374	10					
		8	375 - 384	9					
3	385 - 446	9	388 - 404	16	1	5	54	46	10.8
		10	405 - 422	17					
		11	423 - 438	15					
4	447 - 471	12	447 - 462	15	2	7	54	46	15.4
5	472 - 507	13	489 - 496	7					
		14	497 - 507	10					
6	508 - 524	15	512 - 520	8	1	4	54	46	9.2
7	525 - 545	16	527 - 533	6	1	4	70	30	9.2
		17	534 - 545	11					

Table 3.11.c: Steady state periods (SSP) observed in system 3 (MLE) during the 2nd part of the investigation. Also given are the mass fractions (%), the mixed liquor a- and underflow s-recycle ratios and the frequency of alternation between anoxic and aerobic conditions per day.

Phase Nr	Period	SSP Nr	SSP	Days	Recycles (s)	Recycles (a)	Mass fractions Anoxic	Mass fractions Aerobic	Freq. Altn.
1	512-520	1	512-520	8	1	4	70	30	6
2	521-545	2	527-533	6	1	4	70	30	6
		3	534-545	11					

Table 3.12.a: N & COD mass balances and substrate utilization rates calculated for system 1 (MLE) during part 2 of the investigation.

Phase Nr	Steady State Period	Nr	Mass Balances COD	N	COD Utilization Rates[1] RBCOD[2]	PBCOD[3]	PBCOD[4]
1	260-275	1	76	85	0.304	0.151	1.253
	276-287	2	88	99	0.304	0.658	1.333
	288-300	3	72	109	0.304	0.591	0.775
	301-314	4	73	88	0.304	0.345	1.194
	315-325	5	87	86	0.304	0.302	1.768
	326-343	6	87	88	0.304	0.416	1.483
2	344-351	7	77	88	0.304	0.250	1.362
3	352-363	8	76	105	0.304	0.448	1.128
	364-374	9	87	101	0.304	0.490	1.516
	375-384	10	86	94	0.304	0.392	1.406
4	388-404	11	83	82	0.236	0.280	2.048
	405-422	12	74	103	0.236	0.584	0.812
	423-438	13	80	107	0.236	0.389	1.387
5	447-462	14	67	94	0.236	0.296	1.189
	463-475	15	64	102	0.236	0.204	1.124
6	512-520	16	73	86	0.236	0.408	1.337
7	534-545	17	66	85	0.236	0.115	1.494
Weighted Averages[5]			77	94		0.375	1.324

1 Units in mgCOD/(mgAVSS.d)
2 RBCOD utilization under anoxic and aerobic conditions and limited by RBCOD loading rate.
3 PBCOD utilization rate in anoxic (first) reactor of MLE i.e. $PBCODUR_{anx}$ with influent and self generated PBCOD.
4 PBCOD utilization rate in aerobic (second) reactor of MLE i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD.
5 Average weighted by number of days in steady state period relative to total number of days in the 2nd part of the investigation.

Table 3.12.b: N & COD mass balances and substrate utilization rates calculated for system 2 (Wuhrmann) during part 2 of the investigation.

Phase Nr	Steady State Period	Nr	Mass Balances COD	N	COD Utilization Rates[1] RBCOD[2]	PBCOD[3]	PBCOD[4]
1	260-275	1	63	95	0.354	0.623	0.426
	276-287	2	75	115	0.354	0.522	0.719
	301-314	3	64	107	0.354	0.521	0.484
	315-325	4	62	91	0.354	0.738	0.189
	326-343	5	68	113	0.354	0.391	0.511
2	352-363	6	65	105	0.354	0.699	0.331
	364-374	7	68	110	0.354	0.895	0.330
	374-384	8	66	116	0.354	0.601	0.475
3	388-404	9	70	112	0.354	0.867	0.437
	405-422	10	79	112	0.354	1.264	0.463
	423-438	11	65	105	0.354	0.774	0.280
4	447-462	12	69	108	0.354	0.919	0.332
5	489-496	13	85	111	0.354	1.438	0.509
	497-507	14	74	102	0.354	0.946	0.601
6	512-520	15	66	105	0.354	0.582	0.457
7	527-533	16	61	94	0.531	0.496	0.337
	534-545	17	61	93	0.531	0.472	0.286
Weighted Averages[5]			68	106		0.764	0.415

1 Units in mgCOD/(mgAVSS.d)
2 RBCOD utilization under aerobic conditions and limited by RBCOD loading rate.
3 PBCOD utilization rate in aerobic (first) reactor of Wuhrmann i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD.
4 PBCOD utilization rate in anoxic (second) reactor of Wuhrmann i.e. $PBCODUR_{anx}$ with self generated PBCOD only.
5 Average weighted by number of days in steady state period relative to the total number of days in the 2nd part of the investigation.

Table 3.12.c: N & COD mass balances and substrate utilization rates calculated for system 3 (MLE) during part 2 of the investigation.

Phase Nr	Steady State Period	Nr	Mass Balances COD	N	COD Utilization Rates[1] RBCOD[2]	PBCOD[3]	PBCOD[4]
1	512-520	1	84	90	0.234	0.373	1.387
2	527-533	2	69	102	0.234	0.104[6]	1.034
	534-545	3	80	96	0.234	0.182[6]	1.904
Weighted Averages[5]			79	96	0.234	0.373	1.530

1 Units in mgCOD/(mgAVSS.d)
2 RBCOD utilization under anoxic conditions and limited by RBCOD loading rate.
3 PBCOD utilization rate in anoxic (first) reactor of MLE i.e. $PBCODUR_{anx}$ with influent and self generated PBCOD.
4 PBCOD utilization rate in aerobic (second) reactor of MLE i.e. $PBCODUR_{aer}$ with influent and self generated PBCOD
5 Average weighted by number of days in steady state period relative to the total number of days in the 2nd part of the investigation.
6 Ommitted from weighted average - see text for explanation.

concentrations in the anoxic reactor would therefore limit substrate utilization. As the effluent anoxic nitrate + nitrite concentrations of the MLE systems were frequently below 5 mgN/*l* (see Fig.3.15) it was thought that nitrate depletion was the likely cause of the lower than expected equivalent K_2 denitrification rate. For the 1st MLE system nitrate depletion occurred in 6 of the 17 steady state periods (see Table 3.13.a) and for the 2nd MLE system 1 of the 3 steady state periods (see Table 3.13.c). Accordingly the average PBCODUR measured in the anoxic reactor of the 2 MLE systems was recalculated by excluding the steady state PBCODUR's during which anoxic reactor nitrate + nitrite concentrations were less than 5,0 mgN/*l*. The recalculated average PBCODUR was 0,296 mgCOD/(mgAVSS.d) giving an equivalent K_2 denitrification rate of 0,038 mgNO3-N/(mgAVSS.d). This value of 0,038 $mgNO_3$-N/(mgAVSS.d) is lower than the average value of 0,048 $mgNO_3$-N/(mgAVSS.d) and therefore nitrate depletion in the primary anoxic reactor cannot be the cause of the observed low K_2 rate.

(ii) Measurement error:
Because good N mass balances were obtained for both MLE systems the lower than expected equivalent K_2 denitrification rate cannot be attributed to measurement error.

(iii) High recycle ratios:
The high inter-reactor mixed liquor recycle ratios employed throughout the 2nd part of the investigation was considered as a possible cause of the lower than expected equivalent K_2 denitrification rate. By increasing the inter-reactor mixed liquor recycle ratio the PBCOD concentration available to the organisms in both the primary anoxic and secondary aerobic reactors of the MLE systems would become more equalized, comprising proportions of influent PBCOD and PBCOD generated internally through organism death and lysis. Accordingly the equivalent K_2 denitrification rate measured in the anoxic reactor should be only slightly larger than the equivalent K_3 denitrification rate measured in the aerobic reactor. The PBCODUR in the aerobic reactor of the MLE systems is now discussed to pursue this hypothesis.

(2) PBCODUR in the aerobic reactor of the MLE systems

The average PBCOD utilization rates calculated for the 2nd reactor (aerobic) of the 1st and 2nd MLE systems were 1.324 and 1.530 mgCOD/(mgAVSS.d) respectively. The equivalent denitrification rates, found by dividing the measured PBCOD utilization rates by $2.86/(1-f_{cv}.Y_h)$ and multiplying the result by neta (0.38) giving 0.065 and 0.075 $mgNO_3$-N/(mgAVSS.d) for the 1st and 2nd MLE systems respectively (see Table 3.14). These measured values compare favourably with the established equivalent K_3 rate of 0.072 $mgNO_3$-N/(mgAVSS.d) but are larger than the equivalent K_2 denitrification rate of 0,048 $mgNO_3$-N/(mgAVSS.d) observed in the primary anoxic reactor of the 2 MLE systems. Therefore the hypothesis that the inter-reactor mixing caused by the high inter-reactor recycle ratio was responsible for the lower than expected equivalent K_2 denitrification rate is not valid.

No plausible reason can be forwarded for the lower than expected equivalent K_2 denitrification rate observed in the primary anoxic reactors of the 2 MLE systems and this fact will be borne in mind when commenting on low F/M filament growth in the MLE systems.

(3) PBCODUR in the aerobic reactor of the Wuhrmann system

PBCODUR in the first (aerobic) reactor of the Wuhrmann system varied over the 17 steady state periods between 0.500 and 1.264

Table 3.13.a: Steady state mass of NO_3^- + NO_2^- denitrified per day in the primary anoxic reactor of the 1st MLE system during the 2nd part of the investigation. Also given are the masses of NO_3^- + NO_2^- loading and leaving the anoxic reactor per day.

Phase Nr	Steady State Period	Nr	Anox[1] Dose	Anox[2] Outfl	Denitrification mgN/d Act[3]	Load[4]	Effl[5]
1	260-275	1	12.1	5.3	202	361	159
	276-287	2	13.2	3.3	305	404	99
	288-300	3	11.6	5.9	361	538	177
	301-314	4	10.9	2.1	312	375	63
	315-325	5	11.1	3.1	276	369	93
	326-343	6	11.8	1.2	318	354	36
2	344-351	7	11.1	1.1	260	282	22
3	352-363	8	11.5	9.3	353	911	558
	364-374	9	10.9	4.3	340	598	258
	375-384	10	9.5	2.1	266	392	126
4	388-404	11	10.4	0.5	263	293	30
	405-422	12	10.6	4.9	448	742	294
	423-438	13	13.8	3.1	315	501	186
5	447-462	14	15.8	15.9	310	1580	1270
	463-475	15	20.8	21.5	232	1952	1720
6	512-520	16	8.8	2.2	330	462	132
7	527-533	17	10.3	5.5	202	532	330

1 NO_3^- concentration dosed to the anoxic reactor per *l* influent.
2 Anoxic outflow NO_3^- + NO_2^- concentration (mgN/*l*).
3 Actual denitrification (mgN/d) in system calculated using measured data. Found from the difference between 4 and 5.
4 Daily mass NO_3^- + NO_2^- (mgN/d) entering anoxic reactor.
5 Daily mass NO_3^- + NO_2^- (mgN/d) leaving anoxic reactor. To find NO_3^- + NO_2^- concentration of anoxic reactor i.e. column 2, divide by 10 and (1 + a + s) where a and s are the mixed liquor and underflow recycle ratios respectively.

Table 3.13.b: Steady state mass of NO_3^- + NO_2^- denitrified per day in the secondary anoxic reactor of the Wuhrmann system during the 2nd part of the investigation. Also given are the masses of NO_3^- + NO_2^- loading and leaving the anoxic reactor per day.

Phase Nr	Steady State Period	Nr	Anox[1] Dose	Anox[2] Outfl	Denitrification mgN/d Act[3]	Load[4]	Effl[5]
1	260-275	1	12.8	18.2	173	719	546
	276-287	2	13.4	25.5	239	1004	765
	301-314	3	11.1	28.8	213	1077	864
	315-325	4	11.2	28.3	85	394	849
	326-343	5	11.5	21.5	226	871	645
2	352-363	6	11.7	29.0	153	733	580
	364-374	7	11.6	24.7	140	634	494
	374-384	8	11.2	22.0	184	624	440
3	388-404	9	11.3	24.9	176	1919	1743
	405-422	10	11.7	41.0	201	3071	2870
	423-438	11	13.7	29.0	110	2139	2029
4	447-462	12	7.0	31.9	160	3350	3190
5	489-496	13	6.0	17.7	180	1950	1770
	497-507	14	6.3	21.0	230	2333	2100
6	512-520	15	7.1	21.0	185	1445	1260
7	527-533	16	7.5	19.3	147	1305	1158
	534-545	17	7.3	14.5	139	1009	870

1 NO_3^- concentration dosed to the anoxic reactor per *l* influent.
2 Anoxic outflow NO_3^- + NO_2^- concentration (mgN/*l*).
3 Actual denitrification (mgN/d) in system calculated using measured data. Found from the difference between 4 and 5.
4 Daily mass NO_3^- + NO_2^- (mgN/d) entering anoxic reactor.
5 Daily mass NO_3^- + NO_2^- (mgN/d) leaving anoxic reactor. To find NO_3^- + NO_2^- concentration of anoxic reactor i.e. column 2, divide by 10 and (1 + a + s) where a and s are the mixed liquor and underflow recycle ratios respectively.

Table 3.13.c: Potential and actual masses of NO_3^- + NO_2^- denitrified per day in the primary anoxic reactor of the 2nd MLE system during the 2nd part of the investigation. Also given are the masses of NO_3^- + NO_2^- loading and leaving the anoxic reactor per day.

Phase Nr	Steady State Period	Nr	Anox[1] Dose	Anox[2] Outfl	Denitrification Act[3]	Load[4]	Effl[5]
1	512-520	1	5.3	1.8	319	427	108
2	527-533	2	4.7	16.5	148	1138	990
	534-545	3	5.1	8.5	208	718	510

1 NO_3^- concentration dosed to the anoxic reactor per *l* influent.
2 Anoxic outflow NO_3^- + NO_2^- concentration (mgN/*l*).
3 Actual denitrification (mgN/d) in system calculated using measured data. Found from the difference between 4 and 5.
4 Daily mass NO_3^- + NO_2^- (mgN/d) entering anoxic reactor.
5 Daily mass NO_3^- + NO_2^- (mgN/d) leaving anoxic reactor. To find NO_3^- + NO_2^- concentration of anoxic reactor i.e. column 2, divide by 10 and (1 + a + s) where a and s are the mixed liquor and underflow recycle ratios respectively.

with an average of 0.764 mgCOD/(mgAVSS.d). This average rate is converted to an equivalent K_2 denitrification rate by dividing by $2.86/(1-f_{cv}.Y_h)$ and multiplying the result by neta (0.38), the aerobic PBCODUR reduction factor for anoxic conditions, giving 0.037 mgNO_3-N/(mgAVSS.d) (see Table 3.14). The accepted rate of 0.101 mgNO_3-N/(mgAVSS.d) is 2.7 times greater than the measured equivalent K_2 denitrification rate (0.037 vs 0.101). Like earlier for the 2 MLE systems, so now also for the Wuhrmann system, the equivalent K_2 rate is very much lower than the accepted rate. Two possible causes for this are examined.

(i) Low measured OUR:

The lower than expected equivalent K_2 denitrification rate in the primary aerobic reactor of the Wuhrmann system may have originated from inaccurate oxygen utilization rate measurement technique. This possibility was evaluated but rejected for the following reason. Daily oxygen utilization rate (OUR) measurements were performed approximately every 5 minutes over a complete 24 hour period every second day and 5 to 6 hours on alternate days. The OUR's were measured automatically (see Randall *et al.* 1991) and were stored in the memory of an Automatic OUR meter and data logger (the operation of this instrument is outlined in Appendix B). On a daily basis the OUR's stored in the memory of the OUR meter were transferred to a PC file for

Table 3.14: Equivalent denitrification rates determined for the 2 MLE and Wuhrmann systems during the 2nd part of the investigation with real sewage used as influent feed.

			Denitrification rates[1]		
System Nr	System Type[2]	Operating Period	Reactor 1 K_1	K_2	2 K_3
1	MLE	260 - 545	0.039	0.048	0.064
2	Wuhrmann	260 - 545	0.045	0.037	0.053
3	MLE	508 - 545	0.057	0.030	0.074
-	Accepted Values[3]		0.720	0.101	0.072

1 Units are $mgNO_3$-N/(mgAVSS.d).

2 MLE K_2 obtained directly from denitrification rate
K_3 obtained from carbonaceous oxygen utilization rate times neta where neta = 0,38.
Wuhrmann K_2 obtained from carbonaceous oxygen utilization rate time neta where neta = 0,38.
K_3 obtained directly from denitrification rate.

3 From WRC (1984) at 20°C.

K_1 Determined directly from the RBCOD loading rate in the 1st reactor (anoxic in the MLE, aerobic in the Wuhrmann).

K_2 Determined from the PBCOD utilization rate in the 1st reactor, where PBCODUR = CODUR - RBCODUR. In the 1st reactor CODUR is the rate at which influent RBCOD and PBCOD, both in the influent and internally generated through organism death and lysis, is utilized. In the MLE system this is under anoxic conditions i.e. through denitrification and in the Wuhrmann system this is under aerobic conditions. The equivalent denitrification rate for aerobic conditions was determined using neta, the PBCODUR aerobic reduction factor for anoxic conditions where neta = 0,38.

K_3 Determined from the PBCOD utilization rate in the 2nd reactor. The PBCOD is only PBCOD generated internally through organism death and lysis. For the MLE system this is utilized under aerobic conditions and for the Wuhrmann system this is utilized under aerobic conditions.

evaluation. A close approximation of the daily average OUR was obtained by plotting the measured OUR's versus time. By determining the average OUR by almost continuous monitoring, the possibility of inaccurate OUR estimates caused by factors such as daily feed pattern fluctuation to the systems, was excluded. Furthermore the same OUR meter was used to measure OUR's in the secondary aerobic reactor of the MLE systems, in which equivalent K_3 denitrification rates (0.065 and 0.075 mgNO3-N/(mgAVSS.d) for the 1st and 2nd MLE systems respectively) were calculated to be very close to the

expected K_3 denitrification rate of 0.072 mgNO_3-N/(mgAVSS.d). Therefore the possibility that the cause of the lower than expected equivalent K_2 denitrification rate in the aerobic reactor of the Wuhrmann system was due to inaccurate OUR measurement technique was excluded.

(ii) High inter-reactor recycle ratios:

The high inter-reactor recycle ratios employed throughout the 2nd part of the investigation were considered as a possible cause of the lower than expected equivalent K_2 denitrification rate measured in the aerobic reactor of the Wuhrmann system. As outlined in point 1 above for the MLE systems, high inter-reactor recycles equalizes the PBCOD concentration in both the primary aerobic and secondary anoxic reactors of the Wuhrmann system. Accordingly the equivalent denitrification rates of the aerobic and anoxic reactors should be roughly the same, with the equivalent K_2 denitrification lower than expected and the equivalent K_3 denitrification rate slightly higher than expected. This possibility is discussed below.

(4) PBCODUR in the anoxic reactor of the Wuhrmann system

In the 2nd reactor (anoxic) of the Wuhrmann system the average PBCODUR was calculated to be 0.415 mgCOD/(mgAVSS.d). The equivalent K_3 denitrification rate, found by dividing 0.415 by $2.86/(1-f_{cv}.Y_h)$, gives 0.053 mgNO_3-N/(mgAVSS.d). This value is lower than the established equivalent K_3 rate of 0.072 mgNO_3-N/(mgAVSS.d) but is slightly larger than the equivalent K_2 denitrification rate of 0.037 mgNO_3-N/(mgAVSS.d) measured in the aerobic reactor of the Wuhrmann system (see Table 3.14). Therefore the argument that the high inter-reactor recycle ratio was the cause of the lower than expected equivalent K_2 denitrification rate measured in the aerobic reactor of the Wuhrmann system cannot be applied.

Again, like with the MLE systems, no plausible reason can be advanced for the lower than expected equivalent K_2 denitrification rate measured in the aerobic reactor of the Wuhrmann system but this apparent anomaly is considered when commenting on low F/M filament growth in the Wuhrmann system.

(5) PBCODURanoxic/PBCODURaerobic ratio - neta

The aerobic PBCODUR reduction factor for anoxic conditions neta, was found to be 0,32 and was determined by dividing the average PBCODUR in the anoxic reactor of the Wuhrmann by the average PBCODUR in the aerobic reactor of the 1st MLE system during the 1st operational phase of both systems. During the 1st operational phase the same PBCOD, i.e. PBCOD generated by organism death and lysis, was the principal substrate source in both the anoxic reactor of the Wuhrmann and the aerobic

reactor of the 1st MLE hence permitting valid comparison. The measured neta value of 0,32 compares favourably with the value of 0,38 established by van Haandel *et al.* (1981).

Because the measured equivalent K_2 denitrification rates of the 2 MLE and Wuhrmann systems were lower than expected (0.048, 0.048 and 0.037 mgNO3-N/(mgAVSS.d) respectively) the mass of nitrate denitrified in the MLE systems was roughly 1/3 less than those theoretically predicted by the design equations presented in Chapter 4 of the Design Manual (WRC, 1984) using the K_2 denitrification rate of 0,101 mgNO_3-N/(mgAVSS.d) established by van Haandel *et al.* (1981). For the Wuhrmann system the average mass of nitrate denitrified per day was about 1/4 less than the value predicted by the design equation using the K_3 denitrification rate of 0,072 mgNO_3-N/(mgAVSS.d) established by van Haandel *et al.* (1981).

From the above discussion of the evaluation of the mass balances, substrate utilization rates and denitrification rates, it is evident that the N and COD mass balances of the systems were as expected from the established understanding of nitrification and denitrification systems. Regarding the kinetic response of the systems, the equivalent K_3 denitrification rates measured in the 2 MLE and Wuhrmann systems were consistent with established denitrification rates in secondary anoxic reactors, however the equivalent K_2 denitrification rates measured in the 2 MLE and Wuhrmann systems under aerobic conditions were significantly deviant from expected behaviour. This unusual kinetic behaviour is taken into consideration when commenting on low F/M filament growth in the systems.

3.3.3 Low F/M filament growth in the Wuhrmann and 2 MLE systems

3.3.3.1 System 1 - MLE (see Fig.3.1.c)

Phase 1 (days 260 - 343)

At the commencement of the 2nd part of the investigation into the effect of the nature of the anoxic zone in MLE and Wuhrmann systems fed real sewage, the design and operating parameters of the 1st MLE system differed from the MLE in the 1st part of the investigation in 2 ways; (1) the influent artificial sewage feed was replaced with real sewage and (2) the underflow s-recycle ratio was increased from 1:1 to 2:1. The reason for increasing the recycle ratio from 1:1 to 2:1 was that prior to switchover from artificial to real sewage the 1st MLE system was experiencing operational problems due to inter-reactor blockages caused by excessive glutinous material production in the sludge and in attempt to alleviate the inter-reactor blockages the inter-rector flow rate was increased by increasing the underflow s-recycle ratio. The increased s-recycle ratio increased the frequency of alternation between anoxic and aerobic conditions from 3,1 to 4,6 per day. The design and operating parameters

of the 1st MLE system at the switchover from artificial to real sewage are given in Table 3.9.a.

During the 1st operational phase (days 260 - 343) of the 1st MLE system 6 steady state periods were identified (see Table 3.11.a). The 1st steady state period was regarded as the transitional period as the sludge adjusted from artificial to real sewage as influent feed. In the remaining 5 steady state periods the impact of the increased s-recycle ratio and associated increase in anoxic/aerobic alternation on low F/M filament proliferation was examined.

From day 260 (influent sewage switchover) to day 287 (end of 2nd steady state period) the DSVI steadily increased from 50 to 100 m*l*/g. By day 282 the inter-reactor blockages caused by excessive glutinous material production in the sludge had ceased completely. Filament identification on day 267 (7 days after the influent sewage switchover) showed that the dominant and secondary filaments, type 1851 and *H.hydrossis* respectively, remained unchanged after changing the influent feed from artificial to real sewage. Overall filament abundance was very common and mainly within the flocs.

Over the remaining period of the 1st operational phase of the 1st MLE system i.e. day 288 to day 343 the DSVI gradually increased from 100 to 140 m*l*/g. Filament identification on day 293 showed that type 1851 had moved to the tertiary level and had been replaced by type 0092 as the dominant filament. *H.hydrossis* remained at the secondary level and type 0041 joined type 1851 at the tertiary level. Overall filament abundance was common to very common. On day 317 a further filament identification showed that dominant and secondary filaments, type 0092 and *H.hydrossis* respectively, remained unchanged. Present at the tertiary level were types 0041 and 1851 and *Beggiatoa sp*. The overall filament abundance was very common (see Fig.3.13.a).

Phase 2 (days 344 - 351)

At the start of the 2nd operational phase of the 1st MLE system the s-recycle ratio was decreased from 2:1 to 1:1 effecting a concomitant decrease in anoxic/aerobic frequency of alternation from 4,6 to 3,1 per day. This phase was short (7 days) and no filament identifications were made. From day 344 to day 351 the DSVI decreased slightly from 140 to 135 m*l*/g (see Fig.3.13.a).

Phase 3 (days 352 - 384)

On day 352 the mixed liquor a-recycle ratio was increased from 0:1 to 4:1 which increased the anoxic/aerobic frequency of alternation from 3,1 to 9,2 per day (from Equ.3.15). From day 352 to day 385 the DSVI dropped slowly from 135 to 120 m*l*/g. Filament identification

on day 374 showed *H.hydrossis* as the dominant filament and type 0092 as secondary. Types 0041 and 021N were noted at the tertiary level. At the day of the filament identification the DSVI was 122 m*l*/g and the overall observed filament abundance was very common to abundant (see Fig.3.13.a).

Phase 4 (days 385 - 446)

On day 385 the anoxic mass fraction was increased from 54 to 70% with a concomitant decrease in aerobic mass fraction from 46 to 30%. On day 430 the nitrate dosed to the anoxic reactor was increased from 12 to 20 mgN/*l*. This increase in nitrate dosage was done to prevent nitrate depletion in the anoxic zone. During this period the DSVI remained remarkably constant at the 120 m*l*/g level. Filament identification on day 419 showed that type 0092 had returned as the dominant filament and that *Beggiatoa sp.* was secondary. *H.hydrossis* joined types 021N and 0041 at the tertiary level (see Fig.3.13.a and b).

Phase 5 (days 447 -494)

The mixed liquor a-recycle ratio was increased from 4:1 to 6:1 effecting an increase in anoxic/aerobic frequency of alternation from 9,2 to 12,3 per day. During this period rising sludge in the clarifier, caused by denitrification of the effluent nitrate in the clarifier, was a frequent occurrence. In an attempt to circumvent this source of sludge loss, the nitrate dosed to the anoxic reactor was reduced on day 280 from 20 to 12 mgN/*l*. This had the desired effect and after day 480 the rising sludge in the clarifier disappeared completely.

Filament growth as reflected by the DSVI test fluctuated slightly; from day 447 to day 465 the DSVI gradually increased from 120 to 140 m*l*/g, thereafter, from day 466 to day 480 (nitrate dosage to anoxic reactor reduced from 20 to 12 mgN/*l* on this day) the DSVI gradually dropped from 140 to 135 m*l*/g. From day 481 to day 494 the DSVI dropped more sharply from 135 to 120 m*l*/g. Filament identification on day 457 showed that *H.hydrossis* replaced type 0092 as the dominant filament and type 0041 replaced *Beggiatoa sp.* as the secondary filament. Filament types 021N and 0092 were noted at the tertiary level. Overall filament abundance was very common. A second filament identification on day 472 showed that type 021N replaced *H.hydrossis* as the dominant filament and type 0092 replaced type 0041 at the secondary level. Present at the tertiary level were *H.hydrossis* and types 0041 and 1851. Overall filament abundance was common (see Fig.3.13.b).

Phase 6 (days 495 - 524)

On day 495 the mixed liquor a-recycle ratio was increased from 6:1 to 31:1. This large increase in the a-recycle ratio caused an increase in effluent nitrate concentration and a concomitant reoccurrence of rising sludge in the clarifier. In an attempt to curb the sludge loss in the clarifier the a-recycle ratio was reduced on day 499 from 31:1 to 17:1. The

investigation was temporarily set back by an overnight inter-reactor mixed liquor recycle tube breakage. Roughly 1/3 of the sludge was lost and the waste flow from the Wuhrmann system was seeded to the 1st MLE system to counter-act the sludge mass shortfall. By day 508 the sludge mixed liquor (MLVSS) concentration was restored to its previous levels. For the remainder of this operational phase (days 508 - 524) the 1st MLE system served as a control for the 2nd MLE system which was set up on day 508. The a-recycle ratio was further reduced from 17:1 to 4:1. Due to the short period during which very high a-recycles were in operation (days 495 - 508, i.e. 13 days) and the loss of sludge through the tube breakage, no steady state kinetic calculations were performed for this period.

Low F/M filament growth in the 1st MLE system with high a-recycles of 31:1 (days 495 to 498) and 17:1 (days 499 to 507) remained relatively stable until the inter-reactor mixed liquor recycle tube breakage on day 500. From day 495 to day 500 the DSVI increased from 120 to 130 m*l*/g. After day 500 and up to day 507 the DSVI initially dropped sharply to below 120 m*l*/g and then rapidly rose to 138 m*l*/g. This sharp rise was due to the influence of the sludge seeded from the Wuhrmann system, which at the time had a DSVI of 170 m*l*/g. From day 508 to day 524 (a-recycle ratio = 4:1) the DSVI leveled off at the 140 m*l*/g mark. Filament identification on day 504 showed type 021N as the dominant filament, with type 0092 secondary. *H.hydrossis, M.parvicella* and type 0041 were observed at the tertiary level. Overall filament abundance was very common to abundant (see Fig.3.13.b).

Phase 7 (days 525 -545)

In this final operational phase of the 1st MLE system the sludges of this system and of the 2nd MLE system were blended together. This was done by draining the sludge from each system into a common container, thoroughly mixing the contents and then by proportional volumes dispensing the blended sludge mixture into the empty reactors of the 2 MLE systems.

After blending the sludges (day 525) the effluent nitrate + nitrite concentration increased causing denitrification and associated rising sludge in the clarifier. By day 531 the effluent nitrate + nitrite concentration decreased to its former level (see Fig.3.14.a) and the problem of rising sludge in the clarifier ceased. On day 534 the inter-reactor mixed liquor recycle tube burst again causing minor sludge loss. The lost sludge had accumulated in metal trays, positioned below the reactors for such eventualities, and was returned to the reactors of the 1st MLE system. By day 540 the MLVSS concentration was restored to its former level (see Fig.3.12.a).

The DSVI's prior to sludge blending of the 1st and 2nd MLE systems were 140 and 155 m*l*/g respectively. After blending the sludges (day 525) the DSVI of the 1st MLE system rose

sharplv to 170 ml/g before slowly dropping to 150 ml/g on day 535. A marked drop in DSVI was noted after the tube breakage on day 534 (150 to 125 ml/g by day 538) followed by a rapid increase in DSVI to 150 ml/g on day 543 where it remained until the end of the investigation on day 545. Filament identification on day 531 showed that type 021N was still the dominant filament and type 0092 still secondary. *H.hydrossis*, *M.parvicella* and type 0041 were observed at the tertiary level. Overall filament abundance was common to very common. A final filament identification on day 545 showed that the dominant, secondary and tertiary filaments remained unchanged from the earlier filament identification on day 531 (see Fig.3.13.b).

3.3.3.2 System 2 - Wuhrmann (see Fig.3.1.d)

The Wuhrmann system was set up to investigate the effect of the position of the anoxic post-denitrification reactor on low F/M filament proliferation by operating the system in the same way and in tandem with the 1st MLE system. By keeping the operational parameters of each system identical, comparison could be made of the low F/M filament growth in each system and any dissimilar filament behaviour could be attributed to the position of the anoxic reactor. Operation of the Wuhrmann system was divided into 7 phases, each of which contributed to the examination on the effect of (1) the position of the anoxic reactor, (2) the frequency of alternation between anoxic and aerobic conditions and (3) the size of the anoxic reactor on low F/M filament proliferation.

Phase 1 (days 260 - 351)

At the start of this phase real sewage replaced artificial sewage as influent feed. Due to the presence of glutinous material in the sludge which accumulated during the time the system received artificial sewage the underflow s-recycle ratio was increased from 1:1 to 2:1 in an attempt to stop inter-reactor blockages caused by the glutinous material in the sludge. By increasing the s-recycle ratio from 1:1 to 2:1 the anoxic/aerobic frequency of alternation was increased from 3,1 to 4,6 per day. During this phase (91 days long) 5 steady state periods were identified. The 1st steady state period was regarded as the transitional period during which time the sludge adjusted to the real sewage. Thereafter the effect of the increased s-recycle ratio on low F/M filament growth was examined (see Fig.3.13.c).

Inter-reactor blockages caused by glutinous material production in the sludge ceased almost immediately after increasing the s-recycle ratio. After switching from artificial to real sewage glutinous material accumulation appeared to have stopped and was progressively reduced via sludge wastage and after two sewage batches (27 days) the glutinous material had completely disappeared from the sludge. The DSVI during the transitional period (days 260 - 275) fluctuated daily but increased over the period from 100 to 130 ml/g before dropping again to 100 ml/g. Filament identification on day 267 showed that filament type

1851 was dominant and *H.hydrossis* secondary. Type 0041 was present at the tertiary level. Overall filament abundance was very common and predominantly in flocs (see Fig.3.13.c).

From day 288 to day 351 the daily DSVI fluctuation was far less noticeable than before and the DSVI gradually decreased from 100 to 80 m*l*/g. In contrast over the same period the DSVI of the 1st MLE system had shown an upward trend from 100 m*l*/g and by day 351 was 130 m*l*/g. Filament identification on days 293 and 317 showed type 0092 to be dominant and *H.hydrossis* secondary in both cases. *M.parvicella* was present at the tertiary level on day 293 and types 0041 and 1851 were present at the tertiary level on day 317. Overall filament abundance on day 293 was very common to abundant (DSVI = 105 m*l*/g) and on day 317 very common (DSVI = 95 m*l*/g).

Phase 2 (days 352 - 384)

The underflow s-recycle ratio was decreased from 2:1 to 1:1 on day 352 effecting a decrease in anoxic/aerobic frequency of alternation from 4,6 to 3,1 per day. The DSVI over this period remained unchanged at the 100 m*l*/g level. Filament identification on day 472 showed that *H.hydrossis* was the dominant filament with type 0041 secondary. Filament types 021N and 0092 were present at the tertiary level. Overall filament abundance was very common to abundant (see Fig.3.13.c).

Phase 3 (days 385- 446)

The mixed liquor a-recycle ratio was increased from 0:1 to 5:1 which increased the anoxic/aerobic frequency of alternation from 3,1 to 10,8 per day.

Filament behaviour as reflected by the DSVI test fluctuated marginally. A slight increase in DSVI was noted on day 424 reaching 120 m*l*/g by day 426, but the upward trend terminated and by day 446 the DSVI was 90 m*l*/g. Over the same period the DSVI of the 1st MLE system, with a 4:1 a-recycle ratio and larger anoxic mass fraction (70% compared to 54% of the Wuhrmann system), remained unchanged at the 120 m*l*/g level. Filament identification on day 419 showed that filament type 0041 replaced *H.hydrossis* as the dominant filament and type 0092, which had previously appeared at the tertiary level, was secondary. Noted at the tertiary level were filaments *H.hydrossis* and type 021N. Overall filament abundance was very common (see Fig.3.13.c and d).

Phase 4 (days 447 - 471)

On day 447 the a-recycle was increased from 5:1 to 7:1 and the s-recycle was increased from 1:1 to 2:1. The increased a-and s-recycles caused a rise in anoxic/aerobic frequency of alternation from 10,8 to 15,4 per day. During this operational period it was noted that the sludge had become slightly granular in texture. On two occasions the granular sludge caused

inter-reactor overflow blockages. The DSVI, 90 ml/g on day 447, slowly increased to 130 ml/g on day 471. Filament identification on day 457 showed type 0041 to be the dominant filament and type 0092 secondary. Present at the tertiary level were *H.hydrossis*, *M.parvicella* and types 021N and 1851. Overall filament abundance was common.

Phase 5 (days 472 - 507)

By day 472 it was becoming increasingly evident that the Wuhrmann system would not sustain a bulking sludge (DSVI > 150 ml/g). To examine whether this observation was either circumstantial or a distinct tendency, it was decided to replace all the existing sludge with a bulking sludge from 2 single reactor intermittently aerated systems. Accordingly, on day 472, all the sludge was drained from the Wuhrmann system reactors and discarded; sludge harvested from the 2 intermittently aerated systems (DSVI's of 315 and 400 ml/g) was seeded into the empty reactors of the Wuhrmann system (see Fig.3.13.d).

The filamentous organism population of the new sludge in the Wuhrmann system initially rapidly increased. This was reflected by the DSVI which increased from 130 (day 472) to 260 ml/g within 7 days. Thereafter and up to day 507 the DSVI steadily decreased from 260 to 148 ml/g. Filament identification on day 472 showed that in the new sludge *H.hydrossis* was the dominant filament with type 0092 secondary. Types 0041 and 021N were present at the tertiary level. Overall filament abundance was abundant. On day 504 filament identification showed that the filament population had changed with type 0041 replacing *H.hydrossis* as the dominant filament. No secondary filament was identified and *M.parvicella*, *H.hydrossis* and types 1701, 0092 and 021N were reported in equal quantities at the tertiary level. Overall filament abundance was very common (see Fig.3.1.3.d).

Phase 6 (days 508 - 524)

This operational phase coincided with the start up and operation of the 2nd MLE system. As the 1st and 2nd MLE systems were operating at 70% anoxic mass fraction and 4:1 a-recycle ratio, it was decided to operate the Wuhrmann system under similar conditions to the MLE systems. In this operational phase the 2:1 s-recycle was reduced to 1:1 and the 7:1 a-recycle ratio was reduced to 4:1. These reductions in s- and a-recycle ratios brought about a reduction in the anoxic/aerobic frequency of alternation from 15,4 to 9,2 per day. During this period (days 508 - 524) the DSVI continued to decrease, dropping from 150 to 100 ml/g. No filament identifications were performed during this operational phase.

Phase 7 (days 525 - 545)

In this 7th and final operational phase the anoxic mass fraction was increased on day 525 from 54 to 70% with a concomitant decrease in aerobic mass fraction from 46 to 30%. At

this stage the 3 systems were operating in tandem, each receiving the same mass and concentration of influent feed and each system operating with a 70% anoxic mass fraction and a-recycle ratio of 4:1.
From day 525 to day 545 the DSVI gradually began to increase from 100 to 120 m*l*/g. Filament identification on day 531 showed that type 0041 was dominant and *H.hydrossis* the secondary filament. Present at the tertiary level were *M.parvicella* and types 0092 and 021N. Overall filament abundance (DSVI = 115 m*l*/g) was common to very common. The last filament identification of this investigation on day 545 showed that *H.hydrossis* replaced type 0041 as the dominant filament. Type 0041 was the secondary filament and *M.parvicella* and types 021N and 0092 were observed at the tertiary level. Overall filament abundance (DSVI = 115 m*l*/g) was very common to abundant (see Fig.3.13.d).

3.3.3.3 System 3 - MLE (see Fig.3.1.c)
The 2nd MLE system was set up to investigate the effect of the MLVSS concentration on low F/M filament growth. Start up sludge for this system was harvested from the waste flows of the Wuhrmann system (DSVI = 150 m*l*/g) and the 1st MLE system (DSVI = 130 m*l*/g). The design and operating parameters of the 2nd MLE system are given in Table 3.9.c. During operation of the 2nd MLE system the 1st MLE system (process volume = 6,5 l) was operated in tandem as the control system. Operation of the 2nd MLE system was divided into 2 phases.

Phase 1 (days 508 - 520)
The 2nd MLE system was set up with a 70% anoxic mass fraction and with 1:1 s-recycle and 4:1 a-recycle ratios. The frequency of anoxic/aerobic alternation was 6,0 per day. With the same recycle ratios and anoxic mass fraction the 1st MLE system had 9,2 anoxic /aerobic alternations per day. This difference (9,2 vs 6,0) was due to the differences in process volume (see Equ.3.15). From start up on day 508 to day 520 the DSVI decreased steadily from 170 to 150 m*l*/g (see Fig.3.13.e).

Phase 2 (days 524 - 545)
On day 524 the sludges of the 1st and 2nd MLE systems were drained from the reactors to a common container. The sludges were blended and thoroughly mixed and returned by proportional volumes to the respective MLE systems. With the same sludge in both MLE systems at the start of this operational phase, comparison could be made of the low F/M filament growth in each system.

After blending the sludges of the 2 MLE systems, the organisms required a transitional period to readjust to their new environment. It was observed from the kinetic behaviour of the 2nd MLE system that the PBCODUR in the anoxic reactor was significantly less after

sludge blending than before (0.373 and 0.104 mgCOD/(mgAVSS.d) respectively, see Table 3.12.c). Because the 2nd MLE system was operational for only 3 steady state paeriods the anoxic PBCODUR's after sludge blending were not considered in the kinetic evaluation of the system.

The downward trend of the DSVI, observed in the 2nd MLE system prior to sludge blending, continued but at a slower rate. From day 525 to day 545 the DSVI gradually decreased from 150 to 125 m*l*/g. Filament identification on days 531 and 545 showed filament types 021N and 0092 to be dominant and secondary respectively in both cases. Reported at the tertiary level on both days 531 and 545 were *H.hydrossis*, *M.parvicella* and type 0041. Overall filament abundance on day 531 (DSVI = 142) was abundant and on day 545 (DSVI = 125 m*l*/g) was common to very common (see Fig.3.13.e).

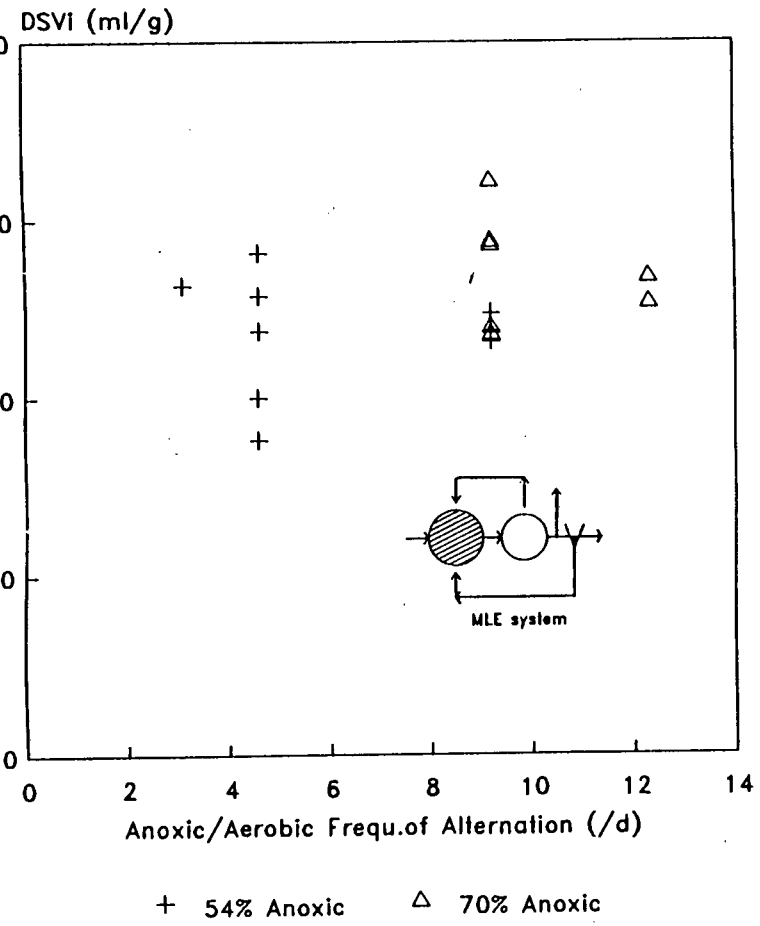
3.3.4 Conclusions for systems fed real sewage

In general it can be said that neither the MLE nor the Wuhrmann systems supported bulking (DSVI > 150 m*l*/g) sludges by low F/M filaments. The measured DSVI's were on the whole considerably less than the DSVI's measured in intermittently aerated systems with similar sized anoxic mass fractions. However the measured DSVI's of both the MLE and Wuhrmann systems (100 - 130 m*l*/g) were generally greater than the DSVI's measured in (1) single reactor fully anoxic systems fed real sewage (DSVI ± 80 m*l*/g) by Ketley *et al.* (1991) and (2) in fully aerobic systems fed real sewage by Gabb *et al.* (1989) and Warburton *et al.* (1991).

Also from time to time the reported overall filament abundance, concluded from microscopic identification, did not reflect the relative filament quantities as suggested by the measured DSVI. Overall filament abundance is a qualitative assessment of the number of filaments in the microscopic sample. The DSVI on the other hand is a measure of the sludge settleability which depends not only on the amount of filaments present but also on the shape of the filaments in the sludge. Filament types 0092, and 0041 tend to be curved in shape and reside within the floc, while *M.parvicella* and *S.natans* are predominantly found outside the flocs. It can be seen, therefore, that high reported filament abundances of a particular filament or group of filaments need not necessarily imply the sludge has a high DSVI value; high DSVI's depend not only on filament abundance but also on filament length, shape and location.

For the 1st MLE system it can be concluded that:

1 The increase in anoxic mass fraction from 54 to 70% did not significantly effect the DSVI.



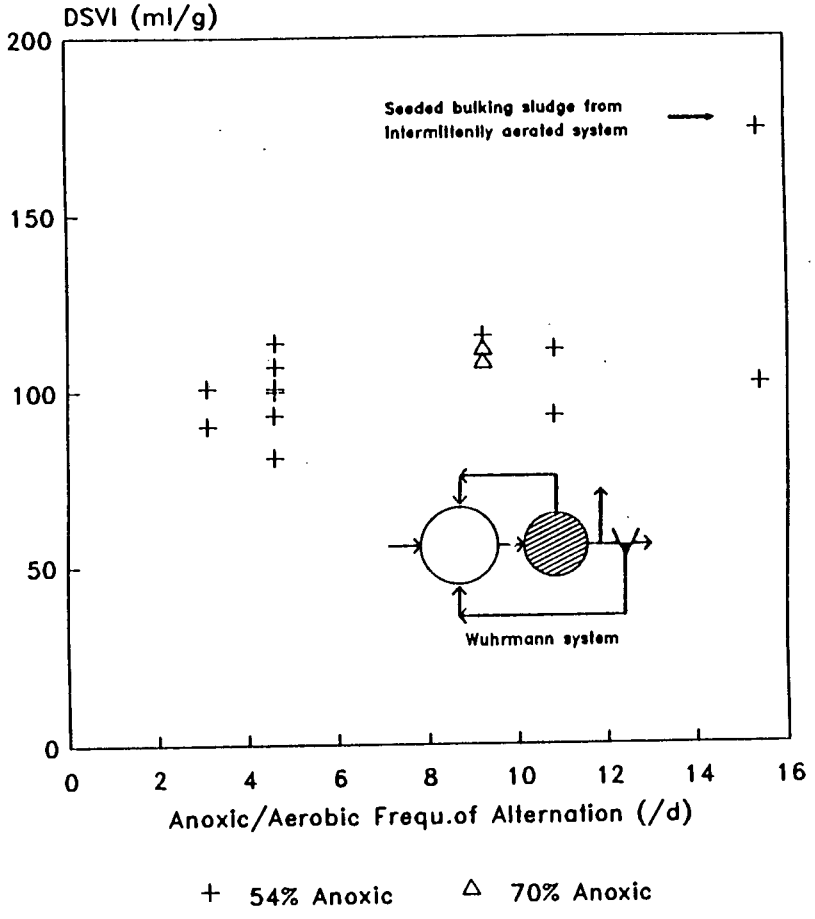


Fig 3.17 Steady state average DSVI's for the 1st MLE and Wuhrmann systems fed real sewage plotted against daily frequency of anoxic/aerobic alternation. Distinction is made between differing anoxic mass fractions.

2 Progressively increasing the anoxic/aerobic frequency of alternation (see Fig.3.17) from 3,1 to 12,3 per day had no significant impact on the DSVI and by implication on low F/M filament growth.

3 Filament types 0092 and 021N were reported as the dominant filament in 7 of 10 microscopic filament identifications. *H.hydrossis* and type 1851 were reported dominant in the remaining 3 filament identifications.

For the Wuhrmann system it can be concluded that:

1 The DSVI of the Wuhrmann system was generally lower than the DSVI of the 1st MLE system the former at an average of about 100 m*l*/g and the latter at an average of about 125 m*l*/g. Regarding the effect of the position of the anoxic reactor it can be concluded that positioning the anoxic reactor after the aerobic reactor does, but only to a limited degree, induce a lower DSVI.

2 Increasing the anoxic mass fraction from 54 to 70% effected a small increase in DSVI; the measured DSVI increased from 100 to 120 m*l*/g immediately after increasing the anoxic mass fraction.

3 Varying the frequency of anoxic/aerobic alternation from 3,1 to 15,4 times per day (see Fig.3.17) did not significantly effect the DSVI and by implication the low F/M filament growth.

4 Filament type 0041 was reported as the dominant filament in 5 of 10 microscopic filament identifications. *H.hydrossis* and type 0092 were reported dominant twice each and type 1851 was dominant only once.

Operation of the 2nd MLE system showed that:

1 The lower MLVSS concentration did not have a significant influence on the DSVI and by implication on the low F/M filament population growth.

2 The dominant filament types were the same for the 1st and 2nd MLE systems irrespective of the difference in MLVSS concentration of each system.

With regard to the occurrence of 021N in the 2 MLE systems, and to a lesser extent in the Wuhrmann, these filaments are generally found in sludges fed septic sewages; 021N was identified as the dominant filament in both the 1st MLE system (4 of 10 microscopic identifications) and in the 2nd MLE system (2 of 2 microscopic identifications). It was subsequently observed that the period during which 021N was the dominant filament in the MLE systems coincided with the extended period during which the sewage transport container had not been cleaned after each delivery and a breakdown in the sewage cold room refrigeration unit. Consequently new sewage batches were contaminated with residual septic sewage from the previously collected sewage batch. In all likelihood the cause of the

021N presence in the systems was the septic residual sewage in the transport container. Other activated sludge systems operated in the laboratory also had 021N present in their sludges. When the cause of the sewage septicity was found and the sewage transport container was again cleaned after sewage collection and the cold room was repaired, progressively 021N disappeared from the laboratory systems. This happened after operation of the MLE and Wuhrmann systems of this investigation had been stopped.

CHAPTER 4

CONCLUSIONS

4.1 BACKGROUND TO THE INVESTIGATION

Filamentous bulking, which causes considerable deterioration in mixed liquor settleability, has been shown, in two separate national surveys (Blackbeard *et al.*, 1986, 1988) to be a problem of considerable proportions in South African N and N&P removal activated sludge plants. From the two surveys it was found that six filaments viz 0092, *M.parvicella*, 0675, 0041, 0914 and 1851 were dominant in sludges microscopically examined. These 6 filaments have been labelled low F/M filaments because of their proliferation in long sludge age plants. Traditionally the specific control method for the amelioration of low F/M filament proliferation was the inducing of the so called "selector effect" in the sludge. In a 4 year research program from 1986-1989, Gabb *et al.* (1989a) found *inter alia* that the selector effect did not control proliferation of the above 6 low F/M filaments. It was found, however, that continuous aeration did control low F/M filament proliferation in both systems with and without the selector effect. Evidently the alternation between aerated and unaerated conditions was the cause of low F/M filament proliferation. With this conclusion in mind a second research program was commenced in 1989.

The research presented in this thesis forms part of a wide ranging research program commenced in 1989 and investigated the effect of

(1) **type** (i.e. anoxic zone compartmentalized into reactors and separated from the aerobic reactors as opposed to single reactor intermittently aerated anoxic-aerobic systems)
(2) **size** (i.e. the anoxic mass fraction)
(3) **position** (i.e. anoxic reactor either preceding or following the aerobic reactor)
(4) **frequency** of anoxic/aerobic alternation and
(5) **MLVSS** concentration of the sludge

of the anoxic zone on low F/M filament proliferation

The experimental investigation was divided into two parts. In the 1st part, two systems, both continuously fed completely mixed 2 reactor in series anoxic-aerobic systems were set up; the 1st a Modified Ludzack-Ettinger (MLE) in which the anoxic reactor (which receives all the influent), is followed by the aerobic reactor and, the 2nd a Wuhrmann in which the aerobic reactor, (which receives all the influent) is followed by the anoxic reactor. Both systems were fed artificial sewage. These systems were set up to examine the effect of

- type
- size

• position
of the anoxic zone on low F/M filament proliferation with artificial sewage.

In the 2nd part of the investigation the above experiments with artificial sewage were repeated with real sewage. Two MLE and one Wuhrmann systems were operated to examine not only the effect of type, size and position of the anoxic zone on low F/M filament proliferation but additionally also the effect of
• frequency of anoxic/aerobic alternation and
• MLVSS concentration of the sludge.

4.2 OPERATION AND MONITORING OF LABORATORY SYSTEMS

In both parts of the investigation the sludge age and temperature of the systems were set at 15 days and 20°C respectively. Altogether the systems were operated for 545 days of which 259 days comprised the 1st investigation period and the remaining 286 days the second part. Through the 545 day investigation a wide range of parameters were regularly monitored such as influent, reactor and effluent COD, TKN, NO_3^- + NO_2^- concentrations, oxygen utilization rate and MLVSS in the aerobic reactor, sludge settleability in terms of DSVI and filament identification.

4.3 RESULTS OF THE INVESTIGATION

4.3.1 Mass Balances and Kinetic Evaluation

During the investigation steady state periods were identified and for these periods the kinetic performance of the systems was evaluated by (1) conducting N and COD mass balances and (2) calculating the active organism specific particulate biodegradable COD utilization rate PBCODUR in both the primary (anoxic in MLE, aerobic in Wuhrmann) and in secondary (aerobic in MLE, anoxic in Wuhrmann) reactors. Comparison of the PBCODUR's in the secondary (anoxic) reactor of the Wuhrmann and the secondary (aerobic) reactor of the MLE systems allowed calculation of neta i.e. the aerobic PBCODUR reduction factor for anoxic conditions, where neta = PBCODUR(anoxic)/PBCODUR(aerobic).

In the 1st part of the investigation, i.e. with artificial sewage influent feed, slime production and accumulation on the feed bucket and feed line walls led to influent COD and TKN losses. These losses were quantified by experimentation and the COD concentration entering the biological reactors was found to be 82% of the influent COD concentration measured in the feed bucket at the start of the 24 hour period and the TKN concentration 3 - 4 mgN/*l* less than the TKN concentration measured in the feed bucket at the start of the 24 hour period. No COD and TKN correction was necessary for the second part of the investigation when real sewage served as influent feed.

For the investigation, (1) the Wuhrmann system had an average COD mass balance of 106% when fed artificial sewage and 65 - 75% with real sewage and N mass balances averaging 95% with artificial and 106% with real sewage; (2) the MLE systems had average COD mass balances of 79% and average N mass balances of 95% throughout the investigation. With the correction factors for artificial sewage the N and COD mass balances were approximately the same for artificial and real sewage. The COD mass balances at first glance appear to be low (95% is considered a good COD mass balance) but are of the same order as those obtained by Warburton *et al.* (1991) in intermittently aerated systems, by Clayton *et al.* (1989) in multi-reactor MUCT/UCT systems and Arkley and Marais (1981) on MLE and Wuhrmann systems all with large anoxic mass fractions. At present no explanation can be forwarded for this tendency of obtaining low COD mass balances in N and N&P removal systems with significant unaerated zones.

Calculation of the PBCODUR in the anoxic reactors of the MLE and Wuhrmann systems fed both artificial and real sewage showed:

(1) The specific denitrification rate K_2 for PBCODUR in the primary anoxic reactor of the MLE systems was 0,049 mgNO_3-N/(mgAVSS.d) for artificial and real sewages.

(2) The specific denitrification rate K_3 for PBCOD utilization in the secondary anoxic reactor of the Wuhrmann system was 0,074 and 0,053 mgNO_3-N/(mgAVSS.d) for artificial and real sewage respectively.

The measured K_3 denitrification rates compared favourably with the K_3 rate of 0,072 mgNO_3-N/(mgAVSS.d) established by van Haandel *et al.*(1981). However the measured K_2 denitrification rate (0,049) compared less favourably to the 0,101 mgNO_3-N/(mgAVSS.d) established by van Haandel *et al.* (1981) and even less so than the K_2 rate of 0,113 mgNO_3-N/(mgAVSS.d) established by Warburton *et al.* (1991) in intermittent aeration systems. No explanation at present can be forwarded for the perplexing observation that the measured PBCODUR in the first reactor, taking due consideration of the aerobic and anoxic conditions, was lower than the PBCODUR measured in the second reactor for both systems. The average aerobic PBCODUR reduction factor for anoxic conditions neta was found to be 0,39 for the systems fed artificial sewage and 0,32 for the systems fed real sewage, both these values compare favourably with the 0,38 established by van Haandel *et al.* (1981).

Because of the measured lower K_2 and K_3 denitrification rates the denitrification potential of the MLE system and Wuhrmann systems (i.e. 25 - 35 mgN/*l* and 15 - 25 mgN/*l* respectively) are about one half lower than the denitrification potential determined by Warburton *et al.* (1991) in intermittently aerated systems (40 - 50 mgN/*l*) with the same anoxic mass fractions and one third lower than predicted with the equations in WRC (1984) for completely mixed reactor systems. Even though the denitrification rates were

quantitatively considerably lower than the measured earlier the kinetic behaviour of the systems qualitatively were similar.

4.3.2 Filamentous Organism Behaviour

4.3.2.a 1st part of the investigation - Systems fed artificial sewage.

(1) It was found that low F/M filaments did not proliferate to severely bulking levels in the MLE and Wuhrmann systems. The DSVI values measured in this part of the investigation (150 - 200 m*l*/g) were significantly less than the DSVI's measured in intermittently aerated systems (> 600 m*l*/g) also fed artificial sewage (Casey *et al.*,1990), but were considerably greater than the DSVI's measured in fully anoxic or fully aerobic systems (± 80 m*l*/g) fed artificial sewage (Casey *et al.*, 1990, Ketley *et al.*, 1991).

(2) Throughout the 1st part of the investigation filaments *H.hydrossis* and type 1851 were identified as the dominant filaments in both the MLE and Wuhrmann systems. These same filaments were identified in bulking sludges harvested from intermittently aerated systems fed artificial sewage (Casey *et al.*, 1990, Ketley *et al.*, 1991).

(3) Reducing the anoxic mass fraction of the MLE system from 70 to 54% did not have an appreciable ameliorating effect on low F/M filament proliferation. Similar anoxic mass fraction reductions in intermittently aerated systems fed artificial sewage did show weak but definite reductions in low F/M filament proliferation (Casey *et al.*, 1990).

(4) Regarding the position of the anoxic reactor, the DSVI of the MLE system was on average 200 m*l*/g while the average DSVI of the Wuhrmann system was 150 m*l*/g. From this it can be concluded that positioning the anoxic reactor after the aerobic reactor does to some degree influence and retard low F/M filament proliferation.

(5) Because (i) glutinous material production and accumulation in the sludge caused serious operational difficulties and (ii) the frequent dominance of filament *H.hydrossis* which is not one of the principle 6 low F/M filaments dominant in N and N&P removal plants in SA, it was decided to continue the investigation, but to replace the artificial sewage feed with real sewage.

4.2.2.b 2nd part of the investigation - Systems fed real sewage.

In the 2nd part of the investigation the same MLE and Wuhrmann systems as well as a 2nd MLE system were operated with real sewage as influent feed. It was observed that

(1) Low F/M filament proliferation in the 3 systems as reflected by the DSVI test was generally less than the DSVI of a bulking sludge (150 m*l*/g) and considerably less than the measured DSVI's of intermittently aerated systems with similar operating parameters. However the DSVI's of the 3 systems were generally greater than the

DSVI's measured in fully aerobic or fully anoxic laboratory scale systems operated with real sewage (Gabb *et al.*,1989a, Warburton *et al.*,1991, Ketley *et al.*, 1991).

(2) The filament *H.hydrossis* was no longer identified in the 3 systems as the dominant filament, but filament types 0092, 0041 and 021N were. Filament types 0092 and 0041 are 2 of the 6 low F/M filament types observed in bulking sludges of full scale N and N&P removal plants. The occurrence of filament type 021N, found to grow in septic sewages, transpired to be a laboratory artifact, the source of which was subsequently identified as a failure to properly clean the sewage transport container.

(3) Increasing the anoxic mass fraction of the 1st MLE system from 54 to 70% had no significant effect on low F/M filament proliferation with the DSVI remaining around 125 m*l*/g, however for the Wuhrmann system the same increase in anoxic mass fraction caused a distinct but small increase in low F/M filament proliferation; the DSVI increasing from 100 to 125 m*l*/g.

(4) Comparing the DSVI's and by implication the low F/M filament proliferation of the MLE and Wuhrmann systems it was evident that the DSVI of the Wuhrmann system (average of 100 m*l*/g) was consistently lower than the DSVI of the MLE systems (average of 125 m*l*/g), irrespective of the anoxic mass fraction. From this it can be concluded that positioning the anoxic reactor after the aerobic reactor in 2 reactor anoxic-aerobic systems, does to a certain degree retard low F/M filament proliferation.

(5) Progressively increasing the frequency of anoxic/aerobic alternation from 3,1 to 15,4 per day in both the 1st MLE and Wuhrmann systems had no significant effect on low F/M filament proliferation and DSVI's for the 1st MLE system ranged between 100 and 150 m*l*/g and for the Wuhrmann system between 80 and 120 m*l*/g. The DSVI's of both systems showed no correlation with the daily anoxic/aerobic frequency of alternation.

(6) From the operation of the 2nd MLE system, identical to the 1st MLE system in all respects except having a greater process volume and accordingly a lower MLVSS concentration than the 1st MLE system, it was observed (i) that the DSVI's of both systems were similar (for the operation period, the DSVI of the 1st MLE system was ± 140 m*l*/g and the DSVI of the 2nd MLE system was also ± 140 m*l*/g) and (ii) the dominant filament types of both MLE systems were the same. From these observations it can be concluded that the MLVSS concentration, in the range 1400 to 2200 mgVSS/*l*, was not a factor influencing the DSVI and by implication low F/M filament proliferation.

4.2.3 Conclusions for systems fed artificial and real sewage.

In summary it is clear from the low F/M filament behaviour of the MLE and Wuhrmann systems fed artificial or real sewage that

(1) filamentous 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; consequently the factors that distinguish the anoxic aerobic conditions in 2 reactor MLE and Wuhrmann systems compared to single reactor intermittently aerated systems influence the low F/M filament behaviour but apparently not very much - the filaments do grow to higher levels in the MLE and Wuhrmann systems compared to fully anoxic or fully aerobic systems, but much less so than in intermittently aerated systems,

(2) changing the size of the anoxic reactor of the 1st MLE system from 70 to 54% and from 54 to 70% did not significantly effect low F/M filament proliferation and

(3) positioning the anoxic reactor after the aerobic reactor did but only to a small degree decrease the DSVI (200 and 150 m*l*/g respectively for the 1st MLE and Wuhrmann systems fed artificial sewage and 130 and 100 m*l*/g respectively for the MLE and Wuhrmann systems fed real sewage).

From the work on the Wuhrmann and 2 MLE systems fed real sewage it was concluded that

(1) adjusting the frequency of daily anoxic/aerobic alternation from 3,1 to 15,4 times per day in both the 1st MLE and Wuhrmann systems and

(2) operating two identical MLE systems, differing only in process volume

did not have any significant effect on low F/M filament proliferation. The DSVI's of the 1st MLE (average of 130 m*l*/g) and Wuhrmann (average of 100 m*l*/g) systems were unaffected by change in daily anoxic/aerobic frequency of alternation. Observed DSVI's in the 2 MLE systems, differing only in process volume, were the same (± 140 m*l*/g) and reported dominant filament types were identical in both systems.

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APPENDIX A

Detailed ingredient list of constituents of artificial sewage used as influent feed during the 1st part of the investigation.

APPENDIX A

Constituents and makeup of the artificial sewage

The artificial sewage was made up using the following 7 suspensions:

1	Vitamins	g/5l
	Pantothenic Acid	1.400
	Nicotonic Acid	1.400
	D-Biotin	0.07
	Cyanocobalamin	0.07
	Folic Acid	0.07
	Pyridoxine	1.400
	Cocarboboxylase	1.400
	4,amniobenzoic Acid	1.400
	Inosetol meso	1.400
	Thiominium Dichloride	1.400
	Riboflavin	1.400
	Choline Chloride	1.400

2	Readily Biodegradable COD (S_{bsi})	g/5l
	Lactose	3.3
	Acetate	13.8
	Succinate	8.7
	Citrate	26.4
	D-Glucose	3.3
	Maltose	3.3
	Glycerol	5.4
	Lactic Acid	$0.020l = 24.2$g
	Ethanol	$0.009l = 7.1$g
	Butanol	$0.0045l = 4.5$g

3	Micro Inorganic Nutrients	g/5l
	$FeSO_4.7H_2O$	8.62
	$ZnSO_4.7H_2O$	2.46
	$MnSO_4.4H_2O$	2.46
	$CuSO_4.5H_2O$	0.50
	$CoCl_2.6H_2O$	0.50
	$Na_2MoO_4.2H_2O$	0.25
	H_3BO_3	0.50
	KI	0.12

4	Additional Micronutrients	g/5l
	$NiCl_2.6H_2O$	0.250
	$AlCl_3.6H_2O$	0.100
	NH_4VO_3	0.025
	Na_2SeO_3	0.010
	TiO_2	0.040
	$Na_2WO_4.2H_2O$	0.015

5	Organic Nitrogen	g/8l
	Casein	10.80
	Peptone	20.20
	Yeast Extract	20.20
	Gelatin	15.80

6	Macro Inorganic Nutrients	g/15l
	NH_4Cl	162.0
	K_2HPO_4	57.0
	KH_2PO_4	3.0
	$MgCl_2.6H_2O$	198.0
	$CaCl_2.2H_2O$	49.5

7	Complex Carbohydrates	g/15l
	Starch	50.55
	Cellulose	39.60
	Agar	7.95
	Dextrin	69.15

Preparation of daily artificial feed

Table A1: Ingredients of artificial sewage comprising proportions of RBCOD and PBCOD fed to the MLE and Wuhrmann systems during the 1st part of the investigation i.e. days 1 to 252. Values given in the Table are ml per 10*l*.

	Final concentrations in feed mg/*l*	mgCOD/*l*	mgN/*l*	
Vitamins	7.68			30
Micro Inorganic Nutrients	9.25	10		30
S_{bsi}		60		200
Additional Micro Nutrients	0.26			50
Organic Nitrogen		85	22	140
Macro Inorganic Nutrients	532.1	70	38	170
Complex Carbohydrates		375		350
Tap water				9250
TOTAL TKN			60	
TOTAL COD		600		

Table A2: Ingredients of artificial sewage comprising RBCOD only fed to the MLE and Wuhrmann systems during the 1st part of the investigation i.e. days 253 to 259. Values given in the Table are ml per 10*l*.

	Final concentrations in feed mg/*l*	mgCOD/*l*	mgN/*l*	
Vitamins	7.68			30
Micro Inorganic Nutrients	9.25	10		30
S_{bsi}		400		200
Additional Micro Nutrients	0.26			50
Organic Nitrogen		85	22	140
Macro Inorganic Nutrients	532.1	70	38	170
Tap water				9380
TOTAL TKN			60	
TOTAL COD		565		

NOTE: All the suspensions, with the exception of Number 7 (Complex Carbohydrates), were kept refrigerated at 4° C. Prior to daily feed preparation each suspension was thoroughly mixed.

APPENDIX B

Procedures for the sampling and testing of the MLE and Wuhrmann systems operated during the investigation.

APPENDIX B

1 Introduction

In this appendix the methods employed for the sampling and testing of the systems operated throughout the investigation are outlined. The procedures covered are :

(1) Daily feed preparation for the systems.
(2) Sampling from each system.
(3) Tests and measurements performed on each system.

2 Daily feed preparation

At the start of each 24 hour period 10 liters of influent sewage was prepared for each system.

2.1 Artificial sewage

The influent artificial sewage feed was made up by taking proportions from each of the 7 artificial suspensions (the preparation of the suspensions is described in detail in Appendix A) and diluting these proportions with tap water to make up the 10 liter volume. The 10 *l* volume of artificial sewage was prepared for and poured into the feed bucket of each system at the start of the 24 hour period.

2.2 Real sewage

Raw sewage was collected once every 10 to 14 days from the Mitchell's Plain wastewater treatment works and stored in a refrigeration room at 4°C. The COD and TKN concentrations of the new sewage batch were measured before feeding to the systems. This step was taken to allow appropriate dilution with tap water to ensure the influent COD concentration, fed to the systems, was approximately 500 mgCOD/*l*. Typically the COD concentration of the new sewage was 1100 to 1200 mgCOD/*l*.

On a daily basis 4 to 5 liters of sewage (depending on the new sewage COD concentration) was mixed with tap water to make up the 10 liter volume. Sodium bicarbonate, in powder form, was added and thoroughly mixed with the 10 liter volume. The amount of sodium bicarbonate added was dependent on the pH of the mixed liquor in the aerobic reactor of each system. Sufficient sodium bicarbonate was added to each 10 liter sewage volume to ensure the pH of the mixed liquor of the aerobic reactor was between 7 and 8. The 10 liter volume was prepared for and poured into the feed bucket of each system at the start of the 24 hour period.

3 Sampling from each system

Daily influent, reactor and effluent samples of ± 100 ml were each kept in 250 ml plastic jars and stored in a refrigeration room at 4°C. Immediately after sampling two drops of mercuric chloride were added to the sample. Each morning samples were taken from (1) the effluent buckets of each system and (2) from the mixed liquor of the anoxic and aerobic reactors of each system. The anoxic and aerobic mixed liquor samples were immediately filtered through firstly course Whatman's No.1 filter paper and secondly through a fine 0.45 μm pore filter. Influent samples were taken from the feed bucket of the systems at the start of each 24 hour period.

Mixed liquor samples for MLVSS and DSVI measurements were taken from the aerobic reactor of each system. Care was taken to ensure that the volume taken for sampling did not exceed the daily waste volume. For the 1st MLE and Wuhrmann systems, both with 6.5 liter volumes and 15 day sludge age, 433 ml of mixed liquor was removed each day.

4 Testing performed on each system

The parameters measured and tested for are listed in Table B1 below. Normally samples for COD and TKN analysis were tested on the day of sampling. Samples for NO_3^- + NO_2^- analysis were kept refrigerated at 4°C and analyzed in batches once per week.

Table B1: Parameters measured in the influent, reactors and effluent of each system

Parameter	Unfiltered Influent	Anoxic Reactor	Aerobic Reactor	Unfiltered Effluent
COD	Daily	---	---	Daily
TKN	Daily	---	---	Daily
NO_3^- + NO_2^-	---	3-5 times	per week	Daily[1]
OUR	---	---	Daily	---
DO	---	---	Daily	---
MLSS and MLVSS	---	---	Daily	---
DSVI	---	---	Daily	---
pH	---	---	Daily	---

1 Samples were filtered through 0.45 μm fine pore filter paper for NO_3 + NO_2 analysis.

The procedure for the analysis of COD, TKN, MLVSS and MLSS were obtained from the "Examination of Water and Wastewater", 16th Edition (1985). NO_3^- + NO_2^- concentrations were measured on a Technicon Auto-analyser in accordance with the Industrial methods test techniques as set out in the Technicon Auto-analyser methodology. The mixed liquor pH was measured with a Copenhagen Type 80 pH meter.

A detailed description of the DSVI test methodology is given by Ekama and Marais (1984).

From day 1 to day 184 a Yellow Springs Instrument (YSI) Co. dissolved oxygen probe and meter was used to measure the aerobic reactor dissolved oxygen (DO) concentration and oxygen utilization rate (OUR). The OUR was measured by

(1) Attaching a Hewlett-Packard Chart pen recorder to the YSI DO meter.
(2) Carefully positioning the DO probe in the aerobic reactor.
(3) Briefly raising the reactor DO concentration to ± 5 mgO/*l* and cutting off the oxygen supply to the reactor as the DO approaches 5 mgO/*l*.
(4) Determining the slope of the DO versus time line plotted by the pen recorder.

The slope of the plot gives the OUR in mgO/*l*/h.

From day 185 to the end of the investigation, i.e. day 545, a digital DO and OUR meter, designed and developed in the UCT Chemical Engineering department (Randall *et al.* 1991), was used to monitor the reactor DO and OUR. The digital OUR meter measured reactor DO's and simultaneously logged the time of measurement. Making use of two potentiometers the OUR meter activated and deactivated a solenoid valve positioned in the reactor oxygen supply line. Upper and lower DO limits were manually set on the OUR meter's user interface. When the reactor DO concentration reached the set upper DO limit the oxygen supply was cut off and when the reactor DO reached the lower DO limit the oxygen supply was returned. The OUR was determined by an on-board micro-chip that executed a linear-regression on the reactor DO's, measured ± every 10 seconds as the DO dropped from the set upper limit to the set lower limit. The period of the aeration cycle depended on the rate of oxygen supply and the magnitude of the difference between the set upper and lower DO limits.

After each aeration cycle, the calculated OUR, time of recording, number of DO measurements used for the OUR calculation and the correlation coefficient were stored in the OUR meter's memory. The OUR meter stored 150 recordings, which at the end of the measuring period, were exported to a personal computer in ASCII format. After retrieving and saving the OUR records the memory of the OUR meter was cleared for further measurements.

APPENDIX C

Procedures for the determination of N and COD mass balances

APPENDIX C

1 N MASS BALANCE

The N mass balance was determined by reconciling the mass of TKN and nitrate entering the system per day with (1) the mass of nitrate generated in the system (2) the masses of TKN and nitrate in the outflow and (3) the nitrogen content of the sludge leaving in the daily waste flow. The method used to determine the N mass balance is applicable to both the MLE and Wuhrmann systems. The equation for the N mass balance is

$$N(\%) = \frac{M(TKN)_e + M(N)_e + M(X_v)_n + M(N)_d}{M(TKN)_i + M(N)_{ndos}} \qquad (C1)$$

where

$M(TKN)_i$ = mass of TKN entering the system
= influent TKN concentration * daily feed flow rate (mgN/d)

$M(N)_{ndos}$ = mass of nitrate dosed to the anoxic reactor
= nitrate concentration dosed to the anoxic reactor * daily feed flow rate (mgN/d)

$M(TKN)_e$ = mass TKN leaving the system
= effluent TKN concentration * daily feed flow rate (mgN/d)

$M(N)_e$ = mass nitrate + nitrite leaving the system
= effluent nitrate + nitrite concentration * daily feed flow rate (mgN/d)

$M(X_v)_n$ = nitrogen content of sludge in waste flow
= $f_n.X_v.V_p/R_s$

where

f_n = TKN/VSS ratio of the sludge

X_v = MLVSS concentration (mgVSS/l)

V_p = process volume (l)

R_s = system sludge age (d)

$M(N)_d$ = mass nitrate + nitrite denitrified per day

(1) for the MLE system

= $Q.[s.N_{ne} + a.N_{naer} + N_{ndos} - (1 + a + s).N_{nanx}]$ (mgN/d)

(2) for the Wuhrmann system

= $Q.[N_{ndos} + (1 + a + s).(N_{naer} - N_{nanx})]$ (mgN/d)

where

N_{ne} = effluent nitrate + nitrite concentration (mgN/l)

N_{naer} = aerobic nitrate + nitrite concentration (mgN/*l*)
N_{nanx} = anoxic nitrate + nitrite concentration (mgN/*l*)
N_{ndos} = nitrate concentration dosed to the anoxic reactor (mgN/*l*)
Q = daily feed flow rate (*l*/d)
s = underflow recycle ratio
a = mixed liquor recycle ratio

2 COD MASS BALANCE

As with the N balance, the COD mass balance is determined by reconciling the mass of COD entering the system with the mass of COD leaving the system in (1) the outflow (2) the COD content of the sludge in the waste flow and (3) COD utilization under anoxic and aerobic conditions. The COD mass balance is calculated from the equation

$$C(\%) = \frac{M(S_{te}) + (M(X_v)_c + M(O)_c}{M(S_{ti})} \qquad (C2)$$

where

$M(S_{ti})$ = mass of COD in influent
= influent COD concentration * influent daily feed flow rate (mgCOD/d)
$M(S_{te})$ = mass of COD in effluent
= effluent COD concentration * influent daily feed flow rate (mgCOD/d)
$M(X_v)_c$ = COD content of sludge in waste flow
= $f_{cv}.X_v.V_p/R_s$

where

f_{cv} = COD/VSS ratio of the sludge
$M(O)_c$ = oxygen required for COD utilization
= $M(O)_t - M(O)_n + M(O)_d$ (mgO/d)

where

$M(O)_t$ = measured mass of oxygen consumed daily
= OUR.24.Aerobic mass fraction.V_p (mgO/d)

where

OUR = measured oxygen utilization rate (mgO/*l*/h)
V_p = process volume (*l*)
$M(O)_n$ = mass oxygen required for nitrification
= 4,57 * $M(N)_g$ (mgO/d)

where

$M(N)_g$ = mass of nitrate nitrified in the aerobic reactor
= $M(N)_d + M(N)_e - M(N)_{ndos}$ (mgN/d)

and

$M(O)_d$ = equivalent mass of oxygen for nitrate denitrified for COD utilization in the anoxic reactor (mgO/d)

= 2,86 * $M(N)_d$ with $M(N)_d$ determined in Equ.C1 above

APPENDIX D

Steady state data and measured data obtained from the MLE and Wuhrmann systems during the 1st part of the investigation.

APPENDIX D

Measured and Operational data used to determine the N and COD mass balances and substrate utilization rates.

System : 1st MLE
Operational Period : Days 1 to 259

OPERATIONAL DATA

Yh	0.45	mgVSS/mgCOD	fup	0.07	mgCOD/mgCOD	fbs	0.28	mgCOD/mgCOD	Rs	15 days
fcv	1.34	mgCOD/mgVSS	fn	0.09	mgN/mgVSS	Rf	0.82	mgCOD/mgCOD		

MEASURED DATA

Steady State	Sti (mgCOD/l)	Ste	Nti (mgN/l)	Nte	Xv (mgVSS	OUR (mgO/l/h)	Nne	Nnaer (mgN/l)	Nnanx	Nndos	Vanx (litres)	Vaer	(s)	(a)	MNd	MNg	MOt	MOd (mgO/d)	MOn	MOc
1	610	108	59.1	4.1	1855	48.3	29.9	26.5	12.5	20.0	3.5	3.0	1	0	249	348	3478	712	1590	2599
2	627	107	56.0	2.0	1778	35.6	23.7	27.0	3.7	15.9	3.5	3.0	1	0	322	400	2563	921	1828	1656
3	650	106	56.1	4.0	1710	37.0	38.0	41.5	25.6	32.4	3.5	3.0	1	0	192	248	2664	549	1133	2080
4	595	93	58.1	1.9	1835	40.8	25.5	26.1	2.4	11.1	3.5	3.0	1	0	318	462	2938	909	2111	1736
5	559	108	53.5	3.0	2019	37.0	22.5	23.0	5.1	12.2	3.5	3.0	1	0	245	348	2664	701	1590	1774

System : MLE (days 182 to 218) and Wuhrmann (days 219 to 259)
Operational Period : Days 1 to 259

MEASURED DATA

Steady State	Sti (mgCOD/l)	Ste	Nti (mgN/l)	Nte	Xv (mgVSS	OUR (mgO/l/h)	Nne	Nnaer (mgN/l)	Nnanx	Nndos	Vanx (litres)	Vaer	(s)	(a)	MNd	MNg	MOt	MOd (mgO/d)	MOn	MOc
1	586	89	55.4	4.5	1940	39.2	29.0	28.3	8.4	11.6	3.5	3.0	1	0	238	412	2822	681	1883	1620
2	513	100	52.0	3.4	2042	46.3	30.4	29.8	28.0	13.5	3.5	3.0	1	0	171	340	3334	489	1554	2269

Legend

Ste	-	Efluent COD (mgCOD/l)
Nti	-	Influent TKN (mgTKN/l)
Nte	-	Effluent TKN (mgTKN/l)
Nne	-	Effluent nitrate + nitrite (mgN/l)
Nnaer	-	Aerobic reactor nitrate + nitrite (mgN/l)
Nnanx	-	Anoxic reactor nitrate + nitrite (mgN/l)
Nndos	-	Nitrate dosed to the anoxic reactor in mgN per litre of influent
Xt	-	Total mixed liquor suspended solids (mgTSS/l)
Xv	-	Volatile mixed liquor suspended solids (mgVSS/l)
DSVI	-	ml/g
fn	-	mgTKN/mgVSS
fcv	-	mgCOD/mgVSS
fna	-	free and saline ammonia fraction of influent TKN (mgTKN/mgTK
DO	-	Dissolved oxygen (mgO/l)
OUR	-	Oxygen utilization rate (mgO/l/h)
(a)	-	Mixed liquor recycle ratio
(s)	-	Underflow recycle ratio
MNd	-	Mass nitrate + nitrite denitrified per day
MNg	-	Mass nitrate nitrified in the aerobic reactor per day
MOt	-	Mass oxygen required for carbonaceous material degradation and nitrification
MOd	-	Equivalent mass of oxygen utilized for denitrification per d
MOn	-	Mass of oxygen utilized per day for nitrification
MOc	-	Mass of oxygen utilized per day for carbonaceous material degradation.

MEASURED DATA - SYSTEM 1 MLE (days 1 - 259)

DAY	Sti	Ste	Nti	Nte	fna	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
1	600	86	61.0	32.0		6.5				756	638	397				
2	600	91	59.0	30.0		20.0				752	692	492				
3	560	87	56.0	21.0		52.5				1110	902	414				
6	635	99	57.0	9.0						1158	1020					
7	580	113	60.0	8.0		54.0				1704	1562	410				
8	600	108	56.0	6.0		69.5				1518	1306	448				
9	583	55	59.0	4.0		63.5				1634	1382	465				
10	555	65	57.0	0.4		56.5				1700	1444	470				
12	555	37	57.0	4.0		50.0										
13	634		59.0	9.0		44.5				1418	1222	451				45.3
14	618	91	56.0	11.0		27.4				1386	1178	491				46.4
15	612	87	59.0	3.0		35.0				1806	1528	414				44.8
16	646	81	59.0	3.0		35.0				1490	1272	416				34.8
17	656	176	57.0	0.6		55.0				1464	1246	423				
19	667	65	70.0	2.0		42.0										
20	623	77	62.0	2.0		44.6				1630	1372	393				53.0
21	474	69	55.0	0.0		45.0				1684	1414	392				37.8
22	700	57	47.0	5.3		55.2				1712	1470	257				34.9
23	566	115	60.0	16.0		40.0				1380	1198	362				39.1
24	528	90	58.0	5.0		28.0				1406	1350	427				43.3
25										1378	1190	435				
26	641	99	64.7	6.9		33.7										
27	725	65	57.0	1.9		50.2				1762	1474	386				
28	591	61	61.0	2.0		34.5				1684	1456	392				
29	558	73	35.0	3.8		43.0				1672	1490	407				14.9
30		74	39.0	4.1		35.0				1544	1326	415				32.4
31	632		40.9	4.2		41.5				1566	1346	396				25.2
33	495	50	26.0	3.4		31.5										
34		145		0.0		36.0				1476	1328	434				
35	604	72	55.0	5.7		38.5				1584	1342	429				31.0
36	700	103	57.0	1.0		19.8				2008	1520	343				26.6
37	680	233	58.0	3.6		23.4				1808	1334	338				40.9
38	602	100	55.0	2.2		21.4				2040	1746	304				38.2
40	659	96	59.0	2.0		2.9										
41		98	61.0	4.2		4.9				1898	1586	278				50.5
42	723	96	65.0	1.4		8.4				1948	1720	277				48.2
43	683	100	57.0	2.2		26.2				1800	1600	278				50.0
44	639	86	59.0	0.0		36.1				1776	1574	293				36.4
45	719	90	59.0	2.9		33.2				1822	1610	285				31.4
47	679	118	55.0	3.5		31.7										
48	664	75	54.0	1.7		36.1				1524	1336	289				42.9
49	599	83	57.0	4.3		39.7				2048	1804	244				34.4
50	648	144	53.0	2.9						2190	1882	234				
51	484	94	56.0	8.0		46.2				1968	1508	254				43.6
52	632	123	59.0	3.6		58.0										
53		103	53.0	0.0												
54		103	53.0	0.0		54.0										
55	714	131	63.0	1.1		50.3										
56	607	90	56.0	0.0		42.8				2320	2012	203				44.8
57	698	82	64.0	4.3		38.6				2116	1860	223				38.4
58	722	107	57.0	2.0		38.6				2176	1932	221				35.8
59	585	111	60.0	0.0		29.3				2246	1978	232				30.1
60	738	99	45.0	0.0		26.1	20.9			2538	2334	205			3.00	36.6
61	585	135	60.0	6.0		15.2	18.8	9.3								
62	593	99					28.6			2150	1930	205			0.90	57.4
63	617	123	60.0	3.8		32.8	33.1			2036	1792	232			4.80	42.7
64	633	119	60.0	3.5		32.3	23.5			2006	1814	233			4.10	39.5
65	657	95	61.0	5.7		25.7	20.9			2430	2144	201			1.10	63.8
66	560	99	58.2	6.3		22.3	16.0	7.8		2150	1834	220			0.90	73.2
67	617	99	60.2	6.6		22.7	14.4			2218	1972	222			0.40	56.9
68	649	95	64.4	7.8		16.0	10.9									
69	610	92	62.0	3.9		21.1	19.2			2284	2042	203			1.00	
70	689	100	60.0	2.9		29.5	21.2			2100	1852	219			1.10	53.9
71	697	92	71.0	4.5		24.8	13.1			2422	2202	193			1.60	54.8
72	647	106	65.5	4.2		17.6	13.5			2428	2164	198			1.30	66.9
73	623	115	61.0	4.3		16.1	14.6			2296	2020	206			1.70	78.3
74	582	98	60.0	7.4		9.5	5.7	0.6		2638	2408	177			1.50	57.4
75	598	131	62.0	12.9		10.6	3.5									
76	614	90	53.0	1.7		18.0	18.0	9.2		2046	1798	215			1.20	59.1
77	623	94	57.0	1.8		23.2	21.0	10.6		2326	2048	189			0.90	55.3
78	664	98	64.0	11.2		24.0	18.4	6.7		2152	1898	186			0.80	31.6
79	600	88	55.0	1.9		7.4	15.6	3.8		2114	1904	204				23.9
80	633	117	59.0	4.9		36.3	24.0	7.8		1928	1680	207			0.60	40.5
81	560	111	65.0	4.3		39.6	32.4	12.4		1688	1554	237			1.50	32.8
82	584	78	57.0	7.8		32.8	27.6	13.2								
83	649	104	57.0	1.8		34.8	30.0	16.4		1694	1550	213			1.00	46.1
84	569	95	60.5	4.3		30.9	26.7	10.1		1670	1532	216			2.20	35.5
85	610	104	63.0	4.2		29.0	35.3	16.0		1710	1504	199			1.30	44.0
86	627	92	58.0	2.5		35.8	38.9	19.3		1638	1438	208			2.70	31.8
87	659	104	55.0	1.7		48.1	37.9	4.0		1752	1572	224			1.80	35.4
88	627	100	62.0	2.5		44.2	33.5	9.5		1656	1456	229			1.60	33.1
89	422	129	57.0	2.8		42.1	34.9									
90	609	99	59.0	3.5	0.85	35.4	41.5	14.1		1980	1784	202		1.52	1.60	45.0
91	594	114	59.0	4.5	0.88	30.7	41.0	18.5		1926	1672	208			0.60	57.9

DAY	Sti	Ste	Nti	Nte	fna	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
92	648	173	67.0	4.3		34.0	32.5	18.5		1874	1764	207			0.90	42.2
93	620	116	59.0	4.5	0.80	38.9	41.0	19.3		2246	2012	196			3.10	64.3
94	543	116	57.0	6.3		42.1	30.7	18.5		2186	1858	201			5.35	44.1
95	624	94	58.0	3.9		39.4	35.4	17.3		2326	2126	189			3.40	50.8
96	657		58.0							2310	2049	186				
97	600	110	57.0	1.9		39.4	36.9	14.1		2294	1972	183				
98	632	100	57.0	2.9	0.81	30.7	22.7	10.3		2108	1860	190			1.30	57.9
99	653	98	56.0	0.0		33.5		17.3		2070	1812	193			5.60	46.5
100	549	126	55.0	1.9		35.4	35.9	12.6		1892	1684	186			2.30	35.3
101	582	130	57.0	2.2		36.9	34.9	19.7		2124	1914	188			2.30	39.0
102	582	113	57.0	1.5		38.4	30.6	10.6		1996	1774	183				
103	570	105	54.0	1.5		38.4	31.1			1868	1634	178				
104	577	123	57.0	7.7		25.2	14.8	1.8		2446	2170	172			3.30	53.1
105	520	139	57.0	11.0	0.82	16.0	19.3	6.5		2304	2050	174		1.78	0.40	63.8
106	643	100	64.0	3.6	0.71	33.0	36.9	19.7		1982	1700	198			0.62	45.8
107	627	136	61.0	1.7	0.76	39.4	43.1	19.7		1880	1678	191			3.71	41.8
108	548	105	55.0	0.0	0.76	42.6	35.4	15.2		1990	1746	181		1.79	1.98	52.0
109	581		57.0	1.9	0.76	36.4	37.4	15.2		1930	1796	187		1.48	2.94	42.2
110	573	109	61.0	3.0	0.80	28.8	26.1	7.6		1982	1796	175		1.37		
111	634	110	61.0	2.5	0.72	25.2	28.3	7.2		2176	1948	162		1.42	0.55	56.3
112	618	114	55.0	1.7	0.73	27.4	24.8	4.7		2038	1890	163		1.36	1.70	46.3
113	698	115	55.0	0.0	0.83	27.4	29.7	6.1		2112	1924	157		1.62	2.01	41.9
114	648	103	55.0	2.1	0.81	24.8	32.9	8.6		2066	1746	155		1.38	1.55	56.0
115	607	86	54.0	0.6	0.79	34.9	31.4	9.4		1940	1770	161		1.33	2.06	49.7
116	640	78	60.2	0.0	0.75	29.5	30.5	10.8		1978	1714	162		1.38	3.10	54.5
117	689	70	56.6	5.0	0.78	27.2										
118	632	119	54.6	0.0	0.69	22.6	19.9	0.0								
119	586	130	53.5	0.0	0.72	19.9	21.2	0.0		1882	1724	170		1.44	2.88	46.0
120	635	86	51.2	0.7	0.96	22.1	26.7	0.0		2016	1804	167		1.42	2.60	40.2
121	603	159	56.6		0.75	4.8	19.1	0.0	17.0	1878	1704	192		1.58	1.6	41.4
122		114	57.7	1.4	0.70	22.1	15.6	3.1	17.0	1832	1602	179		1.58	1.4	31.3
123	578	118	57.4	3.6	0.84	24.4	14.4	4.5								
124	619	114	55.2	15.0	0.74	9.1	9.9	0.0								
125	592	111	54.6	14.1	0.72	14.0	21.7	0.0	16.3	2098	1954	187		1.32	4.8	23.0
126	658	107	55.7	1.0	0.72	21.2	24.8	5.4	16.3	2240	1954	179		1.49	1.1	43.2
127	750	105	56.7	0.0	0.83	26.7	24.4	4.3	17.0	2080	1904	183		1.52	2.0	38.8
128	615	113	54.6	1.7	0.72	24.4	20.8	0.0	12.0	2162	1954	181		1.59	2.5	36.2
129	664	121	61.9	0.8	0.68	30.1	43.0	17.4	15.0	2362	2026	178		1.57	1.4	42.8
130	635	93	54.9	0.0	0.68	40.7	36.3	10.9	12.0	1908	1742	210		1.59	1.8	44.7
131	590	88	54.3	0.0	0.74	33.6	33.1	6.9								
132	602	84	49.8	0.0	0.82	29.6	31.6	5.0	17.7	2092	1834	195		1.45	2.5	41.2
133	557	113	61.0	0.7	0.71	29.1	31.6	2.9	16.8	2080	1746	200		1.45	1.6	37.6
134		90	59.4	0.0	0.73	25.7	28.1	1.7	15.1	1982	1756	212		1.47	1.4	44.1
135	639	57	56.0	0.0	0.78	22.9	24.7	0.3	15.9	2164	1932	222		1.33	1.4	37.3
136	647	115	52.4	0.0	0.79	20.1	29.1	2.2	15.0	1924	1770	260		1.34	1.7	50.3
137	713	90	57.9	0.0	0.70	19.2	22.4	2.2	17.0	1924	1696	260		1.44	3.3	32.8
138	688	111	57.4	0.0	0.70	21.0	23.3	0.0	16.0							
139	573	135	54.6	0.0	0.77	19.7	29.1	5.0	16.8	1776	1608	293			2.6	35.3
140	573	70	54.6	1.4	0.74	26.2	32.1	5.9	16.5	1810	1638	311		1.25	3.0	33.5
141	601	153	59.1	1.8	0.71	28.6	33.1		16.8	1826	1602	318		1.16	3.0	30.3
142		117	54.3	1.1	0.71	30.1	47.1		16.5	1730	1556	324		1.21	3.0	33.0
143	687	131	70.0	2.5	0.54	41.2	41.8		33.6	1738	1572	322		1.38	2.3	35.1
144	638	94	57.7	0.0	0.76	32.6	29.6									
145	589		55.2		0.76											
147	559		57.1	1.1	0.77	38.4	48.4	20.0	32.0	2118	1870	359		1.45	5.0	
148	591	117		7.1		38.4	28.1	16.9	34.0	1572	1440	331		1.18		31.9
149	631	101		5.0		31.9	45.9		30.0	1816	1656	330		1.35	4.8	37.9
150	648	73		2.1		45.3	44.2	28.5	28.0	1792	1624	290		1.35	6.0	31.1
151	591	146	55.4	0.0	0.84	45.3	48.9	35.0	32.0							
152	712	65	79.8	0.3	0.51	47.1	54.5	37.6	32.0							
153	712	69	76.1	1.1	0.63	41.4	50.7	37.1	35.0	1872	1678	320		1.13	5.40	37.6
154		105		0.7		40.3	29.0	31.5	34.2	1702	1506	300		1.42	1.05	31.6
155	688	146	68.6	23.4		27.1	35.5	4.8	30.0	2180	1872	257		1.34	0.25	46.3
156	748	119	88.8	4.2	0.49	27.6	41.9	18.9	35.6	2404	2174	250	0.04	1.12	3.50	44.5
157	617	108	61.0	2.2		30.5	34.5	21.5	29.6	2130	1874	300		1.39	3.65	44.0
158	609	125	67.8	3.1	0.65	23.8			24.0	2156	1926	297	0.08	1.34	3.05	38.0
159	634	108				26.1	25.2	3.2								
160	654	86	59.1	0.7	0.70	23.4			22.5	2024	1828	281	0.07	1.21	3.24	40.6
161	502	90				27.6	33.5	14.1	20.0							30.0
162	630	82	60.5	2.5	0.67	25.7		9.4	0.0	2266	1840	274	0.07	1.24	2.85	36.8
163	600		59.4	5.3	0.72	29.9	26.2	13.8	20.0	1988	1800	362	0.07	1.33		32.1
164	624	106		1.5		26.7		7.0	20.0	1896	1762		0.08	1.42	1.33	44.8
166	690	120	67.2	2.5	0.71	29.4	25.8	0.9	11.7	1746	1574	206	0.07	1.31		23.4
167		159	67.5	1.4	0.69	26.2	25.8		11.5	1830	1658	328	0.07	1.34	2.62	48.0
168	580	147	59.6	1.9	0.74	26.7	24.9	1.0	12.5	1718	1612	233	0.04	1.21	1.82	41.9
169	654	98	60.7	2.0	0.67	24.4	27.1	1.7	10.0	1994	1850	341	0.06	1.37		
170	621	110	59.1	1.5	0.81	29.4	30.3	0.8	11.0	1634	1462	330	0.08	1.15	2.07	40.5
171	630	131	58.2	1.7	0.72	19.7	15.2	1.0	11.0	1912	1688	303	0.08	1.17	1.71	50.0
172	711	82	59.6	3.4	0.77	15.6			11.3	2062	1802	398	0.10	1.25	2.50	35.1
173		122	56.8	1.1	0.75	22.3	27.1	0.9	11.1	2070	1790	319		1.13	0.74	55.7
174	528	77	59.6	5.2	0.80	21.4	23.1	1.2	11.8	1908	1830	325	0.08	1.24	1.15	47.6
176	520	61	54.0	5.2	0.83	27.6	25.8	0.6	11.0	2030	1974	296	0.09	1.30	0.95	59.8
177	573	63	58.8	1.5		22.3	22.7	1.0	10.0	2080	1882	288	0.09	1.28	3.95	40.9
178	557	83	65.2	1.4	0.83	21.4			12.0	2256	2030	275	0.09	1.37	3.45	46.7
180	589	116	57.4	0.8	0.81	25.8	28.0	5.3	13.1	2184		244	0.08	1.11	1.99	43.3

DAY	Sti	Ste	Nti	Nte	fna	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
181	580	71	47.0	0.6	0.94	26.7	24.0	1.0	12.0	2236	1962	250	0.09	1.33	4.09	34.9
182	539	67	60.2	2.5	0.71	23.6	26.5	2.5	10.0	2052	1824	244	0.10	1.34	3.0	34.9
183	572	79	55.1	0.9	0.72	32.1	33.6	8.9	10.5	2124	2000	250	0.08	1.29		31.7
184	621	95	52.6	0.0	0.81	35.0	34.6	9.4	10.0	2040	1848	255	0.08	1.21	3.0	36.3
185	572	112	56.6	0.0	0.70	34.1			11.0	2030	1962	246	0.07	1.09	3.0	35.2
186	588	79				30.2										
187	627	47				26.1	23.4	1.9							3.0	
188	539	91				25.2	23.9	0.6	10.5							
189	586	68	52.9	0.6		25.2	27.2	2.4	10.4	2282	2002	231	0.08	1.20	3.0	38.3
190	610	72	53.2	3.8		15.2			11.0	2338	2110	236	0.09	1.23	3.0	30.9
191	561	109				8.9	27.2	0.5	16.0							
192	668	80	55.4	0.8		21.0	24.3	0.3		2224	2124	198	0.08	1.30	3.0	
193	644	122				21.8				1950	1828	242			3.0	30.5
194	585	93													3.0	27.6
195	644	98	59.9	1.7		23.5	26.8	4.8	11.9							24.9
196	594	89	55.7	2.2		24.7	25.4	3.8	9.0	1856	1696	226			3.0	26.2
197	577	114	53.5	1.4			30.6		8.3	1946	1806	226	0.08	1.25		25.7
198	610	73	55.1	0.0			30.1	5.7	9.9	1664	1594	240	0.08	1.39		
199	540	150	60.8			15.9	8.0	0.8	8.5	2058	1844	194			3.0	56.9
200	506		55.4		0.71	24.0			7.8	2250	2058	187			3.0	58.1
201	581					17.1	9.1	0.8							3.0	55.3
202	563	101	53.5	4.9		17.1	8.7	0.0	10.7	2334	2136	189			3.0	60.1
203	629	93	58.2	7.4	0.63	17.1	10.6	2.8	11.3						3.0	30.9
204	588	105	57.7	20.4		8.1	28.7	0.9	10.9	2296	2196	188	0.08		3.0	59.2
205	573	115	51.2	4.8		25.6	30.0	6.3	10.9	2368	2084	172	0.09	1.35		64.9
206	606	61	54.0	0.4		27.8	29.5		10.5	2294	2078	183	0.09	1.36	3.0	
207	598	82							11.6	2324	2054	172		1.26	3.0	
209	598		54.3	3.1		29.5	31.3	6.5		2660	2280	165	0.08	1.26	3.0	36.6
210	532	135	54.3	2.0		32.7	31.2	6.9	11.1	2198	1926	191	0.09	1.40		31.5
211	647	156	51.5	5.0		22.5	7.5	0.9	11.3	2098	1916	196	0.09	1.41		
212	647		55.2	6.2		21.3	25.9	12.0	12.4	2236	2010	188	0.09	1.32		42.0
213	614	106	58.5	10.2		18.1	15.7		11.0	2232	1938	179	0.08	1.27		
214	528	129				19.7			11.5	2450	2134	163				57.4
215							24.6	3.8								37.0
216	586	88		2.0		20.5	22.9	3.6	10.6	2336	2076	168		1.41		
217			58.0	1.4		23.4			10.3	2128	1868	188	0.09			32.8
218	590	160	57.1	4.6		23.6	18.0	6.9	11.5	2252	2010	192	0.10	1.28		32.8
219	492	119	51.8	1.8		28.6	18.4	6.5	10.2	2214	1990	181	0.11	1.21		47.1
220	451	119	45.9	2.0		26.3	29.0	6.4		2200	2020	182	0.08	1.22		
221	621	94				21.4	21.4		8.8	2174	1930	186				
223	458	90	48.4	0.8		21.4	20.1	0.9	11.7	2250	1968	142	0.09	1.33		31.8
224	580	127	52.6	2.5		23.6	22.3	4.6	9.2	2296	2146	174	0.09	1.26		30.4
225	556	86	52.9	0.8		23.8	22.2		11.7	2038	1820	196	0.09	1.48		31.5
226	425	69	44.2	2.1		25.0	22.6	6.7	10.1	2184	1880	170	0.10	1.11		36.2
227	540	127	56.0	1.0		23.8	23.0	5.3	11.1	2044	1824	190	0.10	1.37		33.2
230	413	154	52.1	2.0		20.6	21.4			2734	2354	146	0.09	1.19	3.0	28.4
231	502	65	56.8	0.8		26.3	23.8	5.3	11.5	2178	1964	174	0.09	1.09	3.0	31.2
232	510	113	56.0	0.4			23.8	7.7	11.5	2324	2072	164	0.09	1.17	3.0	32.2
233	461	154	50.1	0.4			29.7	13.5	10.8	2282	2012	167	0.09	1.35	3.0	27.8
234	550	138				37.7	32.1		9.5	2266	2012	150			3.0	25.9
235	591	65	61.9	1.8		33.6	33.1	15.3	9.9	2294	2024	143		1.30	3.0	29.7
237	471	114	56.6	0.6		29.2	30.6	10.3	12.2	2216	1874	144	0.09	1.30	3.0	40.6
238	606	57	13.2	2.0		15.6	25.9	11.7	11.7	2490	2182	129	0.08	1.36	3.0	39.4
239			51.8	1.3		11.8	6.4	0.6	11.6	2632	2316	122		1.36	3.0	26.0
240	525	144		2.8		18.5	12.5	1.1	11.8	2318	2112	138		1.24	3.0	32.1
241	546	75				20.5	25.0		10.8	2208	1950	127			3.0	34.2
242	550	160	54.9	1.5			27.5		10.5	2582	2344	116			3.0	35.4
243						26.0										
244	521	91	64.4	3.2		28.0	31.0	6.7	13.1	2316	2032	117		1.25	2-3.5	33.3
245	505	148	51.8			28.0	21.5	2.2	11.1	2578	2240	109		1.35	2-3.5	37.2
246	553	79	52.4			25.8	32.2			2590	2298	108		1.23	2-3.5	29.7
247	629		54.3				29.2	10.5	12.1	2568	2268	109		1.31	2-3.5	30.0
248		128		1.8		30.7									2-3.5	28.0
249	634	164	57.7	3.8		26.8									2-3.5	28.0
251	625	164	58.8	0.8		23.9	25.8	5.9	11.7	2590	2068	93		1.30	2-3.5	34.7
252	557	148	54.0	17.5		27.3									2-3.5	30.9
253	508	111	54.6	2.2		17.1	30.7	9.3	9.9	1666	1466	102	0.09	1.37	2-3.5	40.1
254	496	95	54.9	2.9	0.82		18.1	2.0	8.6	1564	1380	100	0.09	1.33	2-3.5	40.6
255	490	61	51.2	1.1	0.67	15.4	12.8	1.6	10.1	1488	1356	74	0.09	1.29	2-3.5	45.0
256	534	49					19.7	3.7	9.5	1894	1660	58			2-3.5	
258	465	78	52.6	4.9			26.3	4.9							2-3.5	
259						14.7									2-3.5	21.5

MEASURED DATA - SYSTEM 2 MLE (days 182 - 218) WUHRMANN (days 219 - 259)

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
182	539	67	60.2	1.4	31.3	36.0	12.3	12.0	1928	1716	270			3.0	26.8
183	572	120	55.1	1.4	38.1	41.2	14.0	11.0	1828	1748	280				29.5
184	621	120	52.6	0.0	41.7	39.1	11.9	13.0	2046	1806	244			3.0	35.4
185	572	63	56.6	0.0	38.1			13.0	2096	2046	225			3.0	40.0
186	588	75			36.0										
187	627	79			34.6	27.9	9.2							3.0	
188	539	92			32.1	28.8	8.0	14.0							
189	586	80	52.9	0.8	32.1	30.7	8.2	13.8	2556	2286	207			3.0	
190	610	84	53.2	0.0	29.8			14.0	2110	1864	227			3.0	
191	561	92			26.4	22.6	3.3								
192	668	72	55.4	1.1	23.9	25.5	4.6		2194	2118	228			3.0	
193	644	102			23.9			14.1	2436	2240	205		1.47	3.0	36.5
194	585	93			23.9	21.4	6.1							3.0	
195	644	89	59.9	0.8	25.9	29.4	8.7	12.5	2064	1894	223	0.09	1.53		32.0
196	594	77	55.7	5.7	21.0	23.6		11.0	2274	2046	194		1.41	3.0	
197	577	64	53.5	0.6		27.2	7.3	10.7	2058	1850	224				33.0
198	610	89	55.1	0.0		31.5	10.2	10.3	2176	2054	217	0.08			
199	540	87	60.8	0.1	33.0	28.6	6.6	8.9	2078	1790	202		1.49	3.0	
200	506		55.4					8.7	2360	2132	183		1.22	3.0	55.2
201	581	66			18.0	17.0	0.8							3.0	
202	563	101	53.5	1.5	22.7	29.6	4.8	11.6	2380	2100	185			3.0	60.1
203	629	88	58.2	1.5	29.6	29.5	3.2	11.4						3.0	48.4
204	588	88	57.7	0.6	29.5	11.0	5.3	11.5	2096	1922	197	0.09		3.0	
205	573	86	51.2	0.6	30.9	30.4	5.9	12.0	2288	2048	184	0.09			35.6
206	606	74	54.0	1.5	28.7	30.4		11.5	2418	2142	160		1.26	3.0	32.9
207	598	74						11.6						3.0	
208					35.1	33.2	10.2							3.0	
209	598		54.3	1.0	33.2	30.9	6.8		2472	2140	129	0.08	1.28	3.0	29.9
210	532	86	54.3	1.8	30.9	28.5	5.9	11.1	2282	2028	145	0.09	1.37		
211	647	106	51.5	1.0	28.1	29.0	8.0	10.7	2080	1878	160	0.09	1.31		
212	647	90	55.2	1.3	29.8	29.8	11.3	11.7	1926	1658	152		1.18		42.0
213	614	90	58.5	1.4	30.3	27.6		11.1	2002	1726	144	0.07	1.26	3.0	32.6
214	528	150			28.5			11.1	2282	1914	149				
215						32.1	11.2							3.0	33.8
216	586	133		0.3	29.8	28.1	8.3	10.5	1942	1756	144		1.32	3.0	29.4
217			58.0	3.6	25.0			10.5	2274	2014	137	0.09			
218	590	70	57.1	9.0	26.3	15.5	2.7	10.6	1858	1628	157	0.11	1.18	3.0	47.5
219	492	74	51.8	7.6	29.0	32.8	30.7	13.3	1960	1768	147	0.09	1.18		
220	451	70	45.9	7.4	27.6	34.8	32.2		2188	1996	133	0.09	1.31	3.0	40.2
221	621	143			32.4	21.0	31.1	11.6	2176	1954	143			3.0	75.6
222															
223	458	90	48.4	2.1	30.4	31.4		11.8	2048	1800	117	0.09	1.41	3.0	37.7
224	580	90	52.6	2.5	30.9	27.6	17.1	11.0	2166	2000	133	0.10	1.31	3.0	78.1
225	556	102	52.9	0.7	32.3	30.6	6.3	12.7	1962	1774	139	0.10	1.38	3.0	53.8
226	425		44.2			34.6	21.4	13.2	1696	1416	144	0.09	1.27		
227	540	65	56.0	0.3	33.7			13.9						3.0	41.0
228															
229															
230	413	97	52.1	2.4	29.2	31.4			2444	2076	139	0.11	1.31	3.0	45.3
231	502	121	56.8	2.5	32.3	29.2	28.4	15.6	2480	2218	135	0.10	1.04	3.0	34.4
232	510	61	56.0	0.6		31.9	26.8		2500	2198	136	0.09	1.12	3.0	39.8
233	461	73	50.1	0.8	32.1	33.1	28.9	12.1	1930	1736	151	0.09	1.24	3.0	38.5
234	550	73			36.6	34.1		13.1	2348	2104	136			3.0	44.6
235	591	81	61.9	2.5	30.6	34.1	25.5	12.1	2174	1960	151	0.09	1.24	3.0	45.0
236															
237	471	150	56.6	0.6	35.1	35.6	24.6	15.1	2246	1932	139	0.10	1.20	3.0	44.5
238	606	61	13.2	12.2	24.5	32.1	23.5	14.6	2230	1954	147	0.09	1.37	3.0	42.6
239			51.8	0.6	15.6	7.2	11.3	14.2	2924	2502	130			3.0	34.8
240	525	164		1.5	26.5	23.0	23.7	14.8	2426	2224	148		1.36	3.0	44.5
241	546	144			31.0	26.0		13.8	2272	1982	136				
242	550	136	54.9	1.6		26.5		13.1	2772	2520	130				
243	451	70	45.9	7.4	31.0	34.8	32.2		2188	1996	133	0.09	1.31	3.0	40.2
244	521	103	64.4	3.1	31.5	32.0	23.7	14.5	2642	2290	121		1.23	2-3.5	75.6
245	505	120	51.8		33.5	31.0	25.7	13.7	2454	2122	147		1.39	2-3.5	47.2
246	553	67	52.4	2.1	42.9	40.1	34.8	11.8	2342	2034	137	0.09	1.27	2-3.5	38.5
247	629	90	54.3	2.5	30.9	38.0	17.1	15.1	1128	976	160	0.10	1.35	2-3.5	78.1
248	556	123	52.9	14.1	21.1	30.6	6.3	12.7	1962	1774	139	0.10	1.38	2-3.5	53.8
249	634	87	57.7	11.3	22.1	34.6	21.4	13.2	1696	1416	144	0.09	1.27	2-3.5	
250	540	65	56.0	0.3	33.7			13.9						2-3.5	41.0
251	625	140	58.8	0.6	35.9	41.2	31.8	11.0	2132	1754	116		1.44	2-3.5	37.9
252	557	148	54.0	0.6	26.8									2-3.5	
253	508	128	54.6	1.1	23.5	31.7	29.7	9.9	1994	1710	105	0.08	1.41	2-3.5	31.0
254	496	128	54.9	17.4	32.3	20.1	19.0	9.3	1532	1342	137	0.10	1.25	2-3.5	53.5
255	490	82	51.2	3.4	28.8	9.5	11.9	12.8	2144	1852	103	0.09	1.59	2-3.5	49.3
256	534	69	50.1	0.8	32.1	31.9	24.2	12.8	1280	1100	138	0.09	1.24	2-3.5	38.5
257	550	73			31.5	34.1		13.1	2348	2104	136			2-3.5	44.6
258	465	65	52.6	2.5	30.6	41.0	33.8	12.1	2174	1960	151	0.09	1.24	2-3.5	45.0
259	471	150	56.6	0.6	35.1	35.6	24.6	15.1	2246	1932	139	0.10	1.20	3.0	44.5

APPENDIX E

Steady state data and measured data obtained from the 2 MLE and Wuhrmann systems during the 2nd part of the investigation.

APPENDIX E

Measured and Operational data used to determine the N and COD mass balances and substrate utilization rates in the 2nd part of the investigation.

OPERATIONAL DATA

Yh	0.45	mgVSS/mgCOD	fup	0.08	mgCOD/mgCOD	fbs	0.24	mgCOD/mgCOD	Rs	15 days
fcv	1.41	mgCOD/mgVSS	fn	0.08	mgN/mgVSS	Rf	1.00	mgCOD/mgCOD		

System : 1st MLE
Operational Period : Days 260 to 545

STEADY STATE DATA

Steady State	Sti (mgCOD/l)	Ste (mgCOD/l)	Nti (mgN/l)	Nte (mgN/l)	Xv (mgVSS	OUR (mgO/l/h)	Nne	Nnaer (mgN/l)	Nnanx	Nndos	Vanx (litres)	Vaer	(s)	(a)	MNd	MNg	MOt	MOd (mgO/d)	MOn	MOc
1	519	82	37.7	2.1	2136	29.8	12.0	15.8	5.3	12.1	3.5	3.0	2	0	202	201	2146	578	919	1805
2	412	65	40.5	3.0	1732	34.0	13.6	13.8	3.3	13.2	3.5	3.0	2	0	305	309	2448	872	1412	1908
3	489	50	49.7	2.7	1959	39.6	21.1	19.9	5.9	11.6	3.5	3.0	2	0	361	456	2851	1032	2084	1800
4	566	44	51.4	2.4	2281	40.9	13.3	15.8	2.1	10.9	3.5	3.0	2	0	312	336	2945	892	1536	2302
5	545	50	49.0	2.9	2399	46.1	12.9	13.5	3.1	11.1	3.5	3.0	2	0	276	294	3319	789	1344	2765
6	555	73	50.7	3.4	2618	42.5	11.8	12.1	1.2	11.8	3.5	3.0	2	0	318	318	3060	909	1453	2516
7	547	38	50.4	2.2	2463	42.1	17.1	21.0	1.1	11.1	3.5	3.0	1	0	260	320	3031	744	1462	2312
8	560	50	46.4	2.0	2350	42.8	15.2	16.1	9.3	11.5	3.5	3.0	1	4	353	390	3082	1010	1782	2309
9	509	44	39.1	1.8	2361	40.9	6.5	10.6	4.3	10.9	3.5	3.0	1	4	340	296	2945	972	1353	2564
10	465	49	37.1	1.9	2303	33.8	7.3	5.6	2.1	9.5	3.5	3.0	1	4	266	244	2434	761	1115	2079
11	484	44	39.7	2.6	2378	47.3	4.1	3.7	0.5	10.4	4.5	2.0	1	4	263	200	2270	752	914	2109
12	505	38	57.3	2.8	2417	57.8	14.0	12.4	4.9	10.6	4.5	2.0	1	4	448	482	2774	1281	2203	1853
13	464	39	36.7	2.2	2500	46.3	11.5	6.2	3.1	13.8	4.5	2.0	1	4	315	292	2222	901	1334	1789
14	539	47	51.6	3.1	2230	53.0	21.2	20.2	15.9	15.8	4.5	2.0	1	6	310	364	2544	887	1663	1767
15	485	40	40.4	4.9	2104	43.5	26.8	24.6	21.5	20.8	4.5	2.0	1	6	232	292	2088	664	1334	1417
16	480	47	50.8	3.3	1989	48.6	7.8	7.4	2.2	8.8	4.5	2.0	1	4	330	320	2333	944	1462	1814
17	556	68	57.1	19.2	2150	42.2	10.5	8.1	5.5	10.3	4.5	2.0	1	4	202	204	2026	578	932	1671

System : Wuhrmann
Operational Period : Days 260 to 545

STEADY STATE DATA

Steady State	Sti (mgCOD/l)	Ste (mgCOD/l)	Nti (mgN/l)	Nte (mgN/l)	Xv (mgVSS	OUR (mgO/l/h)	Nne	Nnaer (mgN/l)	Nnanx	Nndos	Vanx (litres)	Vaer	(s)	(a)	MNd	MNg	MOt	MOd (mgO/d)	MOn	MOc
1	519	75	37.7	3.6	1683	29.9	21.3	19.7	18.2	12.8	3.5	3.0	2	0	173	258	2153	495	1179	1469
2	412	50	40.5	2.5	1955	34.8	28.7	29.0	25.5	13.4	3.5	3.0	2	0	239	392	2506	684	1791	1398
3	520	43	51.4	2.8	2155	41.8	35.0	32.2	28.8	11.1	3.5	3.0	2	0	213	452	3010	609	2066	1553
4	545	56	49.0	3.9	2208	37.1	34.8	27.4	28.3	11.2	3.5	3.0	2	0	85	321	2671	243	1467	1447
5	555	73	50.7	3.1	2527	41.1	35.5	25.2	21.5	11.5	3.5	3.0	2	0	226	466	2959	646	2130	1476
6	560	57	46.4	2.7	2321	41.1	35.0	30.8	29.0	11.7	3.5	3.0	1	0	153	386	2959	438	1764	1633
7	509	48	39.1	2.7	2090	39.7	31.7	25.9	24.7	11.6	3.5	3.0	1	0	140	341	2858	400	1558	1700
8	465	44	37.1	3.1	1954	34.5	27.5	25.6	22.0	11.2	3.5	3.0	1	0	184	347	2484	526	1586	1424
9	484	46	39.7	2.6	2022	39.8	30.0	25.8	24.9	11.3	3.5	3.0	1	5	176	363	2866	503	1659	1710
10	505	35	57.3	4.1	2158	58.3	45.8	42.2	41.0	11.7	3.5	3.0	1	5	201	542	4198	575	2477	2296
11	464	41	36.7	3.0	1950	33.7	32.3	28.6	29.0	13.7	3.5	3.0	1	5	109	295	2426	312	1348	1390
12	539	45	51.6	3.5	2294	48.3	36.0	32.8	31.9	7.0	3.5	3.0	2	7	160	450	3478	458	2056	1879
13	435	50	41.3	11.3	1857	39.8	16.7	18.9	17.7	6.0	3.5	3.0	2	7	180	287	2866	515	1312	2069
14	462	41	49.1	4.1	1791	42.5	22.9	22.7	21.0	6.3	3.5	3.0	2	7	233	399	3060	666	1823	1903
15	480	41	50.8	5.1	2088	39.3	30.2	22.9	21.0	7.1	3.5	3.0	1	4	185	416	2830	529	1901	1458
16	411	42	43.7	3.5	1824	41.1	23.5	20.5	19.3	7.5	4.5	2.0	1	4	147	307	1973	420	1403	990
17	457	46	45.4	9.4	2053	38.1	18.5	15.6	14.5	7.3	4.5	2.0	1	4	139	251	1829	398	1147	1079

System : 2nd MLE
Operational Period : days 508 - 545

STEADY STATE DATA

Steady State	Sti (mgCOD/l)	Ste (mgCOD/l)	Nti (mgN/l)	Nte (mgN/l)	Xv (mgVSS	OUR (mgO/l/h)	Nne	Nnaer (mgN/l)	Nnanx	Nndos	Vanx (litres)	Vaer	(s)	(a)	MNd	MNg	MOt	MOd (mgO/d)	MOn	MOc
1	491	51	52.0	1.9	1928	34.0	7.4	7.5	1.8	5.3	7.0	3.0	1	4	319	340	2448	912	1554	1807
2	411	44	43.7	2.5	1500	29.3	23.9	21.3	16.5	4.7	7.0	3.0	1	4	148	340	2110	423	1554	979
3	457	39	45.4	6.8	1585	34.0	12.3	13.6	8.5	5.1	7.0	3.0	1	4	208	280	2448	595	1280	1763

Legend

Ste	-	Effluent COD (mgCOD/l)
Nti	-	Influent TKN (mgTKN/l)
Nte	-	Effluent TKN (mgTKN/l)
Nne	-	Effluent nitrate + nitrite (mgN/l)
Nnaer	-	Aerobic reactor nitrate + nitrite (mgN/l)
Nnanx	-	Anoxic reactor nitrate + nitrite (mgN/l)
Nndos	-	Nitrate dosed to the anoxic reactor in mgN per litre of influent
Xt	-	Total mixed liquor suspended solids (mgTSS/l)
Xv	-	Volatile mixed liquor suspended solids (mgVSS/l)
DSVI	-	ml/g
fn	-	mgTKN/mgVSS
fcv	-	mgCOD/mgVSS
fna	-	free and saline ammonia fraction of influent TKN (mgTKN/mgTK
DO	-	Dissolved oxygen (mgO/l)
OUR	-	Oxygen utilization rate (mgO/l/h)
(a)	-	Mixed liquor recycle ratio
(s)	-	Underflow recycle ratio
MNd	-	Mass nitrate + nitrite denitrified per day
MNg	-	Mass nitrate nitrified in the aerobic reactor per day
MOt	-	Mass oxygen required for carbonaceous material degradation and nitrification
MOd	-	Equivalent mass of oxygen utilized for denitrification per d
MOn	-	Mass of oxygen utilized per day for nitrification
MOc	-	Mass of oxygen utilized per day for carbonaceous material degradation.

MEASURED DATA - SYSTEM 1 MLE (days 260 - 545)

DAY	N Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
260	461	71			13.2									2-3.5	21.5
261	437	69	36.7	2.2							63			2-3.5	17.1
262					16.6	19.7	9.3	12.6	2378	2046	63			2-3.5	14.4
263						19.7	9.7	13.3	2100	1774	76			2-3.5	24.2
265	614	84	42.6	1.5	20.1									2-3.5	
266	590	96	36.7	1.1	17.7	31.9	16.3		3156	2876	40			2-3.5	
267	594	96	44.0	3.6	14.7	26.3	7.4	11.3	2224	1940	54			2-3.5	31.4
268	573	84	35.8	2.2	8.8	21.3	6.8	12.2	2830	2452	58			2-3.5	30.4
269	480	100	35.6	2.1	8.2	17.3	4.3	12.6	2376	2022	59			2-3.5	32.8
270	553	75	38.1	3.6	7.9	6.3	1.5	12.8	2684	2286	60			2-3.5	31.6
271						7.1	0.7	10.5	2670	2318	60		1.33	2-3.5	37.9
272	553	84	38.4	2.7	7.5										
273	465	73	35.0	0.8	7.1	7.1	0.3	10.2	2086	1806	67	0.08	1.34	3.80	37.0
274	490	65	36.4	1.5	9.3	7.1	0.1	13.1	2524	2156	63	0.08	1.34	2.85	41.1
275	418	84	35.0	1.5	12.5	9.7	1.8	12.8	2152	1820	74	0.09	1.10		38.7
276	381	55	34.2	1.5	14.1	17.3	1.8	13.0	2042	1716	78	0.07	1.32	4.01	36.1
277	467	92	38.6	3.4	15.7	15.3	0.9		2016	1628	72				35.7
279	341	43	40.0	3.2	18.5										
280	508	54	42.8	3.4	17.7	19.8	5.6	12.3	1686	1370	87	0.10	1.33	5.00	31.6
281	537	50	44.2	3.1	10.6	15.7	5.5	12.2	2132	1720	83	0.11	1.61	4.50	31.3
282	378	76	42.8	4.3	8.0	8.7	4.0	13.6	2116	1842	90	0.08	1.55	3.20	33.4
283	353	60	41.2	2.0	12.1	11.7	4.5	12.4	2500	2112	88	0.09	1.22	5.00	34.9
284	349	64	39.5	2.9	12.1	12.1	1.8	13.5	2038	1730	93			4.10	32.9
285								15.5	2068	1742	97			5.30	34.6
286	354	69	37.2	2.9	12.5										
287	455	85	44.2	2.9	14.5	9.5	2.0		2028	1728	104		1.62	3.70	35.3
288	406	57	53.8	2.2	16.9	16.0	3.8	11.6	2544	2164	98		1.03	3.20	35.4
289	390	65	48.7	1.1	18.1	16.5	4.0	11.9	2190	1866	100	0.08	1.20	2.80	34.5
290	484	67	52.1	2.9	22.3	23.2	3.6	10.9	2176	1862	101	0.09	1.18	2.80	31.2
291	386	67	49.0	3.2	26.6	18.1	10.1	12.8	2204	1860	100			4.70	34.2
292									2050	1780	98				
293	562	51	44.2	3.4	26.6										
294	509	31	48.7	0.8	24.4	23.6	10.0		2196	1840	94	0.07	1.41	4.80	
295	507	53	47.6	3.1	23.2	22.3	8.6	11.4	2210	1896	100	0.08	1.54	1.40	50.7
296	489	43	49.8	3.6	15.7	21.0	5.3	11.1	2432	2066	95	0.09	1.46	2.70	52.0
297	482	31	48.7	2.2	17.3	17.3	2.9	11.2	2542	2144	103	0.08	1.50	3.50	40.2
298						21.5	4.8	11.8	2484	2108	114			3.20	38.7
300	671	35	54.6	4.5	20.2										
301	601	51	51.0	3.6	16.1	22.7	4.4		2402	2036	117			3.10	
302	640	45	52.6	3.1	15.3		1.8	10.7	2532	2136	118			2.88	36.2
303						17.7	1.5	10.8	2424	2056	122	0.09	1.46	3.51	
308	453	43	45.1	2.0	14.5										
309	574	49	49.0	1.5	11.6	13.4	2.7	10.7	2976	2494	114	0.08	1.56	1.58	42.9
310		35		2.2		14.5	0.2	11.2	2976	2534	119	0.08	1.48	3.24	43.7
311	503	51	48.7	2.0	11.6									2.92	
312					10.4	10.8			2808	2432	118				
314	623	33	61.9		10.8										
315	619	33	50.7	4.3	12.0	10.0	1.9		2846	2448	123		1.50	2.56	45.6
316	568	47	48.4	2.2	12.9	14.5	1.3	11.4	2772	2402	123				
317						14.1	2.0	10.9	2894	2460	121	0.08	1.46	3.40	43.8
318	552	33	48.7	3.2	12.0										
319					12.9	13.7	1.2	9.1	2794	2384	132			4.75	44.8
320									2662	2330	135			3.33	49.1
321	556	65	51.0	3.5	6.4										
322	536	78	49.6	2.1	21.4	8.8	1.5		2900	2530	128			5.42	
323	439	43	45.4	2.0	12.5	23.7	12.4	12.3	2692	2302	134			4.60	44.8
324						9.6	1.1	12.0	2768	2338	132			3.50	48.5

DAY N	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
325															
326					12.7				3082	2656	133			2.97	
335									2974	2604	148			3.38	
339					12.5				2806	2454	143				
342	555	73	50.7	3.4	10.3				2908	2756		0.07	1.35		
345							0.6		2728	2448	139				
346	465	41	45.9	2.5	16.9										
347	486	45	50.4	1.0		19.3	0.3		2916	2450	130				
349	618	43	52.9	2.9	18.5										
350	549	33			17.4	26.1	3.3		3040	2588	126	0.08	1.60	3.75	44.0
351	618	28	52.4	2.2	15.8	17.6	0.3		2792	2364	132		1.53	3.64	40.2
352	563	30	49.8	2.5	14.7	15.6	0.9		2962	2522	128	0.07	1.42	4.05	42.3
353	612	35	50.7	2.2	14.9	14.5	0.8		2672	2244	135	0.08	1.51	2.57	43.7
354	669	51	53.8	2.4	15.4										
355						16.5	5.6		3032	2658	127			3.73	45.0
356	526	75	42.6	2.0	16.5										
357	557	81	47.9	2.7	16.5	15.6	8.2		2802	2398	125	0.07	1.45	3.85	42.9
358	526	59	44.5	2.4	15.8	14.7	8.7		2858	2396	119	0.08	1.42	4.55	43.8
359	565	37	45.1	1.5	15.8	18.3	8.1		2600	2176	123	0.08	1.39	3.31	40.6
360						14.2	6.0		2886	2330	118	0.08	1.47	4.25	42.1
361	520	41	43.4	1.1	11.9	19.8	11.8		2582	2128	120			4.07	41.6
362						15.5	9.6		2710	2302	119			3.70	43.4
363	499	39	39.5	1.4	15.5										
364	533	77	40.3	1.3	12.9	18.8	10.7	11.1	2830	2368	115	0.08	1.40	3.66	39.9
365	470	10	36.1	1.3	10.5	16.9	7.8	11.3	3070	2586	117	0.08	1.46	4.12	39.9
366	387	37	29.7	2.0	6.3	13.5	6.4	10.7	2662	2246	120	0.08	1.35	4.64	42.0
367	513	45	43.1	1.7	6.3	11.0	3.5	10.6	3006	2522	118	0.08	1.42	4.16	44.4
368					7.1	9.5	1.3	11.0	2838	2404	120			0.53	44.1
369															
370	599	57	42.6	2.4	4.6										
371	588	14	44.2	1.8	4.1	8.1	4.5	10.6	2548	2152	122		1.57	2.25	42.9
372						3.0	0.1	11.4	2724	2284	120	0.08	1.33	0.82	
373	543	39	38.4	2.0	3.5										40.0
374	435	69	38.6	1.7	2.8	4.3	0.1	10.8	2748	2324	122	0.08	1.34	4.84	33.7
375					2.6	3.7	1.8	11.2	2586	2178	122			1.38	30.5
377	475	41	36.1	2.1	3.7										
378	508	53	41.2	1.5	5.3	3.5	0.8	13.0	2704	2252	118	0.09	1.48	1.18	34.8
379	461	59	35.6	2.5	9.8	2.8	0.1	0.0	2764	2328	116	0.08	1.52	2.95	35.5
380	473	43	34.1	1.4	11.9	7.3	2.9	11.7	2734	2334	115	0.08	1.47	0.92	34.2
381					9.8	10.6	5.0	11.6	2830	2424	108	0.07	1.43	2.36	35.4
384	408	47	38.4	2.0	8.0										
385	484	33	39.2	1.8	4.9	4.3	1.3	9.8	2776	2352	114	0.09	1.46	0.27	43.4
386	475	33	37.5	1.5	2.9	7.1	2.5	9.4	2580	2176	116	0.08	1.42	1.15	40.7
387	507	41	41.2	3.4	2.5	4.3	0.4	8.7	2592	2192	116	0.08	1.48	0.91	50.9
388	538	47	44.0	4.5	1.6	2.4	0.4	11.0	2556	2168	118	0.09	1.51	3.02	49.2
389						2.4	0.8	10.9	2378	2004	119	0.08	1.52	2.30	
392	544	49	41.2	2.9	0.7										
393	435	63		3.4	1.0	5.9	0.0	11.0	3074	2630	111	0.08	1.51	2.07	49.3
394	503	53	39.2	2.0	3.1	0.0	0.0	10.8	2998	2580	113	0.09	1.53	3.53	38.9
395	331	36	32.2	2.2	3.5	3.3	4.5	10.4	2896	2500	116	0.08	1.47	3.48	46.2
396					3.4	2.3	0.3	10.6	2714	2350	118	0.09	1.38	3.52	47.4
399	477	36	39.5	2.1	3.6										49.7
400	533	44	42.3	2.5	4.1	5.5	0.6	9.4	2850	2436	119	0.10	1.41	3.71	48.4
401	513	32	39.8	1.5	4.4	3.9	0.5	9.2	2902	2494	120	0.09	1.34	3.25	47.8
402	487	38	38.6	2.2	3.8	6.7	0.9	9.3	2762	2338	123	0.09	1.47	3.55	46.8
403					3.2	4.5	1.1	11.2	2702	2276	122	0.09	1.57	3.24	49.6
405	537	40	44.2	1.5	4.2										
406	523	30	60.8	2.5	5.7	6.4	0.8		2796	2372	120	0.09	1.52	2.87	48.5
407	501	20	59.1	2.9	10.1	7.9	1.7	10.7	2838	2426	118	0.09	1.42	3.33	52.3
408	500	31	61.6	2.5	15.1	11.8	0.0	10.6	2898	2448	117	0.09	1.49	2.21	60.9
409	500	31	57.4	2.9	16.2	13.2	4.5	10.6	2856	2404	122	0.09	1.50	2.41	57.6
410					17.3		6.5	10.3	2832	2406	123	0.09	1.51	2.30	60.8
412	487	27	61.0	2.0	21.8										
413	510	49	53.8	5.2	21.8	21.4	12.2	12.0	2718	2336	120	0.10	1.42	2.13	58.8
414						22.8	12.5	10.9	2806	2388	116	0.09	1.53	3.60	59.6
415	506	58	60.2	3.2	21.1	3.1	1.1	11.0	2794	2402	117			2.63	57.9
416	485	53	57.8	2.1	7.2										
417									3002	2570	113				53.7
419								9.6	2738	2338	117				
421								10.2	2862	2498	112				63.0
425								10.7	2872		118				
426	537	47	40.3	2.2	2.2										
427	516	31	40.0	1.5	2.2	4.6	2.5	9.4	3030		111			3.88	43.6
428	490	55	37.2	2.7	1.9			10.0						3.11	42.7
429	482	26	38.1	1.5	7.1	2.6	0.0		2812		121			3.20	
430	460	43	34.1	2.5	5.2	3.2	1.6	26.4	2724		120			3.77	62.8
431						9.9	3.8		2758		120				
433	371	51	30.5	2.2	8.1										
434	391	22	36.7	2.9	17.4	6.6	3.3		2650		123			3.84	41.6
435						10.2	7.3	19.3	2508		124			5.22	36.7
442	537	43	51.5	3.9	19.8	20.5									41.7
443	519	41	53.8	3.4	20.7	20.9	10.9	22.9	2508	2064	120			4.53	40.4
444	503	49	44.2	2.2	20.2	19.5	10.7	20.4	2488	2130	122			3.96	46.0
445	491	45	49.8	3.2	19.8	18.0	11.5	20.5	2508	2200	126			3.65	49.8
446								20.6	2376	1984	122				

DAY	N	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
447		515	57	45.9	2.4	20.7										
448		552	41	44.8	2.9	17.5			17.9	2620	2112	118			3.41	49.9
449		531	57	45.4	2.9	17.1	16.6	11.2	12.0	2502	2112	118			3.70	50.7
450		580	32	51.5	2.2	18.1	14.6	11.7	16.4	2760	2370	116			2.81	50.7
451		548	37	48.4	3.4	19.2	14.2	9.0	13.7	2386	1942	127			4.17	47.5
452		533	47	46.4	3.1	18.3			20.1						3.27	49.8
453									0.0	2718	2276	121				49.7
455									17.9	2650	2162	131			2.85	54.6
456		614	59	54.6	4.3	17.0										
457		537	51	56.6	2.9	23.5			18.8	2944	2452	129			3.47	56.2
458		460	55	58.2	2.2	27.8	20.1	14.7	19.9	2786	2332	136			2.70	56.4
459						29.7	25.7	19.8	21.1	2772	2308	137			3.42	56.3
461		468	30	52.4	3.6	33.5										
462		586	51	63.8	3.9	34.8	30.1	23.7		2662	2232	137			3.01	60.7
463		477	47	51.2	7.7	28.5	28.7	22.2	19.8	2586	2164	135			1.98	64.5
464		529	51	41.7	2.4	31.7	29.2	22.0	23.0	2536	2138	134			2.98	51.8
465		554	34	47.0	5.0	33.0	26.6	22.0	23.7	2372	2004	138			4.41	45.5
466						33.4	30.6	23.4	25.1	2818	2344	141			5.99	
468		508	43	39.8	6.0	25.8										
469		549	39	44.5	6.3	25.5	25.0	20.2		2396	2100	134			5.47	42.6
470		498	37	40.3	4.0	25.8	20.9	17.5	23.3	2542	2130	136			4.35	43.2
471		547	41	47.6	3.6	21.2	23.1	22.2	16.3	2544	2128	126			5.20	29.3
472		594	43	47.3	5.7	21.6	23.9	20.5	12.2	2434	2036	131			3.51	35.8
473		590	43	44.5	4.3	24.7	16.8	15.6	21.3	2286	1888	131			3.71	35.1
474							20.9	20.0	22.4							
475		0	24	0.0	4.1	23.1										
476		506	33	51.2	2.5	26.1	17.6	16.4	18.6	2360	1998	136			2.65	39.7
477		461	24	44.5	3.4	28.0	23.7	24.2	22.8	2328	1964	133			3.25	39.3

DAY	N	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
478		455	47	46.8	3.1	25.7	23.1	22.6	21.8	2418	1978	132			3.08	41.6
479		496	43	44.0	2.7	24.6	25.6	22.6	22.7	2280	1928	132			4.01	42.3
480		540	43	52.4	3.6	22.3	19.9	13.8	10.3	2246	1960	134			4.23	38.2
481		540	38	32.5	0.3	19.3	22.0	19.5	8.5	2608	2212	131				
482		567	40	37.2	0.3	15.3	20.2	16.7	7.6	2420	2068	132				
483		506	32	33.3	0.1	13.8	17.8	14.4	7.6	2396	2048	134				
484		498	45	34.2	0.1	15.7	12.4	9.3	12.3	2388	2036	130				
485		546	53	45.4	0.6	12.0			9.3							
486		549	62	49.6	4.5	6.7	16.1	13.3		2320	2000	121				
487		533	54	44.0	10.1	2.4			9.2							
488							3.7	2.0	7.8	2592	2120	116				
489		537	45	49.3	13.4	5.4										
490		553	45			5.2	4.4	1.9	9.0	2494	2102	120			0.78	58.7
491		545	45			5.8	6.7	0.9	10.6	2756	2326	120			3.35	53.8
492		502	48	54.3	3.6	6.2	6.5	1.1	10.5	2698	2244	119			0.81	61.9
493		526	39	57.3	3.9	7.1	6.1	1.0	9.7	2726	2242	119			3.18	60.6
494						7.1	9.4	3.5	9.5	2412	1978	129			1.94	62.6
496		502	39	45.4	10.2	38.1				2428	2018	122				
497		559	39	56.6	5.7	17.5			9.5	2334	2030	124			0.70	68.4
498		371	37	40.9	3.6	20.1	33.7	31.8	10.0	2342	2012	128			3.31	61.8
499		445	37	47.0	3.4		7.7	5.8	10.0	2288	1912	131			0.33	78.8
500		466	37	45.1	2.5		4.3		10.0	1044	826	119			0.20	33.0
501									10.0						0.57	
502		440	41	44.8	3.6											
503		432	31	45.4	5.0		4.00	5.10	10.3	2020	1686	114				63.8
504		500	37	49.6	3.6		13.4	12.6	9.3	2276	1942	123			0.25	65.3
505		471	49	54.9	4.8		12.6	19.6	9.2	2246	1854	132			0.06	56.1
506		526	39	57.1	3.4	4.3	2.8	0.2	9.2						0.37	61.1
507		410	45	49.6	3.2	4.5			8.7							30.7
508		557	49	45.9	4.8	4.9			9.4	2042	1716	137			0.32	35.0
509									9.6	2004	1662	136			0.38	38.2
510		416	51	46.5	2.7	5.1			8.7	2168	1814	138			0.30	
511		338	29	37.2	2.1	6.8			8.7	2116	1774	143			3.74	35.2
512		459	44	44.5	3.1	8.3	6.9	4.00	8.7	2286	1882	141			4.11	39.4
513		500	42	53.7	3.0	8.4	8.0	5.5	8.7	2170	1802	147			3.45	40.4
514		580	52	58.3	3.5	5.8	8.5	7.4	8.6	2300	1936	140			2.59	43.7
515						5.9	8.3	5.3	9.0	2126	1820	146			3.42	42.7
518		379	49	46.5	3.8	5.4										57.0
519						5.2	6.1	0.6	9.0	2454	2136	147			2.48	61.2
520						5.7	6.5	0.5	8.7	2720	2356	140			1.58	55.8
521		449	24	53.5	2.4		7.0	1.2	8.7	2500	2126	149			2.96	54.0
522		439	43	37.0	2.9		7.5	2.9	8.8	2408	2058	145			2.48	47.7
523						10.4					2328				3.33	
525		409	30	37.4	1.7	17.5	10.0	6.1		2284	1914	138			2.76	41.7
526		387	32	34.2	3.2	22.0	16.7	24.4	8.7	1990	1708	159			4.24	36.5
527		498	34	39.8	2.7	4.9	22.3	18.9	8.5	2000	1772	168			4.61	47.6
528		341	46	41.8	1.5	4.5			8.6							47.8
529		351	44	40.6	3.9				9.0	2214	1872	160			4.81	36.6
530						4.4			10.2	1890	1618	160				34.9
531		427	36	51.0	2.5	4.8										
532		423	52	45.4		5.2	4.7	4.0	8.4	1832	1556	162			4.48	37.1
533		427	36	43.4	0.6	4.9	5.1	4.4	9.9	2004	1698	153			4.93	43.4
534		520	81	46.8	9.7	4.3	4.9	4.3	10.8	1986	1682	151			4.11	43.0
535		1036	79	95.8	30.2	2.9	21.4	18.1	10.5	2164	1830	152			4.40	
536		938	116	91.8	46.5				10.5	1190	1034	151				18.6
537						0.3			11.7	1790	1568	136				31.1

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
538	478	116	39.8	30.4	0.2										
539	431	73	43.1	13.9	0.5			9.7	2490	2152	133			0.36	48.4
540	441	57	46.2	9.4	0.6	2.5	0.3	10.1	2680	2324	127			0.80	45.2
541	432	61	44.8	7.7	2.5			10.2	2536	2222	138			0.84	44.0
542	467	27	48.4	5.5	3.7	3.3	0.1	10.2	2588	2224	144			0.85	44.2
543	435	27						9.7	2602	2252	150			1.07	40.5
544								9.8	2530	2168	146				36.9
545	379	45			4.4										

MEASURED DATA - SYSTEM 2 WUHRMANN (days 260 - 545)

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
260	461	63			27.5	25.0	22.0	12.5	1962	1700	100			2-3.5	11.8
261	437	65	36.7	1.5	20.5	22.9	17.1	13.1	1952	1704	87			2-3.5	32.5
262				1.5										2-3.5	
263					24.6									2-3.5	
264						24.2	23.4		1700	1534	80			2-3.5	28.1
265	614	80	42.6	1.4	31.9	12.1	22.0	11.0	1614	1428	88			2-3.5	28.1
266	590	84	36.7	1.1	23.7	14.3	19.0	13.9	1578	1386	63			2-3.5	28.1
267	594	80	44.0	1.5	20.1	24.6	20.2	14.7	1652	1392	70			2-3.5	24.7
268	573	63	35.8	2.8				12.9						2-3.5	
269	480	96	35.6	9.4	20.3	19.9	16.8	11.2	1770	1436	113		1.35	2-3.5	24.7
270	553	108	38.1	14.1	12.2										
271						15.6	7.4	9.6	2294	1852	100	0.07	1.18	4.30	41.3
272	553	96	38.4	3.6	9.3	14.5	10.0	13.5	2358	1882	115	0.08	1.15	3.80	40.9
273	465	65	35.0	1.5	16.4	16.8	14.1	14.0	2342	1846	124	0.07	1.01	2.50	34.8
274	490	37	36.4	1.1	19.5	25.3	22.4	13.2	2426	1952	128	0.07	1.20	3.35	33.7
275	418	67	35.0	3.4	29.8	21.5	23.4	14.5	2622	2088	126			3.80	30.4
276	381	59	34.2	2.0	31.7										
277	467	47	38.6	0.7	32.1										
278						28.9	26.6	13.2	2310	1868	130	0.09	1.08		
279	341	63	40.0	4.9	32.6	33.1	23.4	11.9	2496	2016	116	0.08	1.45	4.10	29.7
280	508	54	42.8	3.8	32.6	27.4	24.8	14.1	2406	2006	123	0.08	1.50	3.40	34.6
281	537	29	44.2	2.4	27.4	25.2	23.7	13.2	2472	2038	113	0.09	1.14		34.8
282	378	60	42.8	2.8	26.9	26.9	24.3	14.5	2264	1902	115			4.40	36.2
283	353	35	41.2	2.9	25.2			13.5	2418	1990	114				
284	349	39	39.5	2.0	23.0										
285						26.0	23.7		2316	1948	105		1.15	6.40	38.5
286	354	61	37.2	1.8	26.9	28.7	27.8	13.3	2320	1924	104		1.08	3.10	35.6
287	455	57	44.2	1.5	28.7	35.5	29.4	13.2	2262	1902	108	0.08	1.05	3.00	33.9
288	406	65	53.8	0.8	39.5	35.0	31.1	12.5	2370	2000	108		0.98	3.30	
289	390	49	48.7	5.6	41.2	38.5	35.4	15.0	2318	1950	110				
290	484	51	52.1	3.5	44.3				2246	1966	107				
291	386	39	49.0	2.2	45.4										
292						41.1	29.1		2336	1964	105	0.09	1.47		40.3
293	562	39	44.2	3.6	40.0	39.0	33.7	10.8	2356	2012	103	0.08	1.53	3.20	39.8
294	509	51	48.7	2.4	41.1	36.0	31.1	13.0	2250	1896	102	0.09	1.70	2.90	40.6
295	507	49	47.6	2.9	39.0	42.1	34.1	13.1	2362	1986	102	0.08	1.53	3.50	37.5
296	489	27	49.8	2.2	43.2	38.0	32.6	13.2	2428	2066	95			3.40	36.8
297	482	14	48.7	1.5	45.4										37.7
298						32.1	35.8		2308	1942	88			3.45	31.8
300	671	23	54.6		44.3		32.6	13.1	2302	1956	94			2.01	40.7
301	601	39	51.0	1.8	40.0	31.7	29.4	12.9	2420	2072	87	0.09	1.43	2.75	39.8
302	640	37	52.6	3.8	37.0										
303					35.5	32.1	26.2	9.9	2542	2148	114	0.08	1.50	2.96	37.4
308	453	47	45.1	1.8	35.0	33.7		11.5	2560	2208	119	0.08	1.40	2.17	44.3
309	574	57	49.0	2.7	25.5									2.28	44.5
310		47		4.1		35.2			2462	2164	118				
311	503	35	48.7	2.0	34.2										
312					32.2										
313						30.2	36.9		2558	2222	123		1.39	0.76	42.9
314	623	37	61.9	3.6	32.7	24.6	43.2	10.1	2404	2116	94				
315	619	45	50.7	2.8	34.7	29.3	31.7	10.1	2472	2138	95	0.08	1.50	2.98	36.5
316	568	39	48.4	3.1	34.7										
317						29.8	26.0	8.8	2466	2120	95				
318	552	53	48.7	4.1	35.7				2384	2096	96			2.97	28.1
319					37.3										
320						23.7	29.6		2624	2280	91			3.85	28.1
321	556	74	51.0	3.9	37.8	26.0	29.9	12.3	2578	2200	93			2.36	41.0

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
322	536	69	49.6	6.0	33.7	26.9	23.0	12.3	2812	2382	86			0.88	46.8
323	439	55	45.4	3.6	29.8										
324						29.0	29.4	12.3	2568	2242	94			3.21	41.8
325					34.6										
335															
336															
337									2776	2410	72				
338															
339															
340															
341									3004	2954		0.08	1.28		
342	555	73	50.7	3.1	34.3										
343						25.2	21.5		3082	2684	68				
344															
345						28.5	27.3	11.3	3156	2684	70				
346	465	78	45.9	3.1	35.8										
347	486	65	50.4	3.5											
348						40.2	43.3	26.8	2938	2528	75	0.08	1.41	2.10	40.4
349	618	39	52.9	2.4	47.0	40.2	35.0	10.9	3056	2614	77		1.48	3.66	43.2
350	549	45			41.1	35.8	30.1	10.7	2890	2482	76	0.08	1.39	4.01	42.6
351	618	24	52.4	1.3	34.6	32.0	28.6	9.9	2842	2408	83	0.09	1.54	3.54	42.6
352	563	47	49.8	2.1	34.6										
353	612	35	50.7	2.2	33.9	27.4	27.1		3186	2754	83			3.08	47.0
354	669	67	53.8	2.2	32.7										
355						33.1	28.0		2868	2486	84	0.08	1.48	3.26	43.0
356	526	75	42.6	4.1	32.7	31.3	29.3	11.4	2948	2500	87	0.09	1.43	5.15	33.7
357	557	53	47.9	3.6	33.9	33.1	31.3	11.2	2414	2036	92	0.09	1.37	2.87	38.4
358	526	55	44.5	2.8	35.1	32.3	31.6	11.6	2508	2064	89	0.08	1.47	3.88	42.5
359	565	73	45.1	2.5	35.1	29.9	28.9	12.2	2574	2170	92			3.57	43.4
360						28.9	28.2	11.9	2608	2246	94			3.02	45.6
361	520	61	43.4	1.5	35.9										
362						32.0	30.2	11.8	2828	2390	94	0.08	1.49	3.72	33.3
363	499	47	39.5	2.9	40.7	29.5	26.4	11.9	2630	2240	95	0.07	1.36	3.12	42.6
364	533	41	40.3	2.8	43.6	28.0	26.2	12.1	2632	2254	99	0.07	1.38	3.66	43.1
365	470	26	36.1	2.2	29.3	25.9	23.9	11.9	2582	2196	95	0.08	1.37	3.81	
366	387	45	29.7	3.5	31.0	25.0	25.9	12.0	2624	2248	100			3.39	40.1
367	513	65	43.1	4.3	32.4										
368					33.5										
369						28.3	28.0	11.2	2232	1900	106		1.67	4.19	38.0
370	599	41	42.6	3.4	32.7	27.4	26.5	11.4	2256	1914	104	0.09	1.37	3.55	37.3
371	588	67	44.2	1.5	31.3			11.3						4.12	41.2
372						24.8	20.1	11.5	2440	2094	104	0.08	1.31	3.58	40.4
373	543	26	38.4	2.0	25.3	21.7	22.2	11.5	2376	2024	101			3.06	37.7
374	435	69	38.6	2.2	26.2										
375					27.5										
376						25.3	22.8	13.7	2802	2360	99	0.08	1.45	3.77	44.5
377	475	37	36.1	4.3	26.9	23.9	20.1	11.8	2378	2008	97	0.08	1.30	4.04	34.0
378	508	61	41.2	2.9	26.9	25.6	21.7	11.3	1964	1696	105	0.08	1.50	3.26	33.2
379	461	47	35.6	3.6	26.5	25.6	22.2	11.1	2210	1880	100	0.08	1.46	2.63	33.4
380	473	55	34.1	2.4	31.4										
382					32.2										
383						26.9	21.0	9.3	2260	1920	104	0.09	1.43	4.03	32.7
384	408	18	38.4	2.2	28.2	26.0	24.2	10.0	2190	1860	101	0.08	1.44	4.95	29.2
385	484	73	39.2	1.5	32.8	30.6	30.3	9.8	1882	1600	106	0.08	1.41	3.03	39.0
386	475	29	37.5	1.0	36.8	26.0	27.6	11.7	1786	1520	109	0.09	1.53	5.27	29.2
387	507	45	41.2	1.8	34.3	26.0	26.0	11.7	1836	1572	107	0.08	1.50	3.54	32.50
388	538	43	44.0	1.4	31.3										
390					33.2										
391						26.6	23.9	11.2	2278	1962	98	0.09		2.51	43.7
392	544	74	41.2	3.1	28.6	23.0	21.3	11.5	2260	1942	97	0.09	1.55	4.02	35.1
393	435	63		2.2	26.6	24.0	18.2	11.3	2176	1876	99	0.09	1.50	3.93	37.1
394	503	61	39.2	3.6	25.1	22.6	18.9	10.9	2144	1830	93	0.09	1.32	3.91	36.2
395	331	12	32.2	2.4	27.2										
398	477		40.6		32.4	26.1	21.3	11.2	2330	1988	91	0.09	1.40	3.17	38.3
399	477	24	39.5	1.5	32.4	26.6	28.1	11.0	2736	2334	88	0.08	1.40	2.33	39.2
400	533	48	42.3	5.2	28.7	26.0	26.0	11.1	2376	1994	93	0.09	1.48	4.20	38.4
401	513	44	39.8	2.0	28.4	29.0	30.3	12.0	2404	2024	90	0.09	1.71	3.38	45.8
402	487	42	38.6	2.1	29.7										
403					34.0										
404						28.4	28.1		2636	2246	85	0.08	1.46	2.61	45.5
405	537	36	44.2	1.5	39.2	44.0	34.0	11.5	2780	2376	87	0.09	1.42	3.33	52.3
406	523	38	60.8	2.9	50.1	45.0	41.7	11.6	2750	2320	89	0.08	1.38	2.21	60.9
407	501	20	59.1	3.1		45.0	41.0	11.7	2502	2102	94	0.09	1.50	2.41	57.6
408	500	19	61.6	3.4		49.2	50.0	11.7	2472	2084	97	0.09	1.49	2.30	60.8
409	500	39	57.4	3.6											
411					52.8	44.0	50.0	13.2	2420	2058	95	0.09	1.47	2.13	58.8
412	487	23	61.0	3.6	56.5	22.6		11.6	2424	2028	91	0.09	1.46	3.60	59.6
413	510	41	53.8	3.6	57.8	27.5	46.1	11.7	2288	1950	96			2.63	57.9
414															
415	506	49	60.2	2.2	36.2				2634	2232	92				53.7
416	485	49	57.8	13.0	28.1										
417								10.1	2326	1986	105				
418								13.0						2.57	63.7
419								11.3	2810	2440	85				63.0
425								11.3	2630		106				

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
427						29.6	29.6	10.4	2488		103			3.53	32.3
428	537	39	40.3	2.4	30.6			10.9						2.64	35.8
429	516	43	40.0	2.5	31.7	27.6	29.2		2296		119			3.20	34.2
430	490	39	37.2	3.4	36.1	36.7	40.5	30.4	2428		114			2.47	31.4
431	482	35	38.1	2.0	39.7	28.9	30.6		2286		116				
432	460	30	34.1	3.1	34.2										
434						25.3	26.7		2604		109			3.51	35.6
435	371	43	30.5	4.2	28.9	23.7	25.6	7.7	2284	1950	116			4.43	
436	391	55	36.7	3.1	30.3										
441					33.8										
443						26.7	28.3	8.4	2242	1864	105			2.45	36.0
444	537	34	51.5	1.5	32.1	28.3	29.2	7.4	2270	1932	104			3.13	37.3
445	519	61	53.8	4.3	33.3	27.9	31.0	7.9	2450	2154	100			2.45	38.8
446	503	65	44.2	2.5	32.9			7.9	2288	1918	99				
447	491	69	49.8	3.2	33.3										
448								7.7	2682	2230	91			2.30	39.3
449	515	37	45.9	2.9	35.1	27.6	29.2	5.8	2826	2366	91			2.15	46.3
450	552	61	44.8	3.4	32.0	30.2	30.2	7.0	3068	2732	95			1.13	50.8
451	531	41	45.4	3.4	32.0	28.2	30.6	6.2	2850	2344	95			1.02	45.9
452	588	49	51.5	0.7	32.8			7.7	2510	2108	104			2.37	47.6
453	548	45	48.4	3.1	34.6			8.0	2500	2074	113				
454	533	39	46.4	2.9	34.1										
455								6.3	2888	2402	102			3.24	40.9
457								7.0	2842	2348	104			0.53	46.4
458	614	47	54.6	3.4	33.5	32.3	30.1	6.6	2808	2322	103			2.12	45.4
459	537	47	56.6	7.1	36.8	33.9	31.9	7.4	2674	2252	108			3.42	55.2
460	460	47	58.2	3.8	38.5										
461					39.8										
462						38.5	34.4	7.4	2962	2500	111			1.92	47.5
463	468	39	52.4	3.6	41.2	33.1	34.4	7.3	2480	2088	115			0.32	57.0
464	586	39	63.8	4.1	42.1	38.8	34.3	7.3	2358	1996	126			1.05	48.1
465	477	22	51.2	2.9	34.8	27.6	28.2	7.9	2226	1896	129			1.01	27.7
466	529	47	41.7	0.8	31.0	26.6	25.8	7.9	2156	1816	137			1.48	24.4
467	554	34	47.0	4.9	30.2										
469						23.8	25.5		2802	2438	129			1.17	29.9
470	508	51	39.8	4.6	28.8	23.8	25.8	7.5	2436	2050	131			1.70	25.4
471	549	51	44.5	8.7	18.4			5.2	2314	1954	121			0.84	20.8
472	498	49	40.3	6.9	17.6	9.4	9.1	0.0	2690	2278	126			0.07	28.9
473	547	49	47.6	8.4	12.5	14.0	13.6	0.0	1866	1564	139			1.21	24.9
474	594	51	47.3	12.9	22.9										
475					21.6										
476								5.4	1238	1084	162			0.75	18.3
477	0	37	0.0	14.6	15.4			7.0	1572	1352	191			0.35	24.7
478	506	37	51.2	16.1	17.4			6.6	1588	1314	214			0.55	25.9
479	461	29	44.5	14.7	16.0			6.8	1546	1354	239			0.21	26.6
480	455	47	46.8	14.6	16.1			6.1	1516	1388	261			0.23	25.5
481	496	51	44.0	13.2	18.0	16.5	15.9	6.2	1736	1520	253				
482	540	34	52.4	13.3	17.6	13.6	13.5	5.2	1648	1460	255				
483	540	43	32.5	6.9	14.0	8.9	8.6	5.2	1686	1494	255				
484	567	49	37.2	4.1	12.5	11.6	12.2	5.7	1792	1568	246				
485	506	32	33.3	1.5	18.0			5.6							
486	498	36	34.2	0.1	17.4	14.6	14.6	5.50	1956	1612	225				
487	546	40	45.4	6.0	13.8			5.0							
488	549	50	49.6	10.5	11.1	7.8	7.6	5.6	1936	1602	222				
489	533	41	44.0	9.9	13.5										
490						12.2	12.2	4.6	2042	1706	191			0.51	35.7
491	537	58	49.3	4.5	29.5	21.3	23.6	5.3	1998	1680	190			0.44	32.6
492	0		0.0		27.4	28.2	27.9	6.0	2140	1748	178			0.53	35.2
493	545	58			25.0	11.2	11.4	5.9	2352	1930	162			0.16	39.1
494	502	52	54.3	10.6	21.1	25.0	24.5	6.1	2246	1844	165			0.93	39.1
495	526	35	57.3	14.1	13.3										
496					3.2				2250	1862	158				
497					5.0	8.9	8.8	6.5	2320	1980	158			0.20	45.8
498	502	47	45.4	16.2	9.4		9.7	6.0	2352	1956	162			0.24	47.2
499	559	60	56.6	8.0	17.0	22.1	21.9	6.1	2342	2016	162				
500	371	37	40.9	3.6	22.0	18.4	19.8	5.8	2272	1894	167				
501	445	37	47.0	3.4	20.3	18.4	18.9	6.2	2066	1704	171				
502	466	37	45.1	2.5	17.3										
504	440	41	44.8	3.6	26.7	25.1	25.3	6.4	2254	1890	161				
505	432	31	45.4	5.0	24.5	21.8	22.5	6.0	2212	1864	152				
506	500	37	49.6	3.6	26.7	27.8	25.9	6.7	2266	1858	148				
507	471	49	54.9	4.8	28.9	26.4	24.8	6.5	2184	1824	147				
508	526	39	57.1	3.4	21.5	21.5	23.2	6.2	1926	1562	154				
509	410	45	49.6	3.2	23.6			6.4	1840	1508	147				
510	557	49	45.9	4.8	25.7			6.7	1912	1620	144				
511						25.7	22.2	6.8	2114	1774	134			0.18	31.2
512	416	43	46.5	3.4	31.2	27.5	27.2	6.8	2080	1732	133			0.30	31.4
513	338	39	37.2	5.0	31.4	28.0	22.6	6.7	1894	1586	146			0.19	34.6
514	459	24	44.5	2.4	34.6	27.3	29.3	6.8	2146	1806	121			0.17	44.7
515	500	51	53.7	6.5	44.7		23.6	7.0	2390	ERR	100			0.16	38.3
516	580	36	58.3	2.3											
518					29.3										38.2
519					22.4	6.8	7.5	7.1	2636	2262	99			0.23	42.3

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
520	379	53	46.5	9.2	21.3	29.9	29.2	6.6	2632	2256	97			0.22	39.8
521					29.2	20.4	20.9	7.6	2530	2144	99			0.16	36.7
522					29.9	30.3	29.2	7.6	2406	2050	100			0.23	34.8
523	449	32	53.5	5.9				7.7	2674	2218				0.22	
524	439	34	37.0	2.9					2422	2038	101			0.12	34.6
525					29.2	27.1	25.3								
526					23.3	14.6	15.2	7.4	2398	2028	102			0.18	40.8
527	409	22	37.4	2.4	24.5	25.9	26.2	7.5	2432	2126	107			0.17	40.5

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	fn	fcv	DO	OUR
528	387	44	34.2	6.0	22.8			7.4							42.9
529	498	38	39.8	4.6	25.2			7.6	2272	1906	108			0.24	42.0
530	341	62	41.8	2.2	25.2			7.6	2092	1774	109				
531	351	32	40.6	4.5											
532					20.4	16.9	15.9	5.2	1940	1630	111			0.23	36.5
533	427	28	51.0	4.5	21.5	24.9	17.4	8.4	2300	1910	104			0.26	33.2
534	423	52	45.4	4.5	22.9	17.4	25.5	7.3	2160	1808	105			0.24	34.8
535	427	40	43.4	0.6	25.8	22.8	24.3	7.3	2274	1918	106			1.70	32.9
536	520	57	46.8	9.2	16.7	13.7	20.7	7.4	2238	1908	109			0.31	41.1
537	518	47	47.9	9.7	19.8			7.3	2400	2050	101			0.25	36.9
538	469	55	45.9												
539					8.0			6.2	2578	2146	116			0.30	38.0
540	478	63	39.8		9.8	14.4	13.3	7.1	2486	2106	114			0.34	39.6
541	431	49	43.1		11.9			7.6	2610	2222	115			0.37	38.8
542	441	37	46.2		16.7	18.8	19.6	7.7	2280	1930	118			0.30	39.7
543	432	37	44.8		17.9			7.6	2356	2008	115			0.25	36.4
544	467	31	48.4		22.4			7.8	2322	1936	116			0.20	34.7
545	435	39													

MEASURED DATA - SYSTEM 3 MLE (days 508 - 545)

DAY	Sti	Ste	Nti	Nte	Nne	Nnaer	Nnanx	Nndos	Xt	Xv	DSVI	DO	OUR
509						6.1	0.7	18.9	2426	2096	171	4.31	
510	416	51	46.5	4.2	6.1	6.1	0.3	20.0	2330	2014	172	4.30	
511	427	45	47.1	5.4	6.3	5.5	0.8	2.8	2182	1870	175	3.40	
512	474	47	46.0	2.8	5.8	5.7	0.4	1.8	2328	2006	164	3.01	
513	558	45	60.0	2.4	6.6	5.9	1.7	7.0	2262	1934	149	3.32	
514	551	46	55.4	1.6									
515													
516					6.7							2-4	37.8
517					8.4	6.3	1.5	5.9	2316	1998	151	2-4	34.3
518	379	65	46.5	0.8	6.7	7.3	1.7	5.4	2240	1944	156	2-4	35.7
519					7.6	10.3	1.0	5.8	2120	1806	158	2-4	32.0
520					9.9	9.2	4.4	5.6	2094	1882	160	2-4	30.4
521	449	40	53.5	1.5				5.6	1918	1618		2-4	
522	439	38	37.0	0.7								2-4	
523					10.5	10.6	10.3		1952	1656	154	2-4	26.1
524					14.4	13.9	8.3	5.6	2088	1780	145	2-4	28.2
525	409	47	37.4	2.7	15.9	16.5	10.5	5.8	2044	1786	148	2-4	30.9
526	387	24	34.2		20.7			5.1				2-4	32.7
527	498	58	39.8	1.5	23.9			5.7	1894	1602	146	2-4	26.6
528	341	30	41.8	1.8	24.9			5.6	1846	1570	141	2-4	24.6
529	351	48	40.6	2.2								2-4	
530					22.2	20.6	17.4	5.4	1692	1432	139	2-4	29.4
531	427	44	51.0	4.5	23.1	22.9		5.6	1732	1446	136	2-4	34.3
532	423	40	45.4		25.7	21.5	17.6	0.0	1772	1496	130	2-4	31.5
533	427		43.4		23.9	20.3	17.3	5.7	1722	1456	129	2-4	
534	520		46.8	5.0	21.4			5.3	1774	1522	130	1.2-2	
535	518	37	47.9	8.5	14.4			5.3	1828	1590	133	1.2-2	
536	469	39	45.9	6.9								1.2-2	
537					16.3			5.2	1866	1500	137	1.5-3	37.3
538	478	47	39.8	5.5	9.4	17.7	15.0	5.1	1900	1608	135	1.5-3	36.5
539	431	53	43.1	6.2	7.7			5.1	1894	1604	129	1.5-3	34.3
540	441	45	46.2	4.5	8.6	9.6	5.3	4.6	1914	1628	136	1.5-3	32.5
541	432	37	44.8	4.8	10.9			5.1	1914		134	1.5-3	35.5
542	467	27	48.4	6.7	11.8				1852	1546	135	1.5-3	32.7
543	435	18	45.8	7.1								1.5-3	
544												1.5-3	
545	379	45	43.2	6.5	10.6				1920	1680	138	0.5-2	28.9

APPENDIX F

Mass balance and substrate utilization rate computer program reference and functional procedure listing

APPENDIX F

1 COMPUTER PROGRAM REFERENCE

A computer program compiled in Turbo Pascal Version 4.0 was written to conduct repeated steady state calculations using the measured and configurational data of the MLE and Wuhrmann systems operated during the course of the investigation. The program calculates N and COD mass balances as well as substrate utilization rates. The running of the program is outlined below, whereafter individual aspects of the program are briefly discussed.

1.1 PROGRAM OPERATION

The program operates on an IBM or IBM compatible personal computer with a minimum of 256 kilobytes RAM. To start the program after booting up the PC insert the supplied 5.25" Two Sided Double Density Floppy diskette labelled BALANCE.BAT into the floppy drive and at the A:> prompt type BALANCE **<ENTER>**. The program is then brought into the computers RAM and the following items

(1) File
(2) System Data
(3) Run Balances
(4) S-Utilization
(5) Print
(6) Options and
(7) Quit To DOS

appear at the top of the screen running adjacent to each other from left to right.

Throughout the program the arrow keys are used to move the highlight to a chosen option and by pressing the **<ENTER>** key the chosen option is activated. To return to a previous option the user needs to press the **<ESC>** key.

Regarding data entry, the SYSTEM DATA Option is selected and to enter new data simply move to the desired value with the arrow keys and key in the new value. If **<ENTER>** is pressed the same value remains highlighted, if however, one of the arrow keys is pressed the new value is automatically entered and the highlight moves to the next value. This form of data entry is widely used in well known spread-sheet packages.

Error messages at the bottom of the screen are displayed when some operational or input error is detected. **<ESC>** returns the user to the current menu option.

The items listed above are briefly discussed below.

1.1.1 Program Operation - FILE

Three options are available - RETRIEVE, SAVE and EXIT. In the RETRIEVE option files saved on the default drive (see 1.1.6 below) with the file extension .BSK are listed on the screen. Only one file at a time can be examined and the file to be retrieved is selected by moving the highlight to the appropriate file and pressing **<ENTER>**, afterwhich the contents of the file are read into the computers RAM.

At the SAVE file option the filename appears at the prompt for editing. The filename has no extension (already set to .BSK) and the default drive is preset (see 1.1.6 below). If the file is to be saved on a drive other than the default drive the appropriate drive letter and the filename must be furnished at the prompt, eg C:S1SS09RS.

EXIT returns the user to the main menu. This option can be side-stepped by pressing the **<ESC>** key.

1.1.2 Program Operation - SYSTEM DATA

Twenty four parameters listed in two columns of 12 each are required for the mass balance and substrate utilization calculations. The parameters listed are described on the screen, but the user can refer to Appendix C for further details regarding the particular application of each parameter.

1.1.3 Program Operation - RUN BALANCES

The calculations used to determine the mass balances are displayed on two screens. The calculations used to determine the N mass balance are displayed on the first screen and the calculations of the COD mass balance are displayed on the second. The two screens are viewed sequentially by pressing the **< >** or **< >** arrow keys. **<ESC>** returns the user to the main menu.

The methodology employed to determine the N and COD mass balances is outlined in Appendix C.

1.1.4 Program Operation - S-UTILIZATION

RBCOD and PBCOD utilization rates are displayed on the screen, where distinction is made between substrate utilization in each of the two reactor of the chosen system type i.e. MLE or Wuhrmann (see 1.1.6 below). The methodology used to calculate the substrate utilization rates is described in detail in Chapter 3, section 2.2.

<ESC> returns the user to the main menu.

1.1.5 Program Operation - PRINT

If the printer device is on line and properly connected the output presented below is sent to the printer.

```
                MASS BALANCE AND SUBSTRATE UTILIZATION RATES

Measured and Operational Data

System Type : WUHRMANN
Description : Steady State 2 days 222 - 245
Influent correction factor applied, Rf = 0.82

Influent COD   513.0  mgCOD/l      Sludge age   15.00  days
Effluent COD   100.0  mgCOD/l   Anoxic volume    3.50  l
Influent TKN   52.0   mgTKN/l  Aerobic volume    3.00  l
Effluent TKN   3.4    mgTKN/l     (s) recycle   1.00:  1
MLVSS          2042.0 mgVSS/l     (a) recycle   0.00:  1
OUR            46.3   mgO/l/h             fcv    1.34  mgCOD/mgVSS
Effluent N     30.4   mgN/l               fn     0.09  mgTKN/mgVSS
Aerobic N      29.8   mgN/l               Yh     0.45  mgCOD/mgVSS
Anoxic N       28.0   mgN/l             bh20     0.24  /d
Dosed N        13.5   mgN/l                f     0.20  mgVSS/mgVSS
Influent flow  10.0   l/d                fup     0.07  mgCOD/mgCOD
Temperature    20.0   degrees C          fbs     0.28  mgCOD/mgCOD

                          N MASS BALANCE

MASS TKN entering system        =482.6  mgN/d
MASS Nitrate entering system    =135.0  mgN/d

Total MASS N entering system    =617.6  mgN/d

MASS TKN leaving system         = 34.0  mgN/d
MASS Nitrate leaving system     =304.0  mgN/d
MASS N in waste sludge          = 79.6  mgN/d
MASS N denitrified              =171.0  mgN/d

Total MASS N leaving system     =588.6  mgN/d

N MASS balance  (%)             = 95.3

                         COD MASS BALANCE

MASS COD entering system                =4207     mgCOD/d

MASS COD leaving system                 =1000     mgCOD/d
MASS COD in waste sludge                =1186     mgCOD/d

Measured MASS OXYGEN utilized           =3334     mgO/d
MASS oxygen for NITRIFICATION           =-1554    mgO/d
equv. MASS oxygen for DENITRIFICATION   =489      mgO/d

Total MASS COD leaving system           =589      mgCOD/d

COD MASS balance  (%)                   =105.9
```

```
                    SUBSTRATE UTILIZATION

First Reactor              RBCODUR  =   0.413 mgCOD/(mgAVSS.d)
                           PBCODUR  =   1.860 mgCOD/(mgAVSS.d)

Second Reactor             PBCODUR  =   0.535 mgCOD/(mgAVSS.d)

Equivalent Denitrification rates
                                K1  =   0.022 mgNO3-N/(mgAVSS.d)
                                K2  =   0.098 mgNO3-N/(mgAVSS.d)
                                K3  =   0.074 mgNO3-N/(mgAVSS.d)

Denitrification Potential      dP2  =   17.1  mgN/l
                    Actual          =   17.1  mgN/l
```

If the printer is not properly connected or off-line an Error message is displayed at the bottom of the screen - after pressing **<ESC>** the user is returned to the main menu.

1.1.6 Program Operation - OPTIONS

There are 6 options available each of which is briefly described below.

(1) System Type - Choose between Modified Ludzack-Ettinger or Wuhrmann systems.

(2) Description - Enter or edit a string describing the system and measured data. This information is stored on file together with the system data when saving the file.

(3) Set drive - Choose a valid drive (A - Z) for storing and/or retrieving files with .BSK extensions.

(4) Reduction - This application permits the user to reduce the influent COD concentration by a specified factor, R_f. For the mass balance and substrate utilization rate calculations the influent COD concentration is R_f * Influent COD (mgCOD/l). The factor Rf also impacts on the influent TKN if less than unity (see Chapter 3, Equ.3.12.).

(5) Printer Device - 4 printer devices are supported (LPT1,LPT2,COM1 and COM2); output for printing is sent to the selected printer device. The default device is LPT1.

(6) Exit - Returns the user to the main menu.

1.1.7 Program Operation - QUIT TO DOS

At this option the message HAVE YOU SAVED LATEST CHANGES ? is displayed. **<Y>** or **<ENTER>** terminates the program and **<N>** or **<ESC>** returns the user to the main menu.

2 FUNCTIONAL PROCEDURE LISTING

The procedure used to calculate the N and COD mass balances and substrate utilization rates is listed below. The variable V[*n*] is an array describing the 24 parameters, running

from top to bottom, listed in the SYSTEM DATA option and printed in the output example above.

```
Procedure MassCalcs ;
BEGIN
    MTi             :=  V[11] * (V[3] - V[19]*(1-Rf)*V[1]*V[20]) ;
    MNi             :=  V[11]*V[10] ;
    MTe             :=  V[11]* V[4] ;
    MNe             := V[11]* V[7] ;
    MXn             := V[19]*V[5]*(V[14]+V[15])/V[13] ;
    case ST of
    1 : MNd         := V[11]*(V[16]*V[7] + V[17]*V[8] + V[10] -
                    (1 + V[16] + V[17])*V[9]) ;
    2 : MNd         :=  V[11]*(V[10]+(1 + V[16] + V[17])*(V[8]-V[9]) ) ;
    end ;
    MNg             :=  MNe + MNd - MNi ;

    MSi             :=  Rf*V[1]*V[11] ;
    MSe             :=  V[2]*V[11] ;
    MXc             :=  V[18]*V[5]*(V[14]+V[15])/V[13] ;
    MOt             :=  V[6]*V[15]*24 ;
    MOn             :=  MNg * 4.57 ;
    MdO             :=  MNd * 2.86 ;
    MOc             :=  MOt - MOn + MdO ;

    bh              :=  V[21]*Power(1.029,V[12]-20) ;

    MXa             :=  MSi * (1-V[23]-V[2]/(V[1]*Rf))*V[20]*V[13]/(1+bh*V[13]) ;

    ff              :=  2.86/(1-V[18]*V[20]) ;

 case ST of
 1 : begin
    fx1             := V[14]/(V[14]+V[15]) ;
    fx2             := V[15]/(V[14]+V[15]) ;
    if fx1 > 0 then
    CODUR1          :=  ff * MNd /(MXa * fx1)
    ELSE
    CODUR1          :=  0 ;
    if fx2 > 0 then
    CODUR2          :=  (MOc - MdO) * ff/(2.86 * MXa * fx2)
    ELSE
    CODUR2          :=  0 ;
    end ;
    2 : begin
    fx1             :=  V[15]/(V[14]+V[15]) ;
    fx2             :=  V[14]/(V[14]+V[15]) ;
    if fx1 > 0 then
    CODUR1          :=  ff * (MOc - MdO) /(2.86*MXa * fx1)
    ELSE
    CODUR1          :=  0 ;
    if fx2 > 0 then
    CODUR2          :=  MNd * ff/(MXa * fx2)
    ELSE
    CODUR2 := 0 ;
    end ;
    end ;
```

```
    MSbi        :=  MSi * (1-V[23]-V[2]/(V[1]*Rf) ) ;;
    RBCODUR     :=  V[24] * MSbi/(MXa * fx1) ;
    PBCODUR1    :=  CODUR1 - RBCODUR ;
    PBCODUR2    :=  CODUR2 ;

    EDK1        :=  RBCODUR/ff * (ST * (-0.62) + 1.62 ) ;
    EDK2        :=  PBCODUR1/ff * (ST * (-0.62) + 1.62 ) ;
    EDK3        :=  PBCODUR2/ff * (ST * (0.62) - 0.24 ) ;

    dP1         :=  V[1]*Rf * (1-V[23]-V[2]/(V[1]*Rf))*
                    (V[24]/ff + EDK2*fx1*V[20]*V[13]/(1+bh*V[13]) ) ;

    dP2         :=  V[1]*Rf * (1-V[23]-V[2]/(V[1]*Rf))*
                    fx2*EDK3*V[20]*V[13]/(1+bh*V[13]) ;
END ;
```