UNIVERSITY OF CAPE TOWN

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THE EFFECT OF SLUDGE AGE AND AEROBIC SLUDGE MASS FRACTION ON LOW F/M FILAMENT BULKING IN INTERMITTENT AERATION NITROGEN REMOVAL SYSTEMS

by

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DECLARATION BY CANDIDATE

I,
CHARLES ARTHUR WARBURTON,
hereby declare that this thesis
is my own work and that it has not been
submitted for a degree at another
university.

Signed by candidate

Signature Removed

January 1991

DEDICATION

This thesis is dedicated to my wife KATHRYN and my children VANESSA and WAYNE in sincere appreciation for their understanding, patience and loving support given over the two year study and research period.

SYNOPSIS

Filamentous bulking, which causes poor activated sludge settleability, is a problem of considerable proportions in South Africa, as indicated in two surveys undertaken in 1985 and 1987 on South African activated sludge plants. Sludge settleability governs the daily flow and load that can be treated in an activated sludge plant: Keeping sludge settleability to relatively low DSVI values (< 100 mℓ/g), by controlling the proliferation of filamentous organisms generally would permit higher sewage flows and loads to be treated in existing South African plants, with concomitant large savings in capital costs. The savings that bulking control would bring about have been the driving force behind research into developing preventative and remedial methods for controlling filamentous growth.

From the surveys it is clear that bulking in the relatively long sludge age activated sludge plants in South Africa are dominated by a limited number of filamentous organism types. As their occurrence appears to be limited to long sludge age systems, Jenkins classified them into a group called low Food/Microorganism (low F/M) filaments. Because the low F/M filament types were the most frequently dominant in South African activated sludge plants, specific bulking control methods against their proliferation were investigated by Gabb *et al.* (1989) in a 4 year research programme, from 1986 to 1989. One of the widely promoted specific methods for controlling filamentous organism growth has been the incorporation of selectors at the head of the works. However, Gabb *et al.* (1989) found that selectors did not control low F/M filament proliferation, but that continuous aeration did. The finding that selectors were unable to control low F/M filament proliferation placed the low F/M filament bulking research back into the exploratory phase.

Since 1989 a wide ranging program of research has been under way to identify the factors that effect low F/M filament proliferation. Completed work has established an important factor conducive to low F/M filament proliferation – the presence of anoxic and aerobic zones, or, alternating anoxic-aerobic conditions in a system. It was also established that the presence or absence of readily biodegradable COD (RBCOD) or slowly biodegradable COD (SBCOD) were not deciding factors in their proliferation. The research presented in this thesis focuses on the effects of;

- sludge age,
- magnitude of the aerobic mass fraction,
- magnitude of the nitrate concentration during the anoxic period,

on the low F/M filaments.

The experimental set-up consisted of two intermittently aerated anoxic-aerobic (20 minute cycles, peak DO 2 to 2,5 mgO/ℓ), single reactor completely mixed continuously fed systems. The experimental investigation was chronologically divided into 3 phases and examined the effect of the following conditions on the low F/M filaments:

Phase I

(1) reduction of sludge age from 20 and 10 days on systems having 30% aerobic mass fraction

(2) magnitude of the of nitrate concentration in the anoxic period in systems with 30% aerobic mass fraction. and 10 days sludge age

Phase II

(3) magnitude of the aerobic mass fraction 30% and 70% at 10 days sludge age

(4) 7,5 days sludge age (< 10 days) on systems with 30% and 70% aerobic mass fraction

Phase III

(5) short sludge ages (8,6 and 5 days) on systems with 30% aerobic mass fraction.

In phase I of the investigation, with the aerobic mass fraction fixed at 30%, the sludge ages of the systems were progressively reduced from 20 days to 10 days. It was found that even at 10 days sludge age the low F/M filaments continued to proliferate and caused excessive bulking (DSVI > 300 mℓ/g). It was concluded that the reduction of the sludge age from 20 days to 10 days appeared to have little effect on the low F/M filament proliferation or the filament population types; the commonly occurring low F/M filaments, *M.parvicella* and 0092 but also 0675 and 0041, can proliferate sufficiently at 10 days sludge age to cause severe bulking problems.

With the sludge ages of both systems set at 10 days and the aerobic mass fraction set at 30%, the effects of the nitrate concentration during the anoxic period on low F/M filament proliferation and bulking was examined. Initially nitrate was dosed into both systems. To investigate the effect of the nitrate concentration during the anoxic phase the nitrate dosing to one system was terminated but maintained on the second system. The systems were closely monitored and the effects were recorded over 3 sludge ages. Thereafter the nitrate dosing was interchanged between the two systems a number of times, each time operated for a period of about 3 sludge ages between an interchange of the nitrate feed. The results showed that the system with low nitrate concentrations in the anoxic zone tended to suppress filament proliferation, but only very weakly, not sufficiently to inhibit bulking. With this proviso, in general the sludges in both systems continued to bulk with low F/M filaments.

In phase II, maintaining the sludge age in both systems at 10 days the effect of the aerobic mass fraction on low F/M filaments was investigated by changing the aerobic mass fraction from 30% to 70% on one system the other remaining at 30%. Again the systems were run for 3 sludge ages and the aerobic mass fraction interchanged between the two systems a number of times. The results indicated that the 70% aerobic mass fractions appear to have a significant suppressing effect on the proliferation of low F/M filaments, that is at 70% aerobic mass fraction the DSVI was much lower than at 30% aerobic mass fraction.

As a preliminary experiment to investigate the effect of short sludge ages, the sludge ages of both the systems were reduced to 7,5 days. A 70% aerobic mass fraction was maintained in the one system and 30% in the other. The reduction in sludge age had an ameliorating effect on the low F/M filament bulking because the DSVI was reduced in both systems. However rather unexpectedly later in the experiment a rise in the DSVI of the 70% aerobic system was observed but this appeared to be due to a change in the filament population types in that 021N, which is not a low F/M filament, rose to secondary level.

In phase III, to more closely investigate the effect of short sludge ages, the aerobic mass fraction was selected at 30% for both systems, and on the one system a sludge age of 10 days was set while on the other the sludge age was progressively reduced to 8, then 6, then 5 days. After monitoring the effects of the sludge age reductions on the systems the conditions were interchanged between the two systems and the effects of the reduction of sludge age from 10 to 5 days were monitored on the other system. The results indicate that in these systems (intermittent aeration systems), (1) less severe bulking at short sludge ages (< 10 days) than at long sludge age systems (> 10 days) (2) the low F/M filaments can proliferate in systems operated at short sludge ages (5 days) and can result in bulking (DSVI > 150 $m\ell/g$).

From the investigation it would appear that large aerobic mass fractions ($\geq$ 70%) have the strongest suppressing effect on low F/M filament, reduction in sludge age less so, and low nitrate concentrations in the anoxic zone the least. The lowest DSVI due to low F/M filaments is likely to be obtained at the largest aerobic mass fraction, the shortest sludge age and the lowest nitrate concentration in the anoxic reactor.

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CHAPTER 1

INTRODUCTION

Bulking is a problem of considerable proportions in activated sludge plants in South Africa. In two surveys, one in 1985 which examined 96 activated sludge plants which were principally biological nitrogen (N) (about 2/3rds) and some biological nitrogen and phosphorus (N & P) (26) removal plants, and another in 1987 which examined 33 biological N & P removal plants, it was found that about 3/4 of these plants experienced sporadic bulking problems (Blackbeard *et al.*, 1986, 1988) caused by the excessive growth of filamentous organisms in the activated sludge biocenosis.

Bulking due to excessive growth of filamentous organisms causes a deterioration in the mixed liquor settleability. The filament lengths extend 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, at which the DSVI is greater than 150 $m\ell/g$, 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 $m\ell/g$. 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 $m\ell/g$ possibly is a bulking sludge, and an SVI > 200 $m\ell/g$ usually is.

Sludge settleability governs the daily flow and load that can be treated in an activated sludge plant; the operating experience of Northern Works (Johannesburg) clearly demonstrates this (Osborn *et al.*, 1986). For a particular plant in operation the influent peak wet weather flow (PWWF) sets the maximum overflow rate (m/h) in the secondary settling tank, and the daily mass of COD treated (and sludge age) sets the sludge concentration in the biological reactor. Ekama and Marais (1986) showed that a sludge with a DSVI of 150 $m\ell/g$ can be handled satisfactorily in the settling tank up to a maximum overflow rate of

1 m/h at a mixed liquor suspended solids (MLSS) of 3,5 g/ℓ. Should the DSVI deteriorate to 200 mℓ/g the maximum overflow rate reduces to 0,6 m/h at 3,5 g/ℓ, reducing the treatment capacity of the plant by about a 1/3rd. In contrast, if the DSVI is reduced from 150 to 100 mℓ/g the overflow rate can be increased to 1,8 m/h increasing the treatment capacity by about 2/3rds.

Clearly, keeping sludge settleability under control at a DSVI of 100 mℓ/g by controlling the proliferation of filamentous organisms, that is bulking, will permit not only at least 50% more sewage flow and load to be treated in existing plants but also 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 the surveys mentioned above, the filamentous organism types causing the bulking problems were identified. Only six filamentous organism types were found to be the major contributors to the bulking problems. In the 96 mainly N removal plants the six filaments were, in decreasing order of frequency of dominance[1], type 0092 dominant in 34% of plants, 0914 in 24%, *Microthrix.parvicella* in 20%, 1851 in 17%, 0675 in 16% and and 0041 in 14%. In the 33 N & P removal plants, the same 6 filaments were the 6 most frequently dominant but in a different order, i.e. 0092 dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *M.parvicella* in 33%, 0914 in 33% and 1851 in 21%.

From the surveys it is clear that sludges in activated sludge plants in South Africa are dominated by a limited number of filamentous organism types. Of the 6, 4 i.e. 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 0914 and 1851 also be classified into the low F/M group. Because the low F/M filament types were the most frequently dominant in South African activated sludge plants, specific bulking control methods against the proliferation of this group of filaments were investigated by

[1]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 the poor settleability; a non-bulking sludge usually has only one filament that is dominant. Filaments that are not dominant are termed secondary.

Gabb *et al.* (1989) in a 4 year research programme from 1986 to 1989.

The promoted specific bulking control method against low F/M filaments 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. In the literature, 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 the 4 year research programme mentioned above.

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: Whenever a bulking sludge (DSVI > 250 mℓ/g) from a full scale N (anoxic-aerobic) or N & P (anaerobic-anoxic-aerobic) removal plant was brought to the laboratory and put under *fully aerobic* conditions, low F/M filament proliferation ceased and a DSVI of 50 mℓ/g was obtained in less than 10 days irrespective of whether or not the system incorporated the 3 reactor modifications cited earlier. In contrast, it was found that low F/M filament bulking sludges could be developed in the laboratory in systems that mimic the full scale ones, e.g..in single reactor completely mixed intermittent aeration ditch type N removal plants (like Carousel) or multi-reactor anaerobic-anoxic-aerobic N & P removal plants (like MUCT/UCT or 3/5 stage Bardenpho). When a correctly designed aerobic selector, one of the promoted 3 modifications to control low F/M filament proliferation, which stimulated a selector effect, was installed ahead of an intermittent aeration (anoxic-aerobic) main reactor, it was found that low F/M filament proliferation was not controlled and bulking persisted at a DSVI > 300 mℓ/g for more than 5 sludge ages (110 days) (Gabb *et al.*, 1989). From this research it was concluded that the influent RBCOD, which is removed by floc-formers in the selector reactor, did not appear to play a role in low F/M filament bulking, but that intermittent aeration (anoxic-aerobic conditions) and its absence (continuous aeration) played a major role.

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 the influence of

(1) the influent RBCOD and PBCOD,
(2) alternating unaerated-aerated conditions, and
(3) sludge age

on low F/M filament proliferation.

The research reported in this thesis forms part of this programme and aspects of items (2) and (3) above are investigated, in particular evaluation of the effect of the

(1) sludge age,
(2) magnitude of the anoxic mass fraction, and
(3) magnitude of the nitrate concentration during the anoxic period

on the low F/M filaments.

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 avoided and the influence of the above 3 factors was evaluated on laboratory scale single reactor completely mixed continuously fed intermittent aeration N removal systems only receiving real sewage and operated at 20°C; in the earlier investigation of Gabb *et al.* (1989), this type of N removal system was found to consistently promote bulking by many of the low F/M filaments.

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 ending with some general considerations regarding design of intermittent aeration N removal systems. In Chapter 4, the conclusions of the investigation regarding low F/M filament bulking in intermittent aeration systems and design of these systems, are presented.

CHAPTER 2

SPECIFIC BULKING CONTROL
REVIEW OF LITERATURE

PREAMBLE

A comprehensive literature review into specific bulking control has recently been compiled by Casey *et al.* (1991) 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.

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, are 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.

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 (see Table 2.1). 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).

In 1973, Chudoba *et al.* 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 (μ_H) 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, μ_H rates have high K_s values and ones with low μ_H rates have low K_s values. Slijkhuis (1983) measured the μ_H of *Microthrix parvicella* (one of the principal filaments causing low F/M bulking) to be 1,66/d; this is considerably lower than a μ_H of 4,33/d measured by Richard *et al.* (1981) for a floc-former isolated from activated sludge.

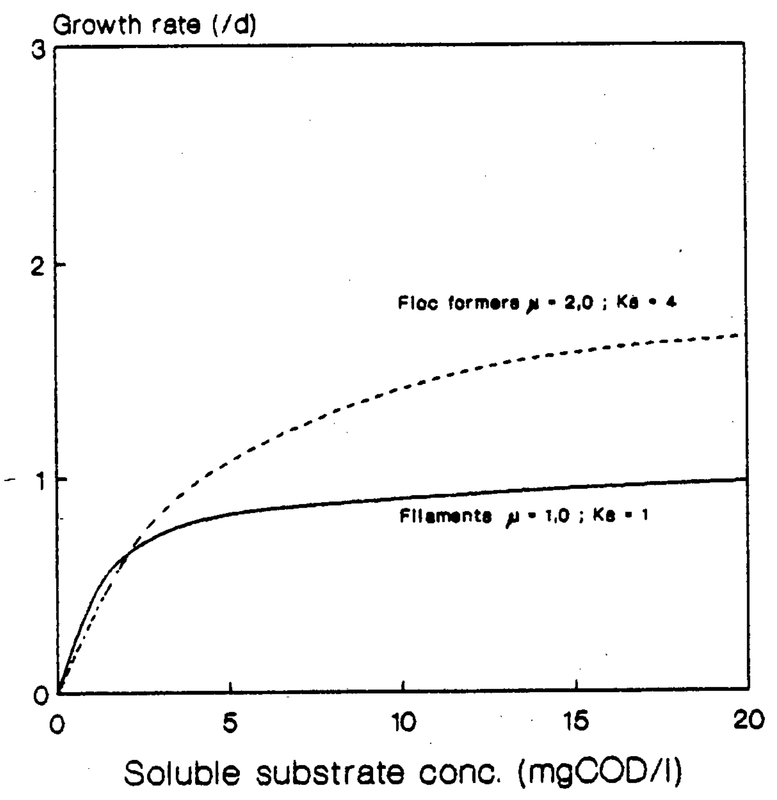
Palm *et al.* (1980) extended the selection criterion to incorporate limiting nutrients: For some filaments (the low DO ones), the limiting nutrient apparently is oxygen whereas for others, the limiting nutrient is the soluble substrate concentration surrounding the organism, as originally conceived by Chudoba *et al.* (1973). 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.* (1973) 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.* (1973) 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

Table 2.1: Dominant filament types as indicators of conditions causing activated sludge bulking

Suggested causative conditions	Indicative filament types
Low DO	type 1701, *S.natans*, *H.hydrossis*
Low F/M	*M.parvicella*, *H.hydrossis*, *Nocardia* sp., types 021N, 0041, 0675, 0092, 0581, 0961, 0803
Septic Wastewater/Sulfide	*Thiothrix* sp., *Beggiatoa* and type 021N
Nutrient Deficiency	*Thiothrix* sp., *S.natans*, type 021N, and possibly *H.hydrossis* and types 0041 and 0675
Low pH	fungi

Richard *et al.*, 1982a; Strom and Jenkins, 1984.



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

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.* (1973) 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.* (1973) 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) 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, 1980; Barnes and Goronszy, 1980; Chiesa and Irvine, 1985; Jenkins *et al.*, 1983; Ekama and Marais, 1986; Still *et al.*, 1986; 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 *et al.*, 1987).

Like in the investigation of Chudoba *et al.* (1973), 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 (<0,45μm) 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, 1986; 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 load. They speculated that the soluble COD (RBCOD) concentration gradient induced by the 3 modifications stimulates the growth of floc-forming organisms with high substrate uptake rates which finds no counterpart in the growth of filamentous organisms with the result that the filamentous organisms are unable to compete successfully for substrate.

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

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

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 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 (1981); 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. However in this work, the filaments were not specified, or where specified, were not low F/M types and had a beneficial influence on sludge settleability. 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 $m\ell/g$) 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.* (1989).

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 aerobic/non aeration periods were imposed on the systems.

The sludge age of all these systems was long (20 d), they were fed Mitchell's Plain raw sewage and started up with low F/M filament bulking sludges (DSVI > 250 mℓ/g) 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 < 0,45μm 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 > 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 selector effect was irrelevant because the low F/M filament proliferation was suppressed both when the selector effect was present or absent.

3. **Bulking caused by *Sphaerotilus natans* (*S.natans*)**
In fully aerobic, and in the particular alternating anoxic-aerobic, long sludge systems, in which there is no selector effect (i.e. O/CFCM and AO/CFCM) when bulking was observed, it was *not* due to low F/M filaments but due to *S.natans* and *Thiothrix*. According to Jenkins *et al.* (1984) *S.natans* sorts into the low DO group and *Thiothrix* into septic sewage or nutrient deficient

groups. Curiously in the South African surveys of full scale N and N & P removal plants *S.natans* had not, and *Thiothrix* only rarely, been observed to cause bulking in full scale long sludge age plants in South Africa.

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

5. **Selector effect controls *S.natans* and *Thiothrix***
   Aerobic selectors and intermittent feeding conditions, which induce the selector effect, controlled the proliferation of *S.natans* and *Thiothrix*. This finding is in conformity with results reported in the literature cited above.

Up to this point in the investigation, the results obtained were in conformity with those reported in the literature - in particular, a general absence of low F/M filaments in the systems, and, when bulking did take place, it was caused by *S.natans*, *Thiothrix* and 021N and occurred only in the systems which did not stimulate a selector effect. However, Gabb *et al.* showed that *S.natans* in particular, proliferated in the systems as a result of seeding from the influent feed lines, and that when the feed lines were regularly cleaned (chlorinated twice weekly) *S.natans* no longer proliferated in the systems. In the systems which stimulated a selector effect *S.natans*, *Thiothrix* and 021N did not proliferate indicating that the selector effect, stimulated under either aerobic or anoxic conditions, controlled bulking by *S.natans* and *Thiothrix*. This observation is in conformity with the results published in the literature. The success of the selector effect in controlling bulking by *S.natans* and *Thiothrix* in laboratory scale low F/M systems possibly contributed to the notion that the selector effect also controls low F/M filament bulking.

In the laboratory systems operated by Gabb *et al.*, the low F/M filaments did not proliferate - indeed from conclusion (2) above the low F/M filament bulking problems in the starter sludge were ameliorated in all the systems operated. In contrast, in biological N & P removal systems [which comprise anaerobic-anoxic-aerobic zones usually in single or multi reactors in series and incorporating an appreciable (50%) unaerated sludge fractions] operated in the laboratory at the time of these experiments, the low F/M filaments did proliferate and cause bulking problems; indeed, 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, 1987b) who calls this type of selection metabolic selection (as opposed to competitive 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).

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 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 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.* (1989) 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 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 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 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 mℓ/g to below 60 mℓ/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 mℓ/g.

These experiments demonstrated 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), 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 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 Carousel or Orbal type N removal plants. It was found that in such systems most of the low F/M filaments proliferated, in particular *M.parvicella* and 0092 but also 0914, 0041, 0675 and 1851. Switching these systems from intermittent to continuous aeration invariably caused a sharp decline in bulking with a concomitant reduction in low F/M filaments; switching back to intermittent aeration caused 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 system single reactor, continuously fed completely mixed intermittently aerated system (?) whether or not aerobic selectors control low F/M filaments. 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.

CONCLUSIONS FROM THE 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, 1986).

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 mℓ/g). From this it would appear that the anaerobic/anoxic conditions that are required to stimulate biological N or N & P removal also stimulate proliferation of low F/M filament 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 now 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, 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.

RECOMMENDATIONS FOR FURTHER RESEARCH

A number of questions emerge from the investigation and conclusions of Gabb *et al.* discussed above, which serve as a useful guide for further research into specific low F/M filament bulking control.

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, 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.

Additionally to developing an artificial sewage, real sewage can be readily separated into its RBCOD and PBCOD constituents by modern ultrafiltration 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, 1986)? 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, characteristics like:

   (i) type - in an intermittently aerated system or in a multi-reactor system as a primary anoxic or secondary anoxic zone,

   (ii) size - because low F/M filaments proliferate (DSVI > 300 mℓ/g) in unaerated-aerated systems with large unaerated fractions (~ 70%) and not (DSVI < 80 mℓ/g) in purely aerated systems (0% unaerated) is there a trend that the greater the unaerated 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?

(iii) nitrate – investigate the effect of the nitrate concentration in the anoxic zone on the proliferation of low F/M filaments.

(iv) 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?

4. Because these low F/M filaments supposedly 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:

(1) 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.

(2) the principle why sludge ages in N and N & P removal plants is long (> 20 days) is to ensure nitrification. Wanner *et al.* (1987) 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.

The above research areas are clearly wide ranging and constitute a major research investigation. Furthermore, the experiments need to be conducted in conjunction with suitable control systems, thereby doubling the experimental work, and operated for around 3 sludge ages after a change, making the research very time consuming. These aspects are particularly important in research experiments of this nature where the causes for proliferation and elimination of the low F/M filaments are not well understood and possibly subject to features incorporated in the experimental set up inadvertently or unavoidably.

SCOPE OF THIS THESIS

In 1989, a research investigation was initiated in which many of the questions raised above would be addressed. This thesis forms part of this research investigation and focuses on the following questions raised above, i.e. evaluate the effect of the:

1) sludge age,

2) magnitude of the anoxic mass fraction and

3) magnitude of the nitrate concentration during the anoxic period on the low F/M filaments.

In this investigation the complicating feature of biological excess P removal promoted by the anaerobic reactor in N & P removal plants was avoided and the influence of the above 3 factors was evaluated on laboratory scale single reactor completely mixed continuously fed intermittent aeration N removal systems only receiving real sewage and operated at 20°C; in the earlier investigation this type of N removal system was shown to consistently promote bulking by many of the low F/M filaments.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 EXPERIMENTAL SET-UP

To test the effect of sludge age, nitrate concentration and anoxic mass fraction on low F/M filament proliferation, two intermittently aerated, completely mixed continuously fed systems were started up. The initial design and operating parameters for the two systems, designated CFR1 and CFR2, were those known to stimulate low F/M filament proliferation, viz. (i) long sludge age i.e. 20 days, (ii) aeration cycle 10 minutes with air on for 1 minute reaching a peak DO of about 2 to 2,5 mgO/ℓ, and (iii) an aerobic mass fraction of around 30% (Gabb *et al.*, 1989).

The experimental investigation was divided into three separate phases, i.e. investigation into (i) effect of sludge age and nitrate concentration (375 days), (ii) effect of aerobic mass fraction and sludge age (293 days) and (iii) effect of sludge age only (120 days). The same two basic experimental systems, CFR1 and CFR2, were operated. Details of the design and operating parameters of the two systems, for phase I of the investigation, are given in Table 3.1.

During all three phases of the investigation the following parameters were measured daily viz:

1. Influent and effluent (unfiltered) COD concentrations.
2. Influent and effluent TKN concentrations.
3. Effluent nitrate concentration, which is the sum of the nitrate and nitrite concentrations. The effluent nitrite concentration was measured also and was generally less than 1 mgN/ℓ and always less than 2 mg/ℓ.
4. Reactor MLVSS concentration.
5. Reactor MLSS concentration. The MLSS on average was 84 to 86% volatile.
6. OUR per gVSS (mgO/gVSS).
7. The peak DO concentration during the aeration cycle.
8. Percentage aerobic.
9. Sludge settleability in DSVI.

Table 3.1 Initial operating conditions and parameters.

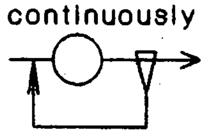
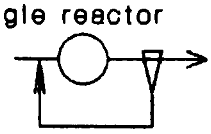
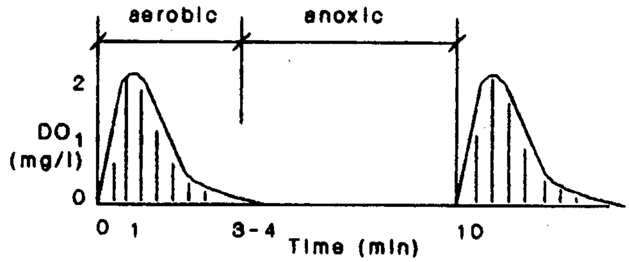
System	CFR1	CFR2
Operating conditions	continuously fed single reactor	
Graphical representation		
Aeration	intermittent	intermittent
DO Concentration (mg/l)	0 to 2-2,5	0 to 2-2,5
DO Profile		
Sewage source	Mitchell's Plain Raw	Mitchell's Plain Raw
Mass of COD fed/d (mgCOD/d)	5500	5500
Volume of feed (l/d)	10	10
Concentration (mgCOD/l)	550	550
Influent TKN (mgN/l)	60 - 100	60 - 100
Sludge age (d)	20	20
Temperature (deg C)	21	21
Volume of reactor (l)	7,5	7,5
MLVSS concentration (mg/l)	2800	2800
MLSS concentration (mg/l)	3500	3500
Hydraulic retention time (h)	18	18
Underflow recycle ratio	1 : 1	1 : 1
pH of mixed liquor	7,3 - 8,2	7,3 - 8,2

Table 3.2: Operational changes made to systems CFR1 and CFR2 during phase I of the investigation; evaluation of the effect of sludge age between 20 and 10 days and nitrate concentration.

Day	Change[1]	Reason
0	Sludge age 20 days [2]Aeration cycle 10 min. [3]Dosed 40 mgN/ℓ NH_4Cl to influent to increase TKN	Set system parameters to favour values that stimulate low F/M filament bulking. Stimulate high OUR by increasing nitrification.
17	Increase sludge wastage in CFR2 from 375 to 500 mℓ/d.	To reduce sludge age from 20 to 15 days.
29	Aeration cycle 20 min. Dosed 60 mgN/ℓ influent nitrate by addition to influent.	To keep aerobic fraction 30% - OUR decreased to 15 mgO/ℓ/h because nitrification died.
33	Aeration cycle 13 min.	Nitrification increasing OUR.
34	Aeration cycle 10 min.	Nitrification increasing OUR.
41	Increased sludge waste from CFR1 to 750 mℓ/d	Reduce sludge age from 20 to 10 days.
43	Aeration cycle 15 min.	OUR approx. 40 mgO/ℓ/h.
48	Aeration cycle 13 min.	
55	Aeration cycle 10 min.	OUR now 50 mgO/ℓ/h.
58	Dose 270 mgN/d nitrate by drip feeding 1 mgN/mℓ direct into reactors.	Avoid nitrate reduction and COD utilization in feed bucket.
72	Aeration cycle for CFR1 20 minutes. CFR2 still on 10 minutes.	10 day sludge on CFR1 reduced nitrification and hence OUR (now 25 mgO/ℓ/h).
76	Dose 540 mgN/d nitrate at 2 mgN/mℓ drip feed to CFR1.	Supplement nitrate due to reduced nitrification.
89	Switched CFR2 to continuous aeration DO 5 to 6 mgO/ℓ.	Attempt to bring down DSVI from 600 mℓ/g.

1 Changes to both systems unless specified.

2 Throughout the experiment the air on period of the aeration cycle remained 1 minute - only the air off time was changed. Air time on + air time off = aeration cycle. Aeration cycle was changed as OUR changed to maintain approximately 30% aerobic time, i.e.

$$[\text{air on} + \text{peak DO}.60/\text{OUR}]/[\text{air on} + \text{air off}] = 0{,}30$$

3 This was done before sampling so that ammonia dosed is included in TKN concentration.

Table 3.2: Operational changes made to syste I of the investigation; evaluation (20 and 10 days and nitrate concent

Day	Change[1]
0	Sludge age 20 days [2]Aeration cycle 10 min. [3]Dosed 40 mgN/ℓ NH_4Cl to influent to increase TKN
17	Increase sludge wastage in CFR2 from 375 to 500 mℓ/d.
29	Aeration cycle 20 min. Dosed 60 mgN/ℓ influent nitrate by addition to influent.
33	Aeration cycle 13 min.
34	Aeration cycle 10 min.
41	Increased sludge waste from CFR1 to 750 mℓ/d
43	Aeration cycle 15 min.
48	Aeration cycle 13 min.
55	Aeration cycle 10 min.
58	Dose 270 mgN/d nitrate by drip feeding 1 mgN/mℓ direct into reactors.
72	Aeration cycle for CFR1 20 minutes. CFR2 still on 10 minutes.
76	Dose 540 mgN/d nitrate at 2 mgN/mℓ drip feed to CFR1.
89	Switched CFR2 to continuous aeration DO 5 to 6 mgO/ℓ.

C
b

1
n

1 Changes to both systems unless specified.
2 Throughout the experiment the air on perio minute – only the air off time was change aeration cycle. Aeration cycle was change approximately 30% aerobic time, i.e.
[air on + peak DO.60/OUR]/[ai
3 This was done before sampling so that am concentration.

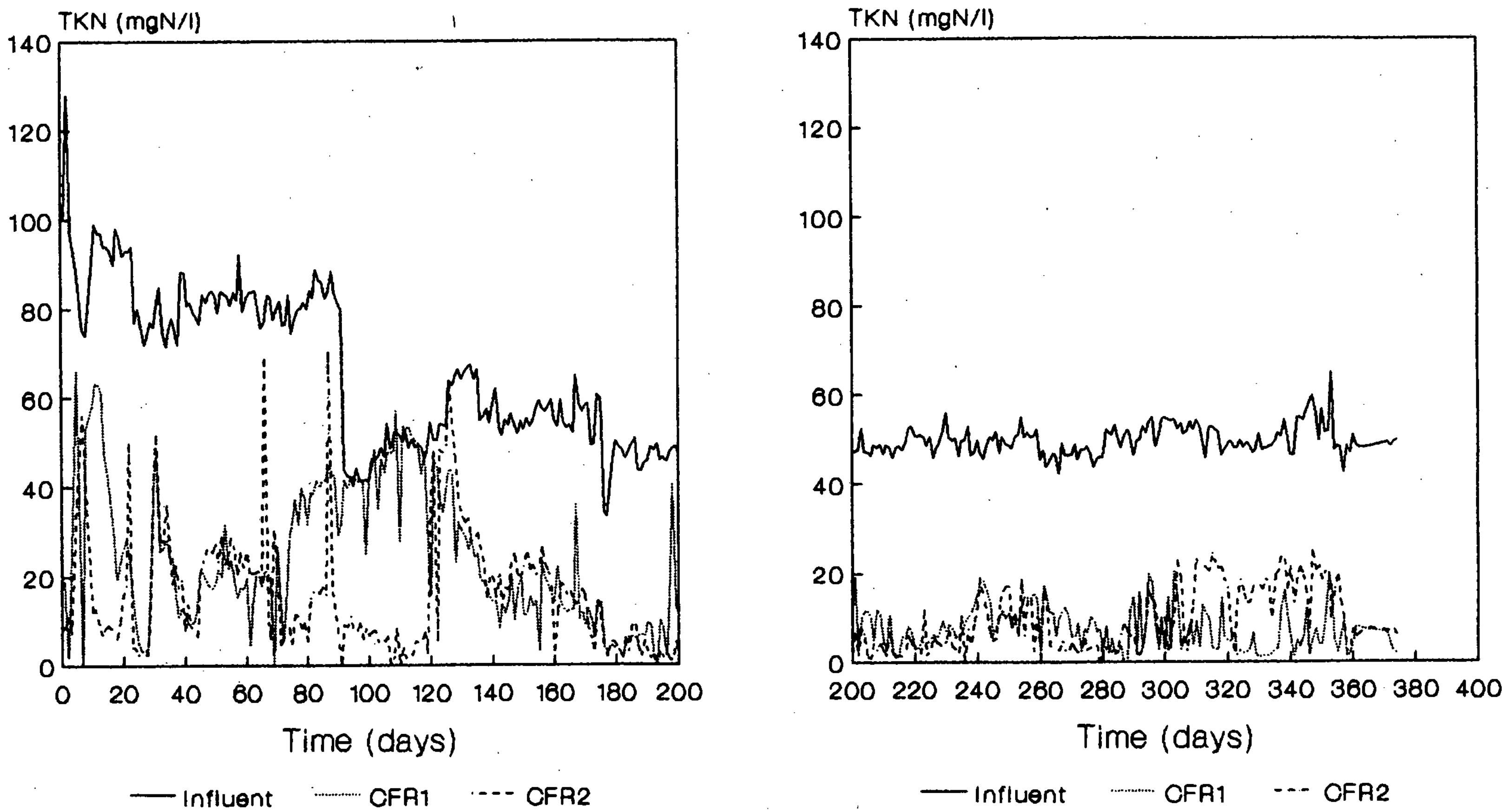


Fig 3.2 Influent and effluent TKN concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation; note the high influent TKN values when NH_4Cl_2 was being dosed into the influent to increase the influent ammonia.

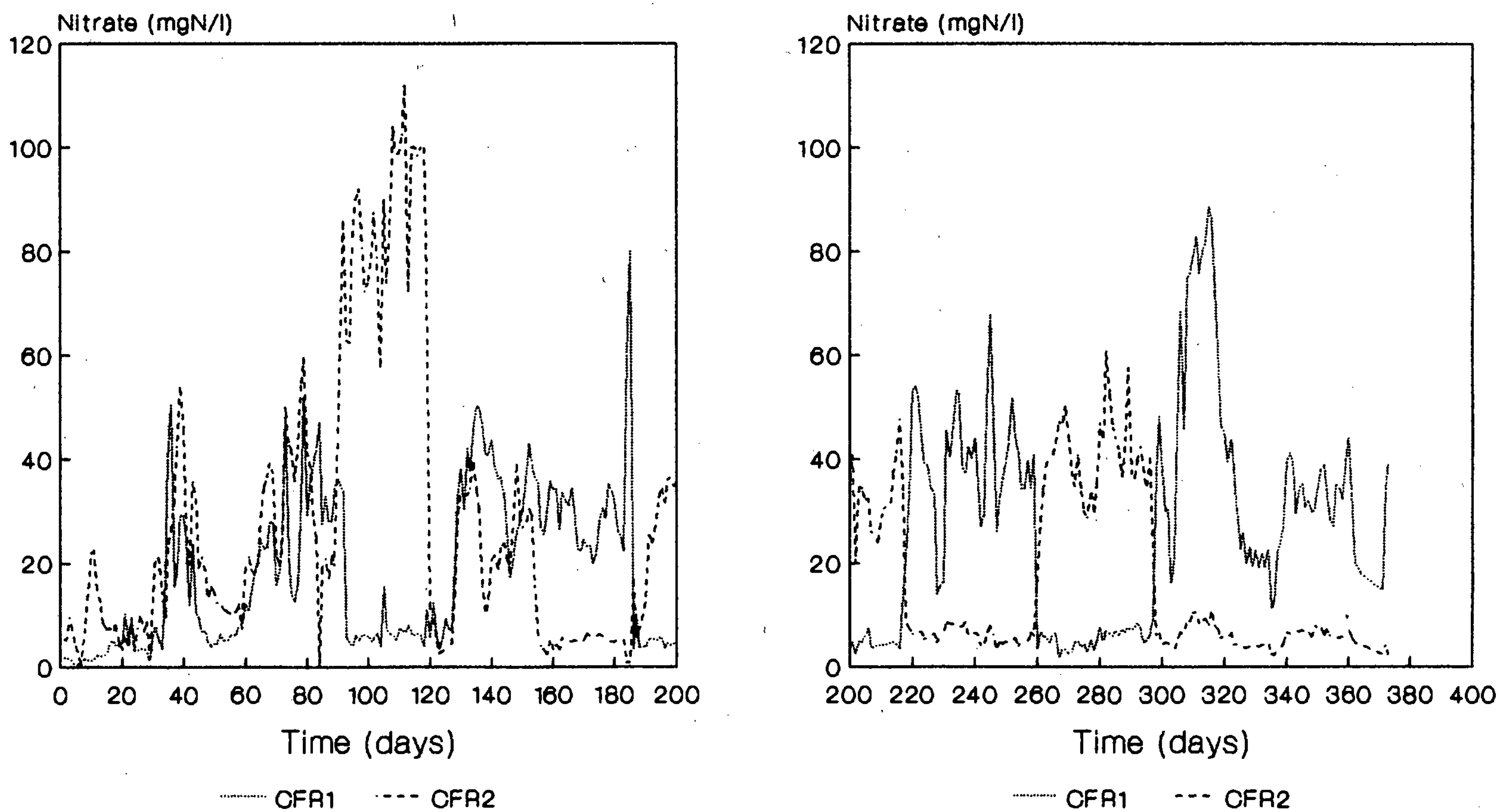
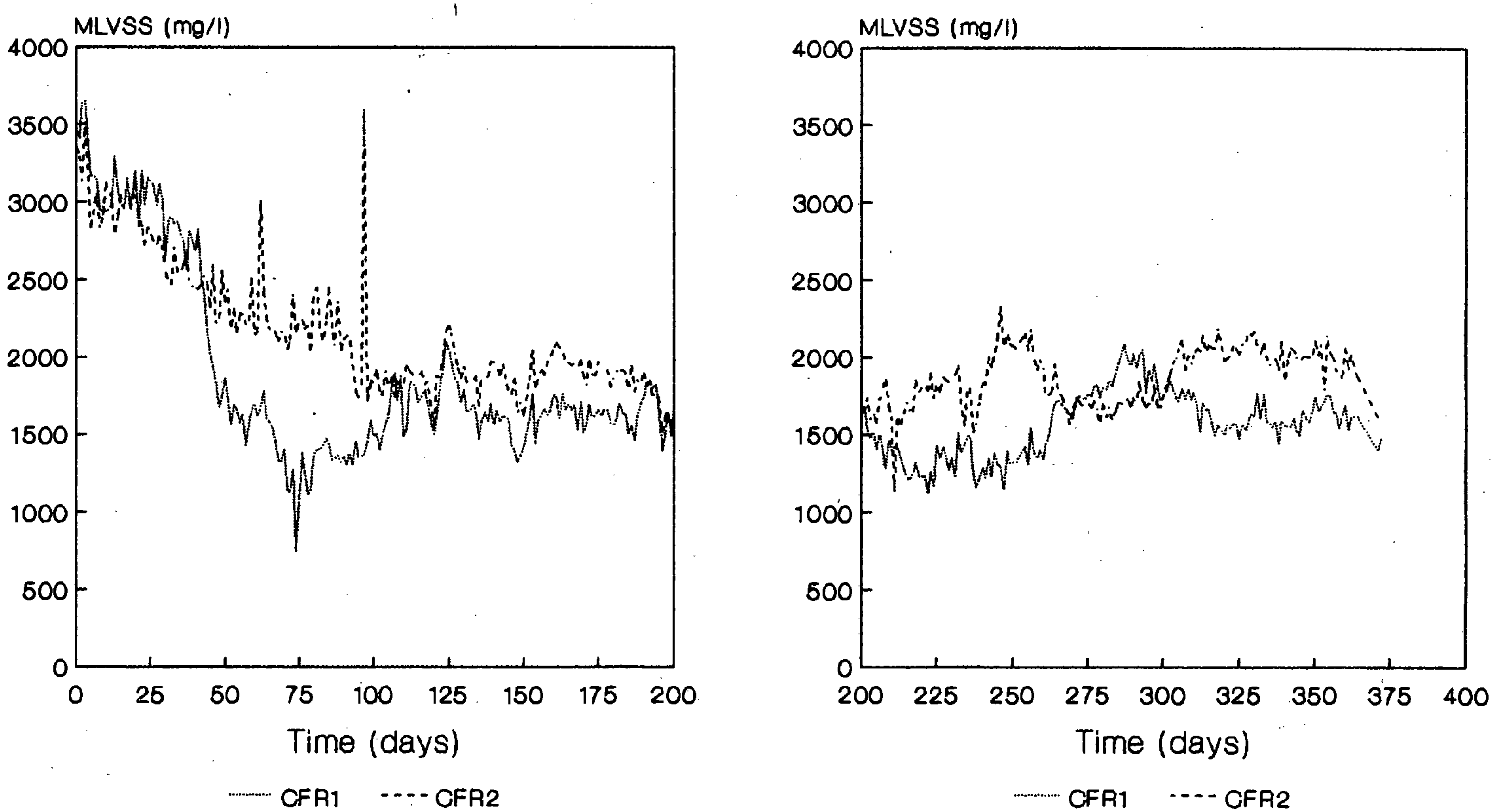


__Fig 3.3__ Effluent nitrate concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation; note that when there was no nitrate supplementation the effluent nitrate values reduced to around 4 mgN/ℓ indicating complete denitrification of the available nitrate and possibly a nitrate deficiency.



<u>Fig 3.4</u> Reactor MLVSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation; the VSS is approximately 80-86% of the TSS.

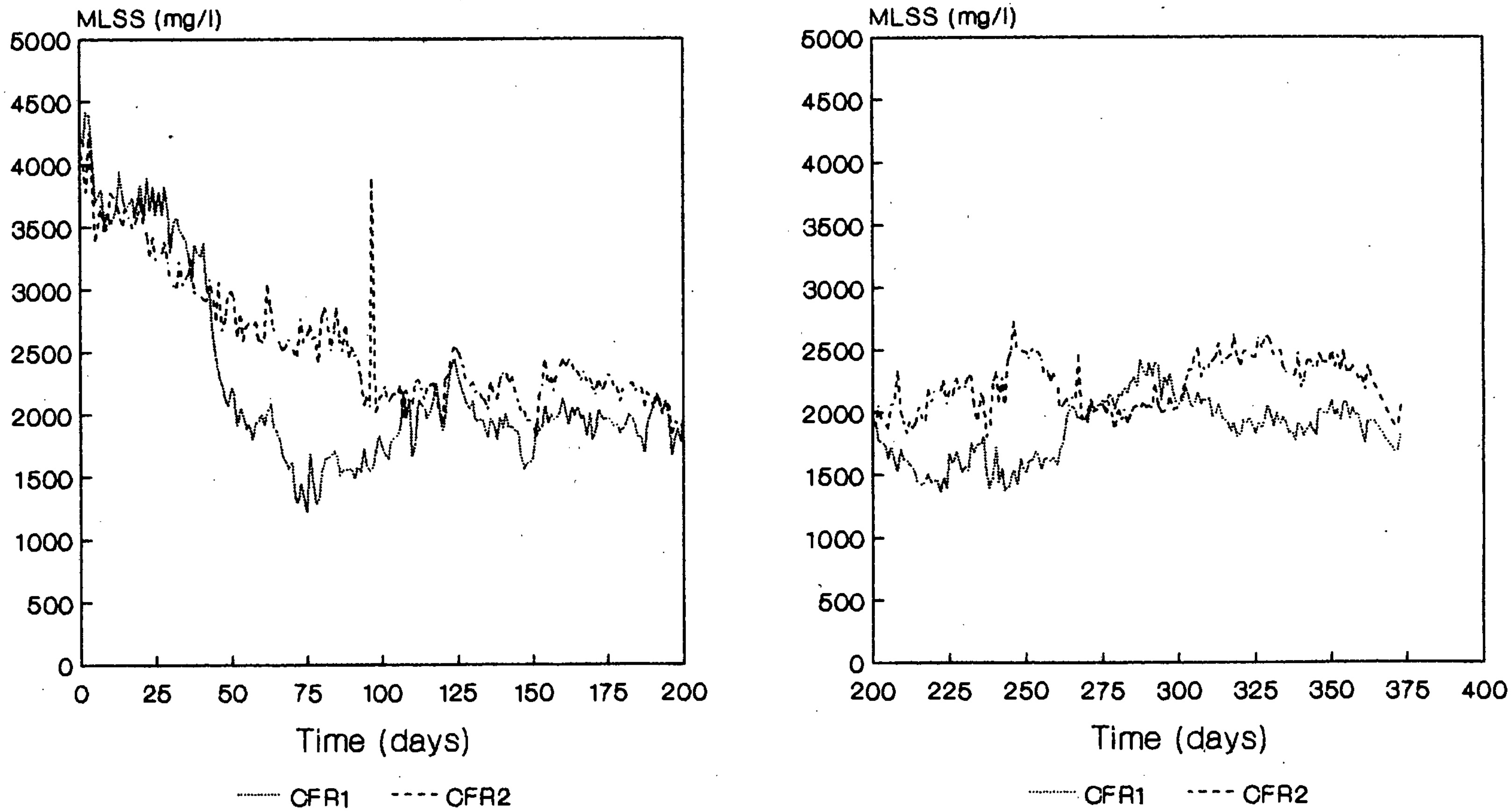


Fig 3.5 Reactor MLSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation.

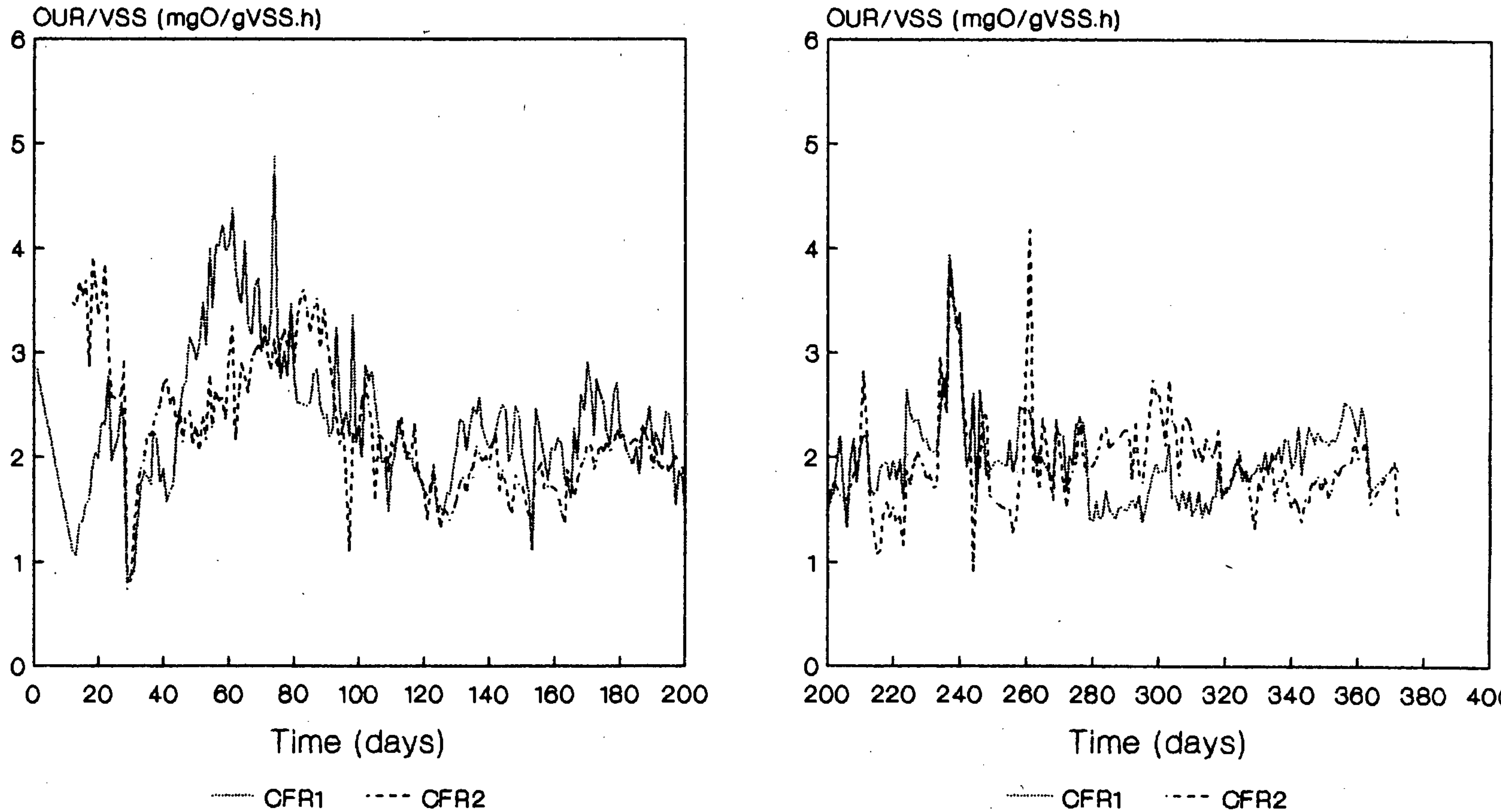


Fig 3.6 Oxygen utilization rate per gVSS measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation.

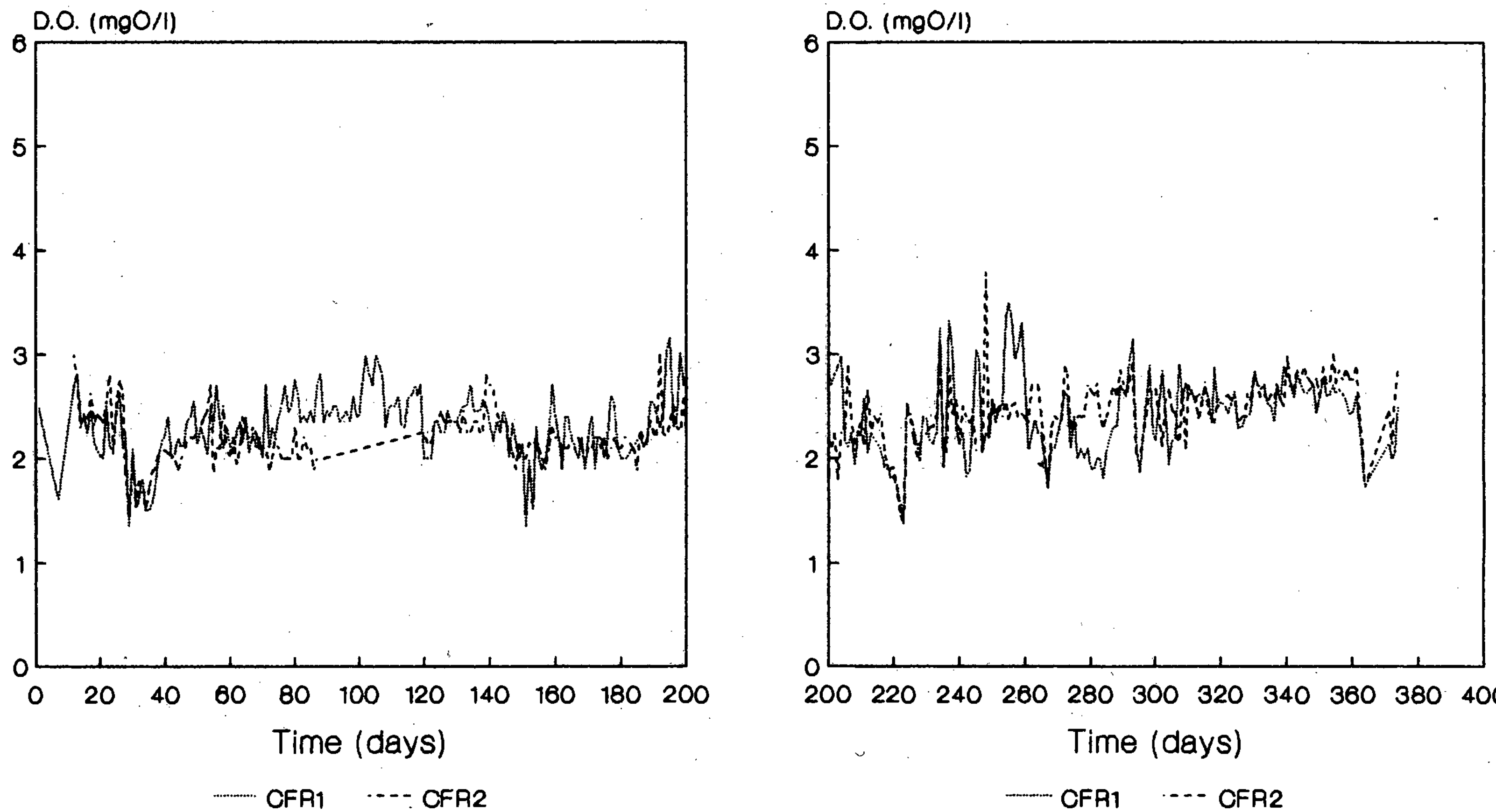
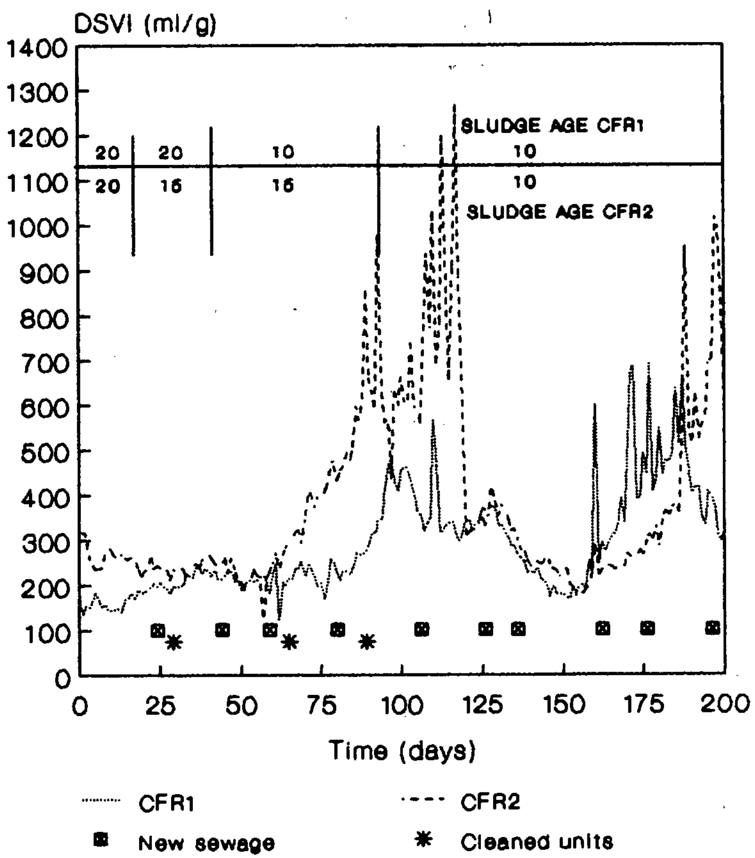


Fig 3.7 Peak dissolved oxygen (DO) concentration (mg/ℓ) on intermittent aeration cycle measured daily on intermittent aeration systems CFR1 and CFR2 during phase I of the investigation.

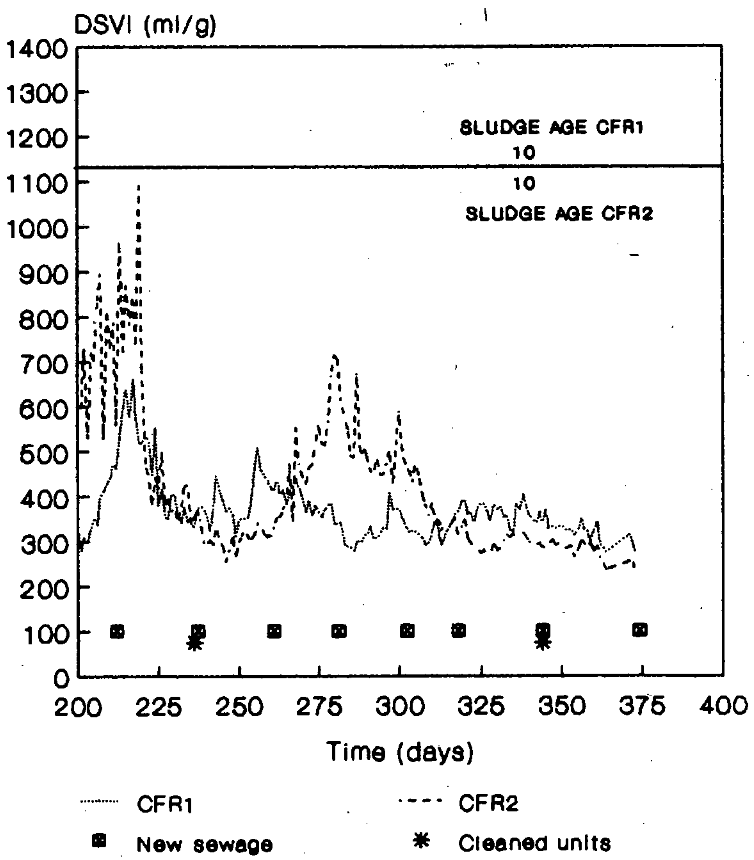


Filament Identification.

Day	Unit	Abundance	Dom	Sec	Other
10	CFR1	Very common	M.parv	0092	Thiothrix Beggiatoa
	CFR2	Abundant	M.parv 0092		0041 Thiothrix
29	CFR1		M.parv	0092	0675,1851,0041
	CFR2		M.parv	0092	1851,0675,0041
42	CFR1	Very common	0092	M.parv	0041,Ni II
	CFR2	Very common	0092	M.parv	0675,0041,Noc Ni II
72	CFR1		M.parv	0092	0675,1851
	CFR2		M.parv	0092	0675,0041,1851 H.hyd
88	CFR1		0092 M.parv	0803	0675,0041
	CFR2		M.parv	0092	0041,0675
105	CFR1		M.parv H.hyd	0092 0092	0041,Thiothrix
	CFR2		M.parv	0092	H.hyd,0041
118	CFR1		M.parv 1851	0092	H.hyd,0675,0041 0914
	CFR2		M.parv 0092		0914,0041,Noc
138	CFR1		M.parv	0092	0803,0041,H.hyd
	CFR2		M.parv 0092		0041,0675
154	CFR1		M.parv	0092	0041,0914
	CFR2		M.parv	0092	0803,0041,0675 Ni I
188	CFR1	Abundant	M.parv	0092	0041,0675
	CFR2	Abundant to Excessive	M.parv	H.hyd	0092,0041

M.parv -Microthrix parvicella
H.hyd -H.hydrossis
Ni I -N.limicola I
Noc -Nocardia

<u>Fig 3.9a</u> Daily DSVI data for the period day 0 to day 200 for intermittent aeration systems CFR1 and CFR2 during phase I of the investigation. Also shown on this figure are the filament identifications done every 3 to 4 weeks.



Filament Identification.

Day	Unit	Abundance	Dom	Sec	Other
208	CFR1	Abundant	M.parv	0092	0041,1851
	CFR2	Excessive	M.parv	0092	0041,Flexibacter
224	CFR1	Abundant	M.parv	0092	0041,Noc.
	CFR2	V.com - Ab.	M.parv	0092	H.hyd,0041
250	CFR1	V.com - Ab.	M.parv	0092	H.hyd
	CFR2	V.com	M.parv	H.hyd 0092	0041
272	CFR1	V.com - Ab	M.parv	H.hyd	1851,0092,0041 Beggiatoa
	CFR2	V.com	M.parv	0092	0041.H.hyd
296	CFR1	V.com - Ab	M.parv	H.hyd	0092,0041,S.nat Fungal Hyphae
	CFR2	V.com	M.parv	0092	0041,H.hyd
343	CFR1	V.com - Ab	M.parv	H.hyd	0041,0092
	CFR2	V.com	M.parv	Noc.	0041,0092,H.hyd

Exc. - Excessive
Ab - Abundant
V.com - Very common
Com - Common

M.parv -Microthrix parvicella
H.hyd -H.hydrossis
Nl I -N.limicola I
Noc -Nocardia
S.nat -S.natans

Fig 3.9b Daily DSVI data for the period day 200 to day 400 for intermittent aeration systems CFR1 and CFR2 during phase I of the investigation. Also shown on this figure are the filament identifications performed on samples taken at approximately 3 to 4 week intervals.

10. Filament identifications done every 3 to 4 weeks.

During the three phases of the investigation, a number of changes were made to the two systems and hinge around changing (1) sludge age and nitrate feed, (2) aerobic fraction and sludge age and (3) reducing the sludge age to less than 10 days. The changes and daily measured results of each phase of the investigation are presented graphically and discussed separately below.

3.2 EXPERIMENTAL RESULTS

3.2.1 Phase I: Sludge age and nitrate concentration

In the first part of this phase of the investigation (day 1 to 118) the sludge age of the systems was progressively reduced from 20 days to 10 days. Once the systems had reached a 10 days sludge age and low F/M filament bulking persisted (day 118) the effect of the effluent nitrate concentration was examined (day 119 to 375). All operational changes made to both systems during Phase I are set out in Table 3.2 and the daily measured experimental data of Phase I is presented graphically in the following Figures:

Fig 3.1 Phase I Influent and effluent COD.
Fig 3.2 Phase I Influent and effluent TKN.
Fig 3.3 Phase I Effluent nitrate concentration.
Fig 3.4 Phase I Reactor MLVSS concentration.
Fig 3.5 Phase I Reactor MLSS concentration.
Fig 3.6 Phase I OUR per gVSS (mgO/gVSS.h).
Fig 3.7 Phase I Peak DO.
Fig 3.8 Phase I Percentage aerobic.
Fig 3.9 Phase I Sludge settleability in DSVI and filament identifications.

All the data plotted in Figs 3.1 – 3.9 are listed in Appendix 3.1.

3.2.1.1 System behaviour – COD Balance

To gauge the reliability of the experimental results a COD balance was conducted on the experimental data. A COD balance involves reconciling the influent COD mass, $M(S_{ti})$, with the outflow COD mass where the latter is the sum of the masses of effluent COD, $M(S_{te})$, COD leaving via the waste sludge, M_{waste}, and the mass of oxygen consumed in COD utilization under anoxic and aerobic conditions, $M(O_c)$. The influent COD, effluent COD and the VSS of the wasted sludge were measured daily. The COD of the wasted sludge was calculated from the mass of VSS wasted daily and an assumed COD/VSS ratio of 1,48 mgCOD/mgVSS (WRC, 1984). Mathematically the COD balance therefore is

$$\text{COD balance} = \frac{M(S_{te}) + M_{waste} + M(O_c)}{M(S_{ti})} \times 100 \quad \%$$

The carbonaceous oxygen demand, $M(O_c)$, was calculated as follows:

$$M(O_c) = M(O_{tm}) + M(O_d) - M(O_n) \qquad (\text{mgO/d})$$

where

$M(O_c)$ = mass of oxygen required for COD utilization

$M(O_{tm})$ = measured mass of oxygen consumed daily

$$M(O_{tm}) = \frac{OUR.24.\%aerobic.V_p}{100} \qquad (\text{mgO/d})$$

where

OUR = measured oxygen utilization rate (mgO/d)

V_p = volume of the reactor (ℓ)

$M(O_d)$ = mass of oxygen recovered through denitrification (mgO/d)

$M(O_n)$ = mass of oxygen required for nitrification (mgO/d)

The measured OUR was obtained from the dissolved oxygen (DO) concentration-time profile during the aerobic period of the intermittent aeration cycle; the slope of the DO-time trace (obtained on a strip chart recorder) as the DO decreased from the peak value of around 2,0 to 2,5 mgO/ℓ to about 0,5 mgO/ℓ after aeration ceased, was accepted as the biological OUR in mgO/(ℓ.h). This OUR comprises both oxygen utilization for COD degradation and nitrification.

The following assumptions were made in the calculations for the COD mass balance:

(1) a 100% nitrogen balance was achieved in the system

(2) the OUR was constant throughout aeration period.

Assumption (1) above needed to be made for the COD balance because for intermittent aeration systems the mass of nitrate denitrified [from which $M(O_d)$ is calculated; $M(O_d)$ = 2,86 x nitrate denitrified] cannot be determined. Consequently the mass of nitrate denitrified was calculated assuming a 100% N balance in that the N shortfall in the N balance i.e. the difference between the influent TKN mass and the sum of the effluent total N (TKN + nitrate) and in the sludge wastage (10% of VSS wasted), was accepted to be the mass of the nitrate denitrified. The equation for the N balance is set out below:

$$MN_d = MN_{ti} - MN_{te} - MN_{ne} - MN_s - MN_w$$

where

MN_d	= mass of nitrate denitrified	(mgN/d)
MN_{ti}	= mass of TKN in influent	(mgN/d)
MN_{te}	= mass of TKN in effluent	(mgN/d)
MN_{ne}	= mass of nitrate in effluent	(mgN/d)
MN_s	= mass of N required for sludge growth	(mgN/d)
	= mass of N in sludge wasted	(mgN/d)
	= 10% of sludge wasted	(mgN/d)

Accepting a 100% N balance for the two systems was permissible because, on one occasion, one of the systems (CFR2) was switched to fully aerobic conditions for 3 sludge ages (~ 30 days, day 90 to 118). During this period, when no denitrification took place, a 98% N balance was achieved indicated that the operation of the systems and the analyses of the samples were being correctly done. Also on systems (outside this investigation) where N balances could be determined, usually better than 95% N balances were achieved. The techniques employed in this investigation were the same as those in which these good N balances were achieved.

With regard to the second assumption, the OUR was accepted as the average slope of the DO time trace about 0,5 mgO/ℓ below the peak DO and 0,5 mgO/ℓ. The aerobic period was measured off the DO time trace and accepted to be that time fraction of the cycle during which the DO concentration was greater than 0,2 mgO/ℓ. As the DO concentration decreased after aeration ceased, it was generally found that the OUR (slope) began to decrease (flatten out) when the DO concentration fell below 0,5 mgO/ℓ. This tended to extend the aerobic period somewhat but was generally small enough to be of little consequence.

The experimental data for the phase I period were subdivided into 29 steady state periods (in CFR1 14 and in CFR2 15) during which no significant system changes were made that would strongly influence the system performance. For each of the 29 periods, COD balances were conducted and the results are shown in Table 3.3.

From Table 3.3 it can be seen that during phase I of the investigation, COD balances ranging between 60 and 127% were obtained with an average for CFR1 of 83% and CFR2 92% giving an overall average for both systems of 87,3%. In Fig 3.10, COD balance obtained is plotted versus sludge age and it can be seen that better COD balances were achieved at long sludge ages (20 days) than at short sludge ages (10 days).

These COD balances tend to be on the low side because normally COD balances better than 95% indicate that the experimental work produced reliable data. The experimental technique and calculation was thoroughly checked but no explanation for the rather low COD balances could be found.

3.2.1.2 System behaviour – Kinetic evaluation of the results

In the COD balance the measured oxygen demand mass [$M(O_{tm})$] during the aerobic cycle is separated into its carbonaceous [COD utilization, $M(O_c)$] and nitrification [$M(_{tm})$] components. Also from the daily mass of nitrate denitrified (MN_d, $mgNO_3$-N/d) in the anoxic period, the equivalent carbonaceous oxygen demand can be calculated, i.e. $M(O_c)$anoxic = 2,86 x MN_d. From this calculation the kinetic performance of the two systems under anoxic and aerobic conditions can be evaluated for each steady state period. In such an evaluation the following kinetic parameters are calculated:

1. Readily biodegradable (RBCOD) loading rate (RBCODLR) under anoxic and aerobic conditions ($RBCODLR_{anx}$, $RBCODLR_{aer}$.).

2. Particulate biodegradable COD (PBCOD) utilization rate (PBCODUR) under anoxic and aerobic conditions ($PBCODUR_{anx}$,$PBCODUR_{aer}$).

3. The ratio $PBCODUR_{anx}/PBCODUR_{aer}$. This ratio in the general activated sludge model of Van Haandel *et al.* (1981) is called neta and is the reduction factor of the PBCOD hydrolysis rate under aerobic conditions for anoxic conditions. From experimental data, Van Haandel *et al.* (1981) found the

Table 3.3: COD balance results for phase I experimental data; evaluation of effect of sludge age between 20 and 10 days and nitrate concentration.

System	Period	Day	to Day	Sludge age (d)	COD Balance (%)
CFR1	1	0	28	20	98,79
	2	29	41	20	89,79
	3	42	58	10	108,37
	4	59	76	10	81,29
	5	77	92	10	71,50
	6	93	118	10	103,35
	7	119	129	10	105,35
	8	130	145	10	75,85
	9	146	154	10	68,74
	10	155	188	10	80,84
	11	191	215	10	59,75
	12	217	259	10	69,06
	13	260	297	10	69,08
	14	298	375	10	74,50
CFR2	1	0	17	20	96,13
	2	18	28	15	103,06
	3	29	41	15	93,08
	4	43	59	15	95,04
	5	60	76	15	84,43
	6	77	89	15	105,05
	7[1]	90	119	10	127,69
	8	130	129	10	110,66
	9	130	145	10	85,48
	10	146	154	10	75,85
	11	155	188	10	100,19
	12	191	215	10	75,29
	13	217	259	10	69,89
	14	260	297	10	80,44
	15	298	375	10	77,44

[1] System fully aerobic for 3 sludge ages.

Note: The N balance assumed to be 100%. This is a reasonable assumption because (1) N balance on CFR2 during steady state period 7 when it was fully aerobic was 98,2% and (2) on systems (outside this investigation) where N balances could be determined usually better than 95% N balances are achieved in the laboratory. The techniques employed in this investigation were the same as those in which good N balances are achieved.

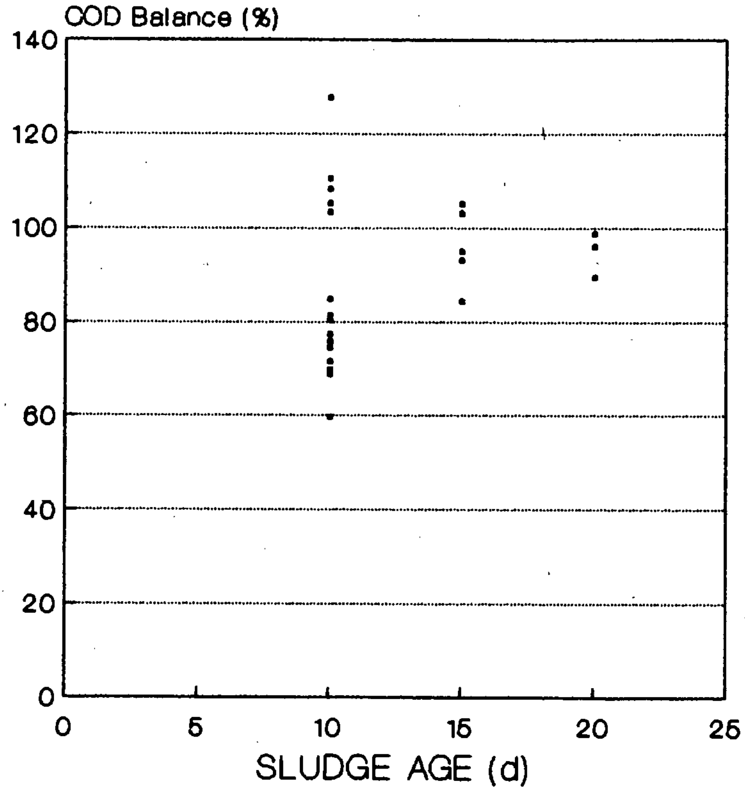


Fig 3.10 COD mass balance percentages plotted against sludge age for the steady state data obtained during phase I of the investigation.

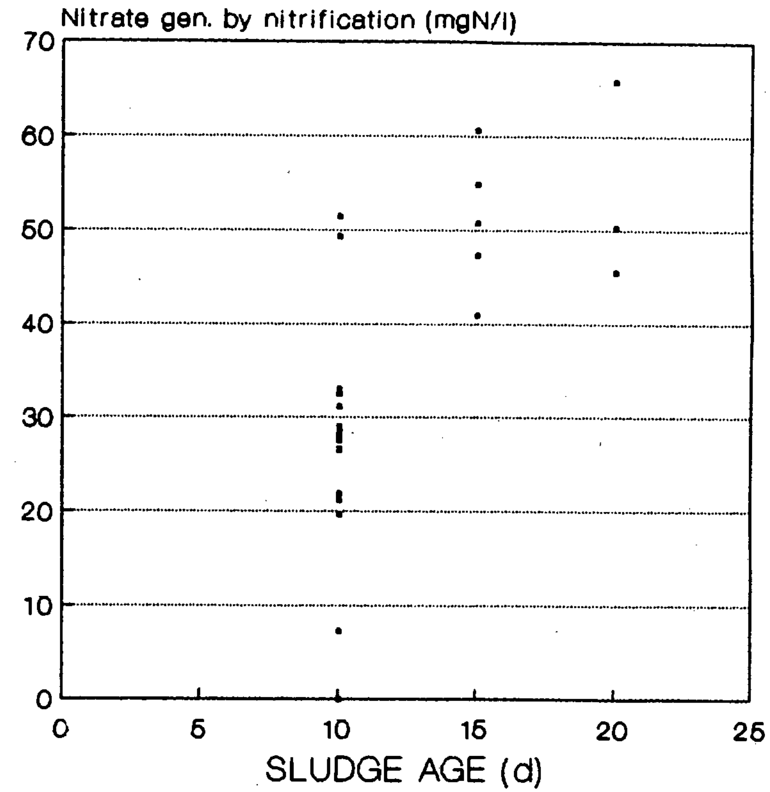


Fig 3.11 Nitrate generated by nitrification plotted against sludge age for the steady state periods identified during phase I of the investigation.

value of neta to be 0,38.

The procedures for the calculation of the kinetic behaviour evaluation are set out below:

1. The carbonaceous OUR under aerobic conditions is the sum of the OUR for the utilization of RBCOD (i.e. RBCODOUR) and PBCOD (i.e. PBCODOUR). Now the intermittent aeration systems were continuously fed so that RBCOD was applied to the system continuously during the aerobic and anoxic periods. Hence the RBCOD loading rate [RBCODLR, mgRBCOD/(mgAVSS.h)] onto the active VSS mass under aerobic conditions can be calculated and is given by:

$$RBCODLR_{aer} = \frac{f_{bs}.M(S_{bi}).\text{aerobic mass fraction}}{24.\text{aerobic mass fraction}.MX_a} \quad \text{mgCOD/(gVASS.h)}$$

$$= \frac{f_{bs}.M(S_{bi})}{24.MX_a} \quad \text{mgCOD/(gVASS.h)}$$

where

f_{bs} = readily biodegradable COD fraction of the influent COD with respect to the biodegradable COD concentration

$M(S_{bi})$ = mass of biodegradable COD in the influent – $M(S_{bi}) = M(S_{ti}).(1-f_{up}-f_{us})$

$M(S_{ti}$* = mass of influent COD

f_{up} = unbiodegradable particulate fraction of S_{ti}

f_{us} = unbiodegradable soluble fraction of S_{ti}

MX_a = volatile active mass in the system

where

$MX_a = f_{av}.MX_v$

where

MX_v = mass of VSS in reactor
$= X_v V_p$

X_v = measured VSS concentration (mgVSS/ℓ)

V_p = volume of the reactor (ℓ)

f_{av} = active fraction of the VSS.

The active fraction of the VSS f_{av} is calculated via the steady state activated sludge theory of Marais and Ekama (1976) (see also WRC, 1984) as follows:

(1) First the value of f_{up} i.e. the unbiodegradable particulate fraction of the influent COD is calculated;

Now in the steady state activated sludge theory

$$MX_v = M(S_{ti}) \left[\frac{Y_h . R_s . (1 - f_{us} - f_{up})}{(1 + b_h . R_s)} (1 + f . b_h . R_s) + \frac{f_{up} . R_s}{f_{cv}} \right] \tag{3.1}$$

where

Y_h = yield coefficient
= 0,45 mgVSS/mgCOD

R_s = sludge age (d)

b_h = endogenous respiration rate
= 0,24/d at 20°C

f = unbiodegradable fraction of the active VSS (endogenous residue)
= 0,20

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

The f_{up} is found by substituting the known values of the kinetic parameters (Y_h,f_{cv},b_h and f) and the measured values for MX_v, $M(S_{ti})$ and R_s into Eq (3.1) leaving only f_{us} and f_{up} undefined. Now the unbiodegradable soluble COD fraction, f_{us}, is estimated from the ratio of the measured filtered effluent COD concentration divided by the total influent concentration (i.e. $f_{us} = S_{ue}/S_{ti}$, see WRC, 1984). Knowing f_{us} leaves f_{up} the only remaining unknown parameter it can be calculated by solving Eq (3.1), with average experimentally measured values for MX_v, MS_{ti} and R_s for each steady state period.

(2) Knowing f_{up}, the active mass MX_a and active fraction of the VSS, f_{av}, viz. MX_a can be calculated as follows:

$$MX_a = M(S_{ti}).(1 - f_{us} - f_{up}) Y_h . R_s / (1 + b_h . R_s)$$

Then the active fraction is given by

$f_{av} = MX_a/MX_v$

where MX_v is the experimentally measured value.

The RBCOD loading rate [RBCODLR, mgRBCOD/mgAVSS.h)] onto the active VSS under anoxic conditions also can be calculated and is given by

$$RBCODLR_{anx} = \frac{f_{bs}.M(S_{bi}).\text{anoxic fraction}}{24.\text{anoxic fraction}.MX_a} \quad mgCOD/(mgAVSS.h)$$

$$= \frac{f_{bs}.M(S_{bi})}{24.MX_a}$$

$$= RBCODLR_{aer}.$$

From the above calculation it can be seen that the $RBCODLR_{aer}$ is the same as the $RBCODLR_{anx}$.

Now for continuously fed completely mixed systems i.e. ones wherein a selector effect is not induced, the RBCODUR under anoxic and aerobic conditions have been measured (see Gabb et al., 1988) and were found to be approximately the same under anoxic and aerobic conditions and in the range 50–150 mgRBCOD/(gAVSS.h) [which corresponds to a maximum specific growth rate of 0,7–2,1 mgAVSS/(mgAVSS.d)]. The RBCODUR on the two intermittent aeration systems operated in this investigation always was much lower [i.e. 6,4 to 7,6 mgRBCOD/(gAVSS.h), see Table 3.4] than the utilization rate cited above. From this it was accepted that the RBCOD would be utilized as fast as it was loaded onto the intermittent aeration system. Accepting this, it is possible to calculate the PBCOD utilization rate under anoxic and aerobic conditions by deducting the RBCODUR from the measured total (PBCOD + RBCOD) utilization where this is calculated from the measured carbonaceous oxygen demand under anoxic or aerobic conditions.

2. The PBCOD utilization rate [PBCODUR, mgPBCOD/(mgAVSS.h)] under

Table 3.4: COD utilization rates for phase I experimental data; evaluation of effect of sludge age between 20 and 10 days and nitrate concentration.

Period	Sludge age d	[1]RBCODUR	[1]PBCODUR anoxic	[1]PBCODUR aerobic	neta	% aerobic
CFR1						
1	20	6,4	40,1	109,9	0,365	44
2	20	6,4	63,5	125,6	0,506	34
3	10	7,6	89,6	205,5	0,436	32
4	10	7,6	46,6	92,7	0,503	39
5	10	7,6	36,1	79,9	0,452	36
6	10	7,6	34,5	184,3	0,187	32
7	10	7,6	47,9	166,4	0,288	36
8	10	7,6	29,9	95,3	0,314	31
9	10	7,6	37,9	76,5	0,495	35
10	10	7,6	44,0	111,8	0,394	34
11	10	7,6	[3]14,8	42,6	0,38	38
12	10	7,6	35,3	76,9	0,519	39
13	10	7,6	[3]13,5	50,6	0,268	34
14	10	7,6	35,9	81,8	0,439	39
CFR2						
1	20	6,4	37,6	167,2	0,225	30
2	15	6,8	44,2	183,3	0,241	32
3	15	6,8	60,2	153,9	0,391	32
4	15	6,8	67,3	170,4	0,395	30
5	15	6,8	35,6	113,0	0,315	37
6	15	6,8	61,1	165,9	0,368	38
7	10	7,6	[2]00,0	87,9	0,000	100
8	10	7,6	44,4	192,4	0,231	35
9	10	7,6	42,0	139,2	0,301	31
10	10	7,6	36,1	106,6	0,330	33
11	10	7,6	73,0	192,8	0,379	33
12	10	7,6	49,8	88,0	0,566	39
13	10	7,6	[3]13,8	65,2	0,212	32
14	10	7,6	33,0	91,8	0,359	35
15	10	7,6	[3]8,6	78,5	0,110	33

Note: At first sight it may seem strange that the PBCODUR under aerobic and anoxic conditions is higher than the maximum RBCODUR rates measured by Gabb *et al.* (1989) quoted in the text [50 to 150 mgRBCOD/(gAVSS.h)]. This is because the PBCODUR rates in the Table include the OUR for endogenous respiration, which is equivalent to 35 mgCODS/(gAVSS), so that the actual PBCODUR rates are 35 mgCOD/(gAVSS.h) lower than the rates quoted in the Table above. However, the PBCODUR rates are not adjusted for endogenous respiration because in the general activated sludge model, a death regeneration approach is employed requiring neta to be calculated on unadjusted PBCODUR rates (see Dold *et al.*, 1980, Van Haandel *et al.*, 1981, Dold and Marais, 1986).

[1] Units of RBCOD and PBCOD utilization rates are mgCOD/(gAVSS.h).
[2] System 100% aerobic.
[3] Nitrate deficiency during anoxic period (see Section 3.2.1.5 Denitrification, below).

aerobic conditions is calculated as follows:

$$PBCODUR_{aer} = \left[\frac{M(O_c)/(1-f_{cv}.Y_h)}{24.\text{aerobic fraction}.MX_a} \right] - RBCODUR \qquad \text{mgCOD/(gAVSS.h)}$$

$M(O_c)$	= carbonaceous oxygen demand mass (mgO/d)
	$= M(O_{add}) + M(O_d) - M(O_n)$

where

$(1-f_{cv}.Y_h)$	= 0,33 mgO consumed/mgCOD utilized.	
$M(O_{tm})$	= measured mass of oxygen consumed daily	
	= OUR.24.aerobic fraction.V_p	(mgO/d)
OUR	= measured oxygen utilization rate	(mgO/ℓ/h)
V_p	= reactor volume (ℓ)	
$M(O_d)$	= mass of oxygen consumed through denitrification	(mgO/d)
$M(O_n)$	= mass of oxygen required for nitrification	(mgO/d)

3. The PBCOD utilization rate (PBCODUR, mgPBCOD/mgAVSS.h) under anoxic conditions can be calculated and is given by:

$$PBCODUR_{anx} = \left[\frac{2,86.M(N_d).(1-f_{cv}.Y_h)}{24.\text{anoxic fraction}.MX_a} \right] - RBCODUR \qquad \text{(mgCOD/gAVSS.h)}$$

where

2,86	= oxygen equivalent of nitrate	($mgO/mgNO_3$-N)
MN_d	= mass of nitrate denitrified	(mgN/d)

4. Now the ratio of the PBCOD utilization rates under anoxic and aerobic is the neta value i.e.

$$neta = PBCODUR_{anx}/PBCODUR_{aer}$$

For each of the 29 steady state periods the abovementioned COD utilization rates and neta values were calculated and are tabulated in Table 3.4.

On analysis of the calculated RBCODUR values (in Table 3.4) one can see that the loading rate increases with a decrease in the sludge age of the system (6,4, 6,8 and 7,6 mgCOD/gAVSS.h for 20, 15 and 10 days sludge age respectively). This happens because the RBCOD is applied onto a decreasing active VSS with a reduction in sludge age. Further it can be seen that the PBCOD utilization rates are significantly higher than the RBCOD utilization rates. The reason for this is that the RBCOD utilization rate is limited by the RBCOD loading rate.

On closer examination of the PBCOD utilization rates in Table 3.4, it may seem strange that the PBCODUR under anoxic and aerobic conditions is in the same order of magnitude as the RBCODUR rates measured by Gabb *et al.* (1989) in batch tests, wherein the RBCODUR rates are not limited by the RBCOD loading rate from batch tests i.e. 50-150 mgRBCOD/(gAVSS.h). The reason for this is that the PBCODUR rates include the COD utilization rate arising from endogenous respiration, which amounts to about 35 mgCOD/(gAVSS.h) for aerobic conditions[1] and neta.35 = 13,3 mgCOD/(g.AVSS.h) for anoxic conditions. Subtraction of 35 mgCOD/(gAVSS.h) from the calculated $PBCODUR_{aer}$ values and 13,5 mgCOD/(gAVSS.h) from the calculated $PBCODUR_{anx}$ values in Table 3.4, now brings the rates in the approximate expected ratio between RBCODUR not limited by loading rate and PBCODUR under anoxic and aerobic conditions.

Finally the reduction factor of the PBCOD hydrolysis rate under aerobic conditions for anoxic conditions, neta, ranges between 0,110 and 0,566 with an overall average of 0,356 (CFR1 0,396 and CFR2 0,316) which is close to the

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[1]Calculated from the specific endogenous respiration oxygen utilization rate O_e/X_a viz.

$$\begin{aligned} O_e/X_a &= f_{cv}\,(1\text{-}f)\,b_h \qquad \text{mgO/(mgAVSS.d)} \\ &= 1{,}48\,(1\text{-}0{,}20)\cdot 0{,}24\cdot 1000/24 \\ &= 11{,}8 \text{ mgO/(gAVSS.h)} \end{aligned}$$

Now from bioenergetics, in the utilization of 1 mgO oxygen $1/(1\text{-}f_{cv}Y_h) = 3$ mgCOD are utilized. Hence the specific PBCOD utilization rate corresponding to the specific endogenous respiration rate is 11,8·3 = 35 mgCOD/(gAVSS.h).

predicted value of van Haandel *et al.*, 1981, of 0,38. From these results in Table 3.4 it was concluded that as far as could be determined, the kinetic behaviour of the two systems was normal.

3.2.1.3 System performance – COD removal

COD removal by the systems when operated in the sludge age range 20 days to 10 days was generally greater than 80% with effluent COD rarely exceeding 100 mgCOD/ℓ. For the influent COD of around 500-600 mgCOD/ℓ (see Fig 3.1 – influent and effluent COD). No appreciable increase in effluent COD values was obvious after reduction of the sludge age from 20 days to 10 days. This was not unexpected because COD reductions of between 75 to 90% have been reported in the literature even for very short sludge age systems (i.e. less than 5 days).

The effluent nitrate concentration in the reactors had no apparent influence on the COD removal. Similar effluent COD values were recorded in the systems when one had high (40 mgN/ℓ) effluent nitrate concentrations and the other had low effluent nitrate concentrations (4 mgN/ℓ), as evident when comparing – effluent COD – Fig 3.1 with Fig 3.3 – Effluent nitrate.

3.2.1.4 System performance – Nitrification

The effects of sludge age on nitrification are shown in Fig 3.11 which shows the nitrate generated by nitrification vs sludge age. Generally better nitrification is achieved at the longer sludge ages. The primary reason for this is that the mass of nitrifiers decreases with a decrease in the sludge age of the system, thus there are fewer nitrifying organisms available to nitrify the influent TKN at the shorter sludge ages. Also more N is required for sludge production with decreases in sludge age.

At the short sludge age of 10 days and 30% aerobic mass fraction, nitrification was no longer complete in the two systems (effluent TKN ~ 10 mgN/ℓ, Fig 3.2) so that it became unnecessary to supplement the influent TKN with ammonia. Consequently on day 128, ammonia chloride supplementation was stopped, but to ensure that a high concentration of nitrate was maintained during the anoxic period, additional nitrate was dosed into the reactors at an equivalent influent concentration of 55 mgN/ℓ.

The dosing of nitrate, either indirectly by addition to the influent (day 29 – 58) or

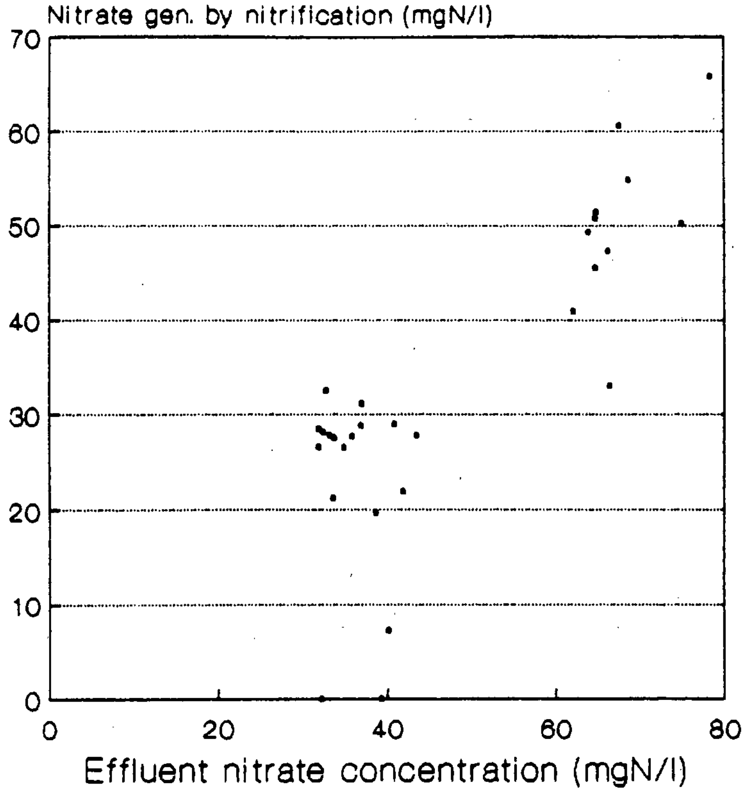


Fig 3.12 Nitrate generated by nitrification plotted against the effluent nitrate concentration for the average data of each of the steady state periods identified for systems CFR1 and CFR2 during phase I of the investigation; note that high effluent nitrate concentrations appear to have little influence on the nitrification ability of the systems.

directly by drip feed (day 59 – 375) into the reactors gave rise to higher effluent nitrate concentrations but appears to have had little or no effect on the nitrification capability of the systems. In Fig 3.12, where the nitrate generated by nitrification vs effluent nitrate concentration is given, clearly nitrification is independent of the magnitude of the effluent nitrate concentration.

3.2.1.5 System performance – Denitrification

In intermittent aeration systems the mass of nitrate denitrified cannot be directly measured. However it can be calculated assuming a 100% N balance in the system where the mass of nitrate denitrified is accepted to be the shortfall in the N balance i.e. mass of nitrate denitrified is the difference between the influent TKN mass (and nitrate mass dosed) and the sum of the effluent total N (TKN + nitrate) and the N in the sludge wasted (10% of VSS wasted). Since no denitrification takes place under fully aerobic conditions the validity of the 100% N balance assumption could be verified using the experimental data of system CFR2. This system was continuously aerated for about 3 sludge ages (day 90 to 118) during the investigation. Considering the average results for CFR2 for this period

Influent TKN concentration	49 mgN/ℓ
Nitrate drip fed into reactor	55 mgN/ℓ
Effluent TKN concentration	6 mgN/ℓ
Effluent nitrate concentration	85 mgN/ℓ
N in sludge wasted (10% of VSS wasted)	14 mgN/ℓ

$$\text{N balance} = [(49 + 55 - 6 - 14)/85].100$$
$$= 98.2\%$$

From the above calculation it can be seen that the 100 % N balance is a reasonable assumption to accept for the two experimental systems. Good N balances (> 95%) are indicative that the experimental procedures and test methods were accurately executed. Since the same methods were applied throughout the investigation, the 100% N balance assumption can be used with confidence to estimate the mass of nitrate denitrified in systems that were not fully aerobic.

The mass of nitrate denitrified estimated from the 100% N balance for the 14 and

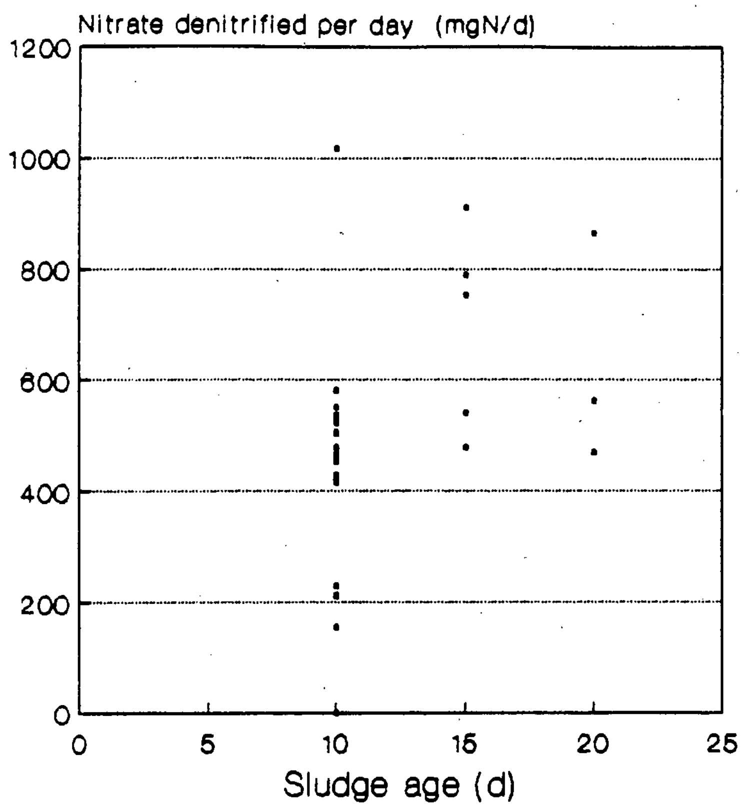


Fig 3.13 Mass of nitrate denitrified per day plotted against sludge age for the average data of each of the steady state periods identified for systems CFR1 and CFR2 during phase I of the investigation.

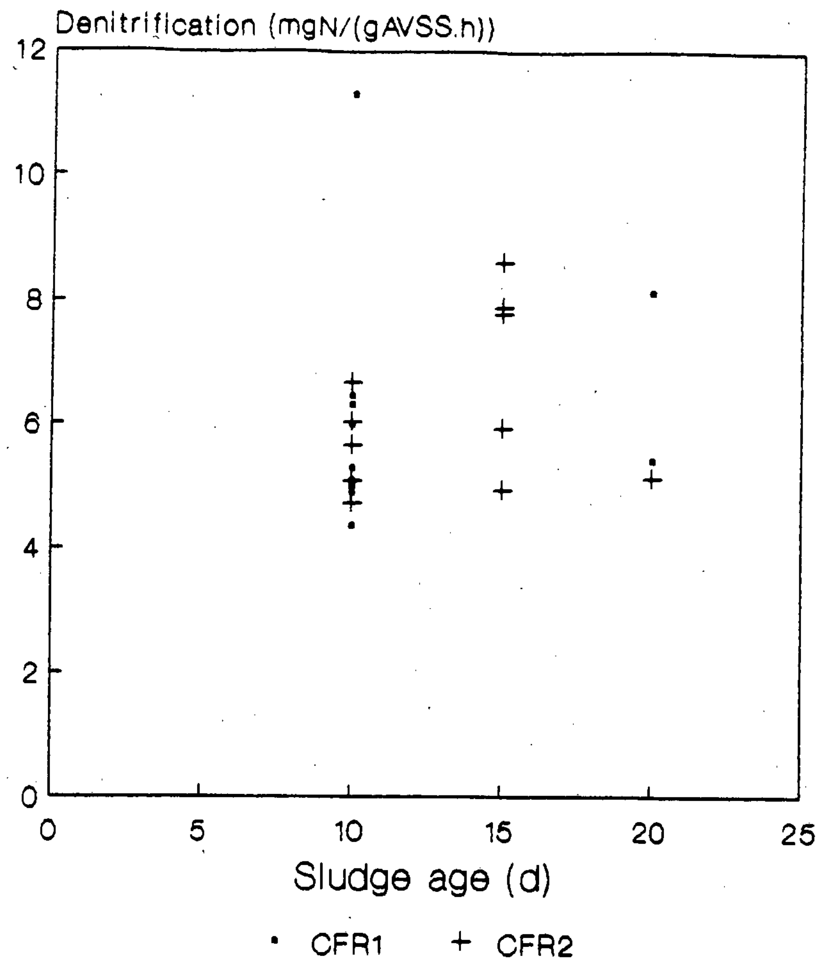


Fig 3.14 Specific denitrification rate (mgN/[gAVSS.h]) plotted against sludge age for the average data of each of the steady state periods identified for systems CFR1 and CFR2 during phase I of the investigation.

15 steady state periods of CFR1 and CFR2 respectively are plotted versus sludge age in Fig 3.13. From Fig 3.13 it can be seen that denitrification is reduced with a reduction in sludge age. This arises from reduced active mass generated at the shorter sludge ages. A plot of the specific denitrification rate i.e. $mgNO_3/(gAVSS.h)$ versus sludge age is given in Fig 3.14 and from this it can be seen that the specific rate does not change with sludge age for sludge ages between 10 and 20 days.

In the intermittent aeration system the effluent nitrate concentration is not reduced to zero (Fig 3.3). This is because effluent flows from the system during the aerobic period in which nitrification takes place. The fact that nitrate is always present in the effluent does not necessarily mean that the denitrification during the anoxic period is not nitrate limited. The measured effluent nitrate concentration is the composite value from the aerobic and anoxic periods – it varies similarly as the DO concentration (Table 3.1), increasing during the aerobic period to a peak value and decreasing during the anoxic period possible to zero at some time before aeration again commences. In the steady state periods of CFR1 and CFR2 where the nitrate concentration did decrease to zero during the anoxic period, the denitrification was nitrate limited and the effluent nitrate concentration was around 4-5 mgN/ℓ. Consequently, where effluent nitrate concentrations greater than about 6-8 mgN/ℓ were measured the denitrification was not nitrate limited. For three periods on CFR1 (days 153-186, days 216-259, days 296-375) and two periods on CFR2 (days 186-216, days 259-296), each of 3 sludge ages duration, nitrate dosing was stopped and caused a nitrate deficiency on denitrification during the anoxic period. The nitrate dosing was stopped on one system and commenced on the other system specifically to investigate the effect of the nitrate concentration and nitrate deficiency on the low F/M filament proliferation. Consequently the nitrate dosing was interchanged between the CFR1 and CFR2 systems so that while one, which did not receive dosed nitrate, was nitrate deficient and the other, which did receive nitrate was not nitrate deficient. The degree of nitrate deficiency can be estimated by comparing the denitrification performance of the two systems during the same period e.g. for the period day 153 and 186 (Fig 3.3), in which CFR2 did not receive nitrate (see Appendix B for details of the data) viz.

Influent TKN concentration (CFR1 & CFR2)	= 55 mgN/ℓ
N required for sludge growth (CFR1 & CFR2)	= 13 mgN/ℓ

Effluent TKN concentration (CFR1)	= 15 mgN/ℓ
Hence nitrate generated (CFR1 & CFR2)	= 27 mgN/ℓ
Nitrate dosed to (CFR1)	= 54 mgN/ℓ
Nitrate available for denitrification (CFR1)	= 83 mgN/ℓ
Effluent nitrate (CFR1) (Fig 3.3)	= 29 mgN/ℓ
⇒ Nitrate denitrified (CFR1)	= 54 mgN/ℓ
Effluent nitrate (CFR2) (Fig 3.3)	= 5 mgN/ℓ
Nitrate denitrified CFR1 = 29 − 3	= 24 mgN/ℓ
⇒ Nitrate deficiency in CFR1 = 54 − 24	= 30 mgN/ℓ

Hence system CFR1 not receiving dosed nitrate could denitrify 30 mgN/ℓ more nitrate if it were available. In the other 4 periods, during which CFR2 and CFR1 alternatively did not receive dosed nitrate the nitrate deficiency when nitrate was not dosed was 28, 22, 13 and 20 mgN/ℓ respectively. Despite the nitrate deficiency, causing temporary anaerobic conditions in the systems, biological excess P removal was not observed in the system.

When the systems were not nitrate deficient, on average during the investigation, CFR1 and CFR2 denitrified 568 and 585 mgN/d respectively giving a nitrate denitrified per ℓ influent of 56,8 mgN/ℓ and 58,5 mgN/ℓ. From a design point of view, accepting (1) complete nitrification so that the effluent TKN concentration of about 4 mgN/ℓ is achieved, (2) 15 days sludge age at which the N requirement for sludge production is about 15 mgN/ℓ, (3) an effluent nitrate concentration of 4 mgN/ℓ, then the influent TKN/COD ratio for which the intermittent aeration systems with 30% (70%) aerobic (anoxic) fraction would not be nitrate deficient is (57+4+15+4)/520 = 0,154 mgN/mgCOD. Therefore for a raw sewage with a TKN/COD ratio of 0,154 an intermittent aeration system at 70% anoxic mass fraction, at 20°C and 15 to 20 days sludge age (long to ensure nitrification is complete at 30% aerobic mass fraction), can produce an effluent total N (nitrate and TKN) of 8 mgN/ℓ for TKN/COD ratios up to 0,15 mgN/mgCOD. A procedure for predicting the denitrification potential of an intermittent aeration system is present at the end of this Chapter in Section 3.4.

A factor which greatly affects the nitrate denitrified, is the magnitude of the aerobic mass fraction, the larger this fraction the less nitrate denitrified. This aspect will be discussed in detail in phase II of the experimentation.

3.2.1.6 System behaviour – Low F/M filament bulking

From the above evaluation of the experimental data measured on systems CFR1 and CFR2, it is evident that kinetically, the two systems performed as expected in terms of the established kinetic understanding and modelling of nitrification and denitrification systems; in particular, the data shows (1) good N (where this could be measured) and COD mass balances (98,2% and 87,3% respectively), (2) kinetic rates close to those measured previously in other nitrification denitrification experiments and modelling viz. the average K_2 denitrification rate of 0,126 $mgNO_3$-N/(mgAVSS.d) (see Table 3.4) measured on the two systems compares well with the K_2 rate 0,101 $mgNO_3$-N/(mgAVSS.d) established earlier in compartmental anoxic-aerobic N removal systems (WRC, 1984) and the average ratio of the measured anoxic and aerobic particulate biodegradable COD utilization rates, neta, of 0,36 compared very well with the 0,38 value established earlier by Van Haandel *et al.*, 1981.

Because the kinetic performance of the two systems was close to that expected from previous experience, the bulking behaviour of the systems cannot be attributed to an unusual kinetic behaviour.

Effect of sludge age on low F/M filaments

On the day monitoring of the systems commenced (day 0) the DSVI of CFR1 was 160 mℓ/g and that in CFR2 300 mℓ/g. The bulking was caused by the low F/M filaments *M.parvicella* and 0092 (Fig 3.9). On day 17, about 3 sludge ages after starting the systems, sludge wastage from CFR2 was increased to establish a sludge age of 15 days. For the following 72 days (up to day 89), the DSVI remained above 200 mℓ/g caused by filaments 0092, *M.parvicella*, 9675 and 0041. Moreover from day 60 to day 89 the DSVI increased from 200 to 600 mℓ/g caused mainly by the explosive growth of *M.parvicella*. Other low F/M filaments 0092, 0675, 0041, 1851 and *H.hydrossis* were also present but not dominant. Because by day 41 it was already evident that at 15 days sludge age the low F/M filaments could still proliferate, sludge wastage from CFR1, which was operating at 20 days sludge age, was doubled to establish a sludge age of 10 days. From day 41 to day 120 i.e. 8 sludge ages, the DSVI remained above 200 mℓ/g in CFR1 with the causative filaments *M.parvicella* and 0092 but also with 0675 and 0041 secondary. Indeed by day 80 the DSVI had increased to 450 mℓ/g mainly due to the proliferation of *M.parvicella* and also some 0092. This indicated that the low F/M filaments *M.parvicella*, 0092, 0675 and 0041 still were able to proliferate at 10 days sludge age.

When the DSVI in CFR2, the 15 days sludge age system, reached 600 mℓ/g, solid/liquid separation problems in the clarifier were encountered. Two strategies were adopted to reduce the DSVI to more reasonable and workable bulking levels by (i) introducing continuous aeration with a DO between 5-6 mgO/ℓ on day 89 and (ii) increasing sludge wastage to reduce the sludge age from 15 days to 10 days. To accelerate the MLSS reduction to the 10 day sludge age value, 2ℓ of mixed liquor was additionally wasted on day 93. While the latter (additional sludge wastage) brought some relief to the clarifier, the former (continuous aeration) had no influence on the DSVI. This was surprising and unexpected because on *all* previous occasions with intermittent aeration systems bulking with low F/M filaments, including *M.parvicella*, when aeration was changed from intermittent to continuous, the DSVI responded very quickly and in 10 days would decrease from around 250 mℓ/g to below 80 mℓ/g. In this particular case, (CFR1), initially continuous aeration seemed to hold the DSVI in check at 600 mℓ/g but after 18 days it increased to 750 mℓ/g. Even increasing the DO from 5-6 to 8-9 mgO/ℓ did not cause a reduction in the DSVI. When after a further 12 days there was still no improvement in the DSVI, the sludge in the system was discarded. No explanation can be advanced for the continuation of the bulking, mainly by *M.parvicella* under continuous aeration; it is possible that *M.parvicella* had become so dominant and firmly entrenched in the biocenosis that it could maintain its dominance compared to the other organisms despite the change to a more hostile (continuous aeration) environment.

It was concluded from these results that low F/M filaments, in particular *M.parvicella* and 0092 but also 0675 and 0041, can proliferate sufficiently at 10 days sludge age to cause severe bulking problems (DSVI > 200 mℓ/g).

The effect of sludge ages less than 10 days on low F/M filament proliferation is discussed further in phase II and in detail in phase III of the investigation.

Effect of nitrate concentration on low F/M filaments

Having established that low F/M filaments proliferate to cause severe bulking at 10 days sludge age, it was decided to change the aim of the experiments with the two systems and investigate the effect of the nitrate concentration during the anoxic period on low F/M filament proliferation and bulking.

The CFR2 system was restarted on day 120 by mixing 4ℓ of sludge harvested from a laboratory modified UCT system (which had a DSVI of 200 mℓ/g with dominant filaments 0092, 0914 and secondary filaments 0041 and *M.parvicella*), with the sludge from CFR1 and dividing the blend equally between CFR1 and CFR2. The DSVI of the blend was 349 mℓ/g (Fig 3.9).

At 10 days sludge age, and 30% aerobic mass fraction, nitrification no longer was complete in the two systems (effluent TKN ~ 10 mg/ℓ, Fig 3.2) so that it was no longer necessary to supplement the influent TKN with ammonia. Consequently on day 128, ammonia chloride supplementation was ceased, but to ensure that a high concentration of nitrate was maintained during the anoxic period, additional nitrate was dosed into the reactor at an equivalent influent concentration of 55 mg/ℓ.

From day 128 to 153 while nitrate was dosed into both systems, the DSVI declined from 350 mℓ/g and leveled off at 200 mℓ/g. During this time the effluent nitrate concentration varied between 20 and 40 mgN/ℓ in both systems. On day 153, the nitrate dosing to CFR2 was stopped so that the only source of nitrate was that produced by the nitrification in the system. From the kinetic evaluation above, this caused a nitrate deficiency during the anoxic period of 20-30 mgN/ℓ i.e. in comparison to the system CFR1, into which nitrate was dosed, 20-30 mgN/ℓ nitrate more could have been denitrified than was available. The nitrate deficiency caused the nitrate concentration to decrease to zero at some point during the unaerated period, and it is estimated from the concentration of nitrate that it could denitrify (about 57 mgN/ℓ) and the concentration that it did denitrify (i.e. about 30 mgN/ℓ) that the nitrate concentration reached zero about halfway through the period after the DO reached zero and commencement of aeration in the next cycle. Thus with nitrate deficiency, the system was 30% aerobic, 40% anoxic and 30% anaerobic.

The DSVI of CFR1 (with nitrate dosing) increased from 200 mℓ/g to 550 mℓ/g and the DSVI of CFR2 (no nitrate dosing) increased from 200 mℓ/g to 350 mℓ/g. On day 186, the nitrate dosing was switched between the two systems, i.e. it was removed from CFR1 (which had received dosed nitrate) and transferred to CFR2 (which had not received dosed nitrate). Now the DSVI of CFR2 (with dosed nitrate) increased from 350 to 750 mℓ/g and the DSVI of CFR1 (without dosed nitrate) initially declined from 550 to 300 mℓ/g but then increased up to 600 mℓ/g. On 3 further occasions about 3-4 sludge ages apart, (i.e. on days 216, 257 and 296), the nitrate dosage was interchanged between the two systems. The effect of this is outlined below.

Throughout the experiment the sludges in both systems continued to bulk with low F/M filaments in particular *M.parvicella* and 0092 but also *H.hydrossis*, 0041 and 0675 i.e. manipulating the nitrate concentration to low values (less than 4 mgN/ℓ) during the anoxic period or high values (> 30 but < 50 mgN/ℓ) did not influence the filaments sufficiently to inhibit bulking (see Fig 3.16). The DSVI remained above 300 mℓ/g.

Even though the sludges bulked throughout the experiment by the filaments cited above, the nitrate concentration did influence the DSVI and therefore by implication the filaments. Generally the high nitrate concentration stimulated greater filament proliferation than the low nitrate concentrations (see Fig 3.15). In the period day 153-186, the DSVI in the high nitrate system (CFR1) increased (from 200 mℓ/g) more sharply and to a higher value (550 mℓ/g vs 350 mℓ/g) than the low nitrate system (CFR2). Then, on day 186, when the nitrate dose was interchanged, the DSVI in the now high nitrate system (CFR2) increased sharply (from 350 to 750 mℓ/g) in 10 days while that in the now low nitrate system (CFR1) declined initially (from 550 to 300 mℓ/g in 20 days) but then increased up to 600 mℓ/g. Then, on day 216 the nitrate dose was switched again, the DSVI in both systems decreased, but in the now low nitrate system (CFR2) much more rapidly (from 750 to 350 mℓ/g in 14 days) than in the high nitrate system (CFR1) (from 600 to 350 mℓ/g in 14 days). Further the DSVI in the high nitrate system (CFR1) increased again to 450 mℓ/g, while that in the low nitrate system leveled off at 300 mℓ/g. When, on day 259 the nitrate dose was switched again, the DSVI in the now low nitrate system (CFR2) fluctuated between 300 and 400 mℓ/g, initially increasing then decreasing and stabilizing at 350 mℓ/g. During the same period the DSVI in the high nitrate system (CFR1) increased from 450 mℓ/g to 700 mℓ/g, then decreased to and leveled off at 500 mℓ/g. After the final nitrate dose switch (day 296), the DSVI in the high nitrate system (CFR1) fluctuated between 300 and 400 mℓ/g, while that in the now low nitrate system (CFR2), the DSVI decreased from 500 mℓ/g to 300 mℓ/g over three weeks and leveled off at this value for the remainder of the investigation (40 days) (Fig 3.15).

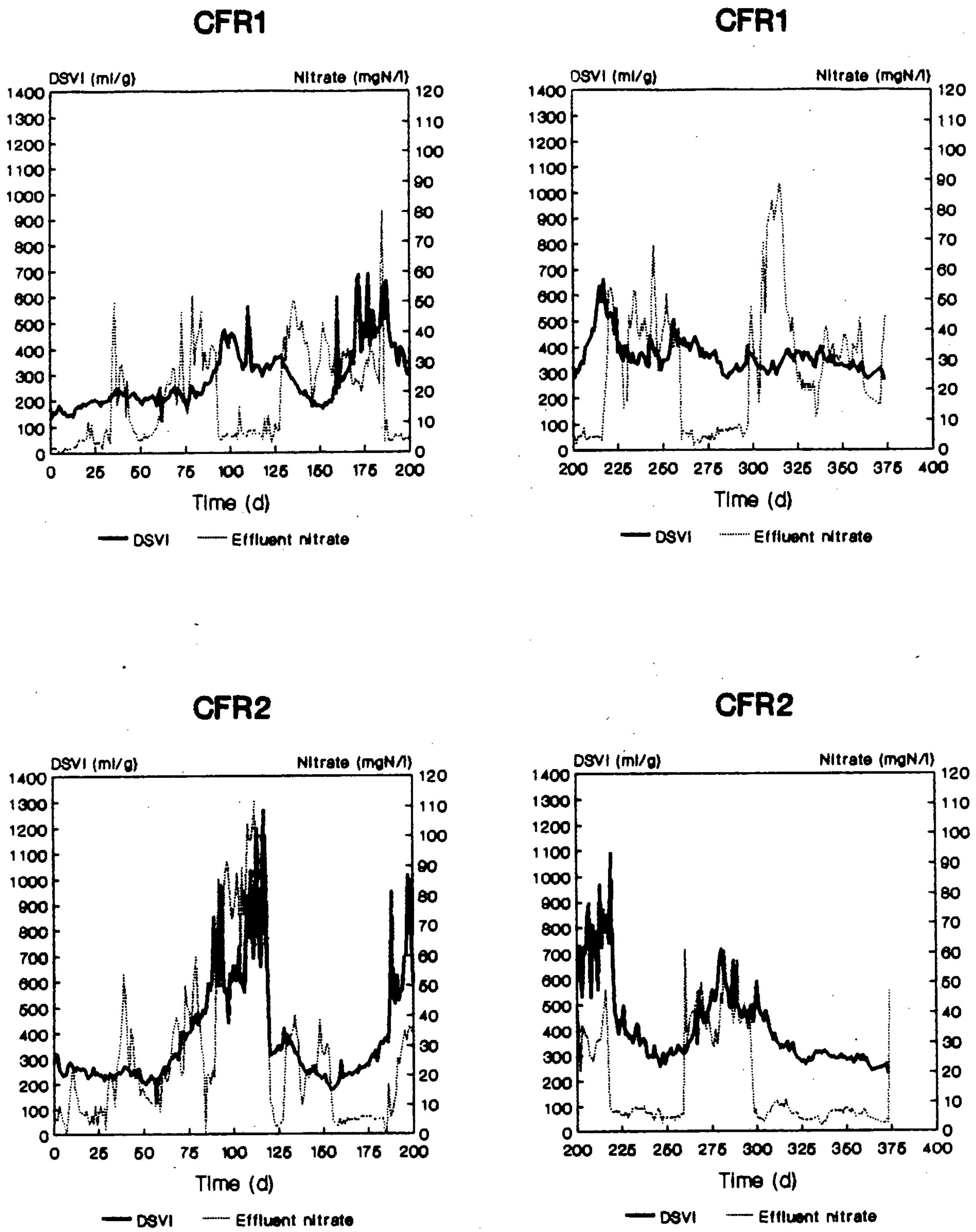
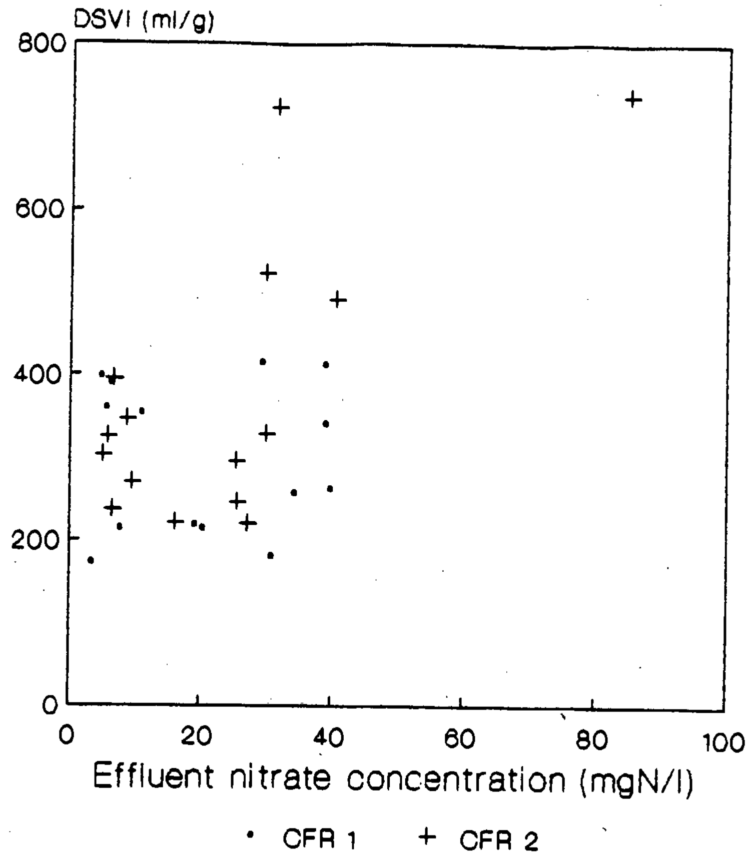


Fig 3.15 Daily measured DSVI and effluent nitrate concentration for intermittent aeration systems CFR1 and CFR2 plotted together against time for phase I of the investigation to check the effect of effluent nitrate concentration on DSVI.



<u>Fig 3.16</u> Average DSVI versus average effluent nitrate concentration for the steady state periods identified in intermittent aeration systems CFR1 and CFR2 during phase I of the investigation.

3.2.1.7 Conclusions

1. Essentially throughout this first phase of the investigation, in which the sludge age was reduced from 40 to 10 days and the nitrate concentration in the anoxic period was varied between high (40 mgN/ℓ) and low values (4 mgN/ℓ), the two systems CFR1 and CFR2 produced low F/M filament bulking sludges with DSVI's greater than 200 mℓ/g but increasing to as high as 600 mℓ/g, caused mainly by filaments *M.parvicella* and 0092.

2. Low F/M filamentous organisms, in particular *M.parvicella* and 0092 but also 0675, 0041, *H.hydrossis*, are able to proliferate to levels to cause bulking problems and DSVI in excess of 300 mℓ/g at 10 days sludge age in intermittent aeration (20 minute cycle, 30% aerobic mass fraction) single reactor continuously fed completely mixed systems.

3. In the intermittent aeration systems, the nitrate concentration during the anoxic period does influence the low F/M filament proliferation; generally the higher the nitrate concentration (> 30 but < 50 mgN/ℓ) or low (< 4 mgN/ℓ) values increases and decreases respectively in DSVI could be effected; however, even when the nitrate concentration was low, low F/M filament proliferation was still sufficient to cause bulking problems (DSVI > 200 mℓ/g).

3.2.2 Phase II: Aerobic mass fraction and sludge age

In this phase of the investigation, the same two systems CFR1 and CFR2, operated in phase I described above were adopted. In Table 3.5 the initial operating conditions and parameters are given. Note that at the commencement of this phase the sludge age was 10 days and the aerobic mass fraction 30% in both systems.

Over the first 236 days of this phase the effect of the aerobic mass fraction on low F/M filaments was investigated at 10 days sludge age by changing the aerobic mass fraction from 30% to 70% on one system and then interchanging these conditions on a number of occasions, the two systems on

Days		1-167	168-206	207-235	236-293
% Aerobic mass fraction	CFR1	60	70	30	30
	CFR2	30	30	70	70
Sludge Age (d)	CFR1	10	10	10	7,5
	CFR2	10	10	10	7,5

t phase of the investigation, in which the sludge days and the nitrate concentration in the anoxic (40 mgN/ℓ) and low values (4 mgN/ℓ), the two duced low F/M filament bulking sludges with but increasing to as high as 600 mℓ/g, caused *la* and 0092.

ns, in particular *M.parvicella* and 0092 but also able to proliferate to levels to cause bulking f 300 mℓ/g at 10 days sludge age in intermittent 30% aerobic mass fraction) single reactor xed systems.

systems, the nitrate concentration during the e low F/M filament proliferation; generally the n (> 30 but < 50 mgN/ℓ) or low (< 4 mgN/ℓ) es respectively in DSVI could be effected; ate concentration was low, low F/M filament to cause bulking problems (DSVI > 200 mℓ/g).

<u>action and sludge age</u>

on, the same two systems CFR1 and CFR2, bove were adopted. In Table 3.5 the initial ers are given. Note that at the commencement 10 days and the aerobic mass fraction 30% in

se the effect of the aerobic mass fraction on low at 10 days sludge age by changing the aerobic on one system and then interchanging these ns, the two systems on

7	168-206	207-235	236-293
	70	30	30
	30	70	70
	10	10	7,5
	10	10	7,5

ns and parameters.

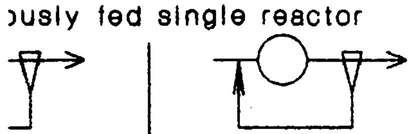
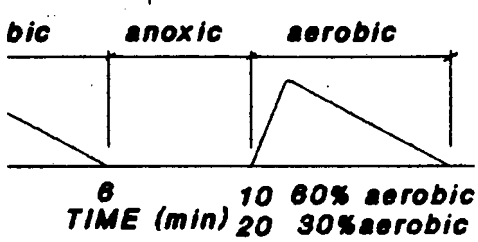
FR1	Unit CFR2
usly fed single reactor	
	
tent	Intermittent
5,6	0 - 3,4
	
aln Raw	Mitchell's Plain Raw
	5000
	10
)	500
90	40 -90
	10 7,5
	20
	7,5
	18
1	1 : 1
8,2	7,3 - 8,2

Table 3.6: Operational changes made to systems CFR1 and CFR2 during phase II of the investigation; evaluation of the effect of the magnitude of the aerobic fraction and sludge age of 7,5 days.

Day	Change	Reason
1	Started monitoring units	
56	CFR1 set at 60% aerobic by increasing peak DO from 2-2,5 to 5-6 mg/ℓ.	To investigate the effect of a of a longer aerobic period on the filaments.
78	Nitrate feed to CFR1 & CFR2 changed to 750 mgN/d.	Tubes through nitrate pump changed to larger size because small ones unavailable.
84	Aeration cycle of CFVR1 reduced from 20 to 10 minutes. Reduced peak DO from 5-6 to 2-2,5 mg/ℓ.	To reduce variability in 60% aerobic fraction.
91	Reduced nitrate feed to 500 mgN/d.	High effluent nitrates.
106	Nitrate feed to CFR1 disrupted for 24 h.	
118	Nitrate feed to CFR2 disrupted for 24 h.	
168	CFR1 set to 70% aerobic.	
207	Switched air supply tubes between CFR1 and CFR2. CFR1 now 30% and CFR2 70% aerobic.	To confirm filament reaction to longer aerobic fraction.
236	Reduced sludge age on both units to 7,5 days.	To investigate the effect of shorter sludge ages on filament proliferation.
294	Closed units down.	

The operational changes made to the systems during this second phase of the investigation are listed in Table 3.6.

In the intermittently aerated systems, the aerobic mass fraction can be increased from 30 to 70% in two ways i.e. by (1) increasing the peak dissolved oxygen (DO) concentration during the air-on period of the aeration cycle so that DO is present for a longer time period in the aeration cycle, or (2) decreasing the length of the aeration cycle while retaining the same peak DO during the air-one period. Both methods were employed in this investigation. Method (1) was initially employed to increase the aerobic mass fraction on system CFR1 from 30% to 60% (day 56 to 84). This method was chosen because with it, the number of anoxic-aerobic alternations is not increased - reducing the aeration cycle time [method (2)] increases the number of anoxic-aerobic alternations and it was speculated that such an increase might stimulate proliferation of low F/M filaments and so nullify the possible inhibiting effect of the increased aerobic mass fraction on the low F/M filaments. However in operating CFR1 during days 56 to 84, it was found difficult to maintain a 60% aerobic mass fraction with this method; the aerobic mass fraction varied considerably between 40 and 80% depending on the OUR, Fig 3.24. Such a large variation in the aerobic mass fraction made it very difficult to interpret the effect of the increased aerobic mass fraction on the low F/M filament proliferation (DSVI).

In an attempt to maintain a more constant aerobic mass fraction at 60%, it was decided to adopt method (2) i.e. to reduce the aeration cycle time while maintaining the peak DO at 2-2,5 mgO/ℓ. Accordingly on day 84, the aeration cycle of CFR1 was reduced from 20 to 10 minutes and the peak DO concentration reduced from 5-6 to 2-2,5 mgO/ℓ (Table 3.6). This method gave the desired result in that now the aerobic mass fraction was far less variable. However this method did increase the number of aerobic-anoxic alternations from 72 per day to 144 per day (i.e. 20 minute cycle time giving 3 per hour reduced to 10 minute cycle time giving 6 per hour). All further aerobic mass fraction adjustments on CFR1 and CFR2 were made by method (2) i.e. by either increasing or decreasing the aeration cycle time and maintaining the peak DO concentration during the air-on period at 2 to 2,5 mgO/ℓ so that with each of the changes in the aerobic mass fraction a change in the aerobic-anoxic alternation frequency also was made.

After establishing the trends and effects of changing the aerobic mass fraction on the proliferation of the low F/M filaments, the sludge age of the systems were both reduced from 10 days to 7,5 days (day 236) while the systems had differing aerobic mass fractions; i.e. the aerobic mass fractions of CFR1 and CFR2 were maintained at 30% and 70% respectively. The effects of this reduction in sludge age were then monitored and recorded up to and including day 293 (57 days i.e. about 7,6 sludge ages) on which day this phase of the investigation was terminated. The operational changes made to the systems during this phase of the investigation are listed in Table 3.6.

The experimental data measured daily on the two systems throughout this phase of the investigation are presented graphically in the following Figures:

Fig 3.17	Phase II	Influent and effluent COD.
Fig 3.18	Phase II	Influent and effluent TKN.
Fig 3.19	Phase II	Effluent nitrate concentration.
Fig 3.20	Phase II	Reactor MLVSS concentration.
Fig 3.21	Phase II	Reactor MLSS concentration.
Fig 3.22	Phase II	OUR per gVSS [mgO/(gVSS.h)].
Fig 3.23	Phase II	Peak DO.
Fig 3.24	Phase II	Percentage aerobic.
Fig 3.25	Phase II	Sludge settleability in DSVI and filament identification.

3.2.2.1 System behaviour – COD balance

As in phase I of the experimental investigation discussed above, in this second phase also a number of steady state periods i.e. 12 for CFR1 and 14 for CFR2 were identified in the experimental data. During these steady state periods the aerobic mass fractions were held constant and no significant operational or parameter changes were made that would affect the system performance. Results of COD balances performed (as described in Section 3.2.1.1 – COD balance) on the average experimental data over these steady state periods are given in Table 3.7 noting that, as in phase I data, a 100% N balance was accepted to determine the nitrate denitrified. As in phase I, the phase II COD balances are also on the low side with an overall average of 86,6% (CFR1 85,4% and CFR2 87,7%) and ranging between 70 and 100%. This average value compares favourably with that of phase I (87,33%) and as before no explanation for the low COD balance can be advanced.

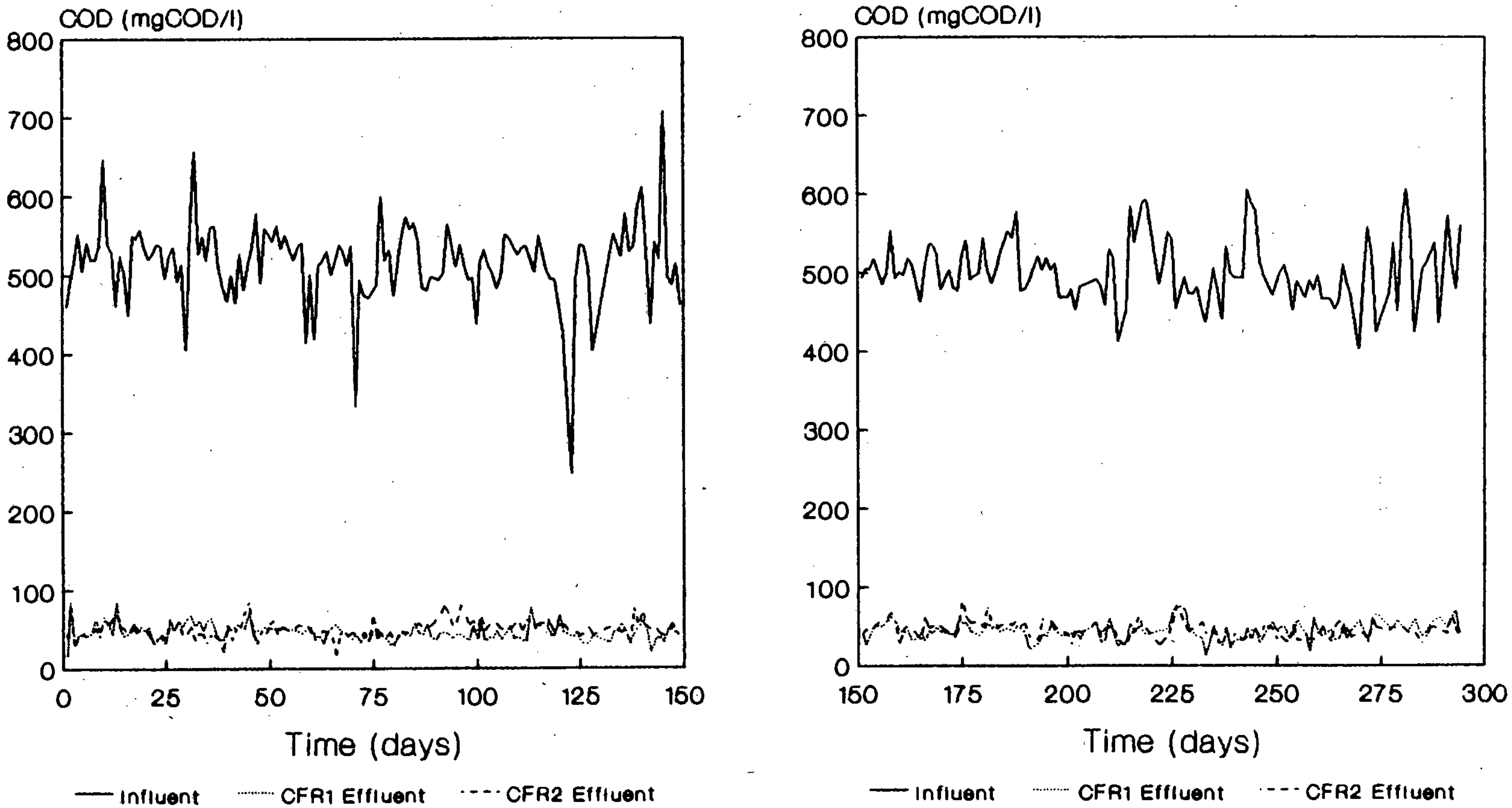
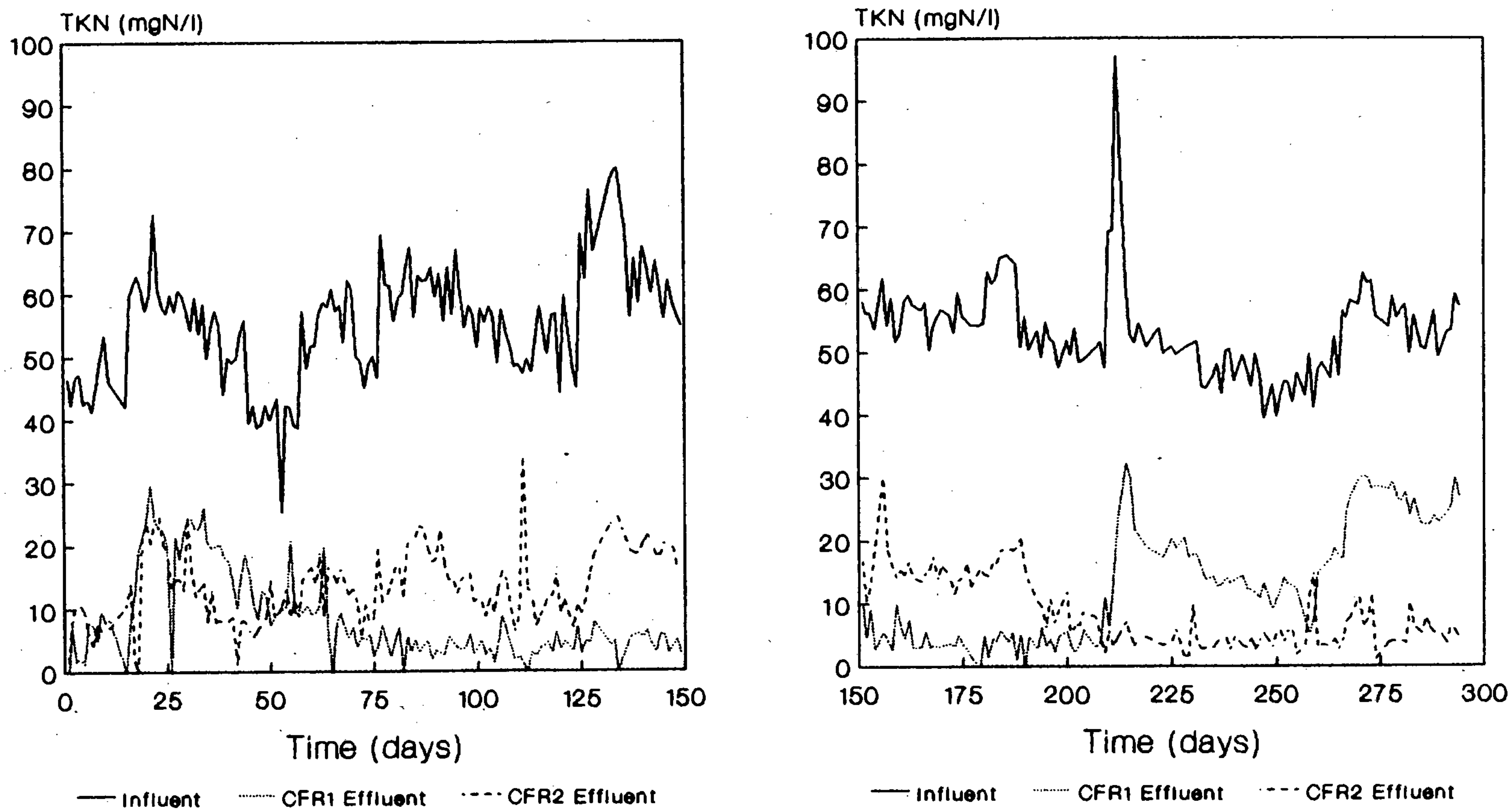


Fig 3.17 Influent and effluent COD concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.



<u>**Fig 3.18**</u> Influent and effluent TKN concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation; note high effluent TKN concentrations correspond to low % aerobic mass fractions.

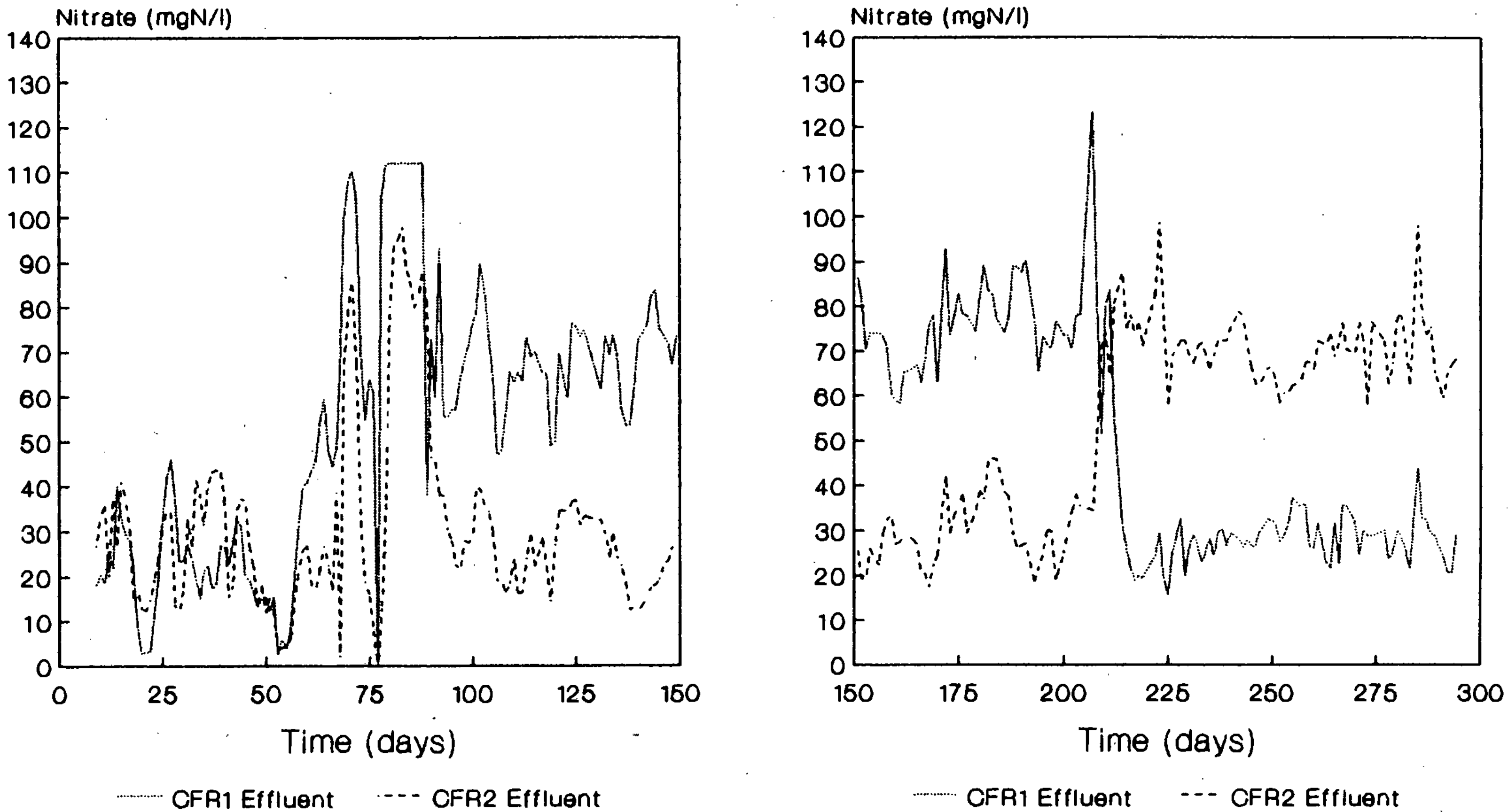


Fig 3.19 Effluent nitrate concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation; note that at high aerobic mass fractions (> 50%) the effluent nitrate concentration is high indicating reduced denitrification.

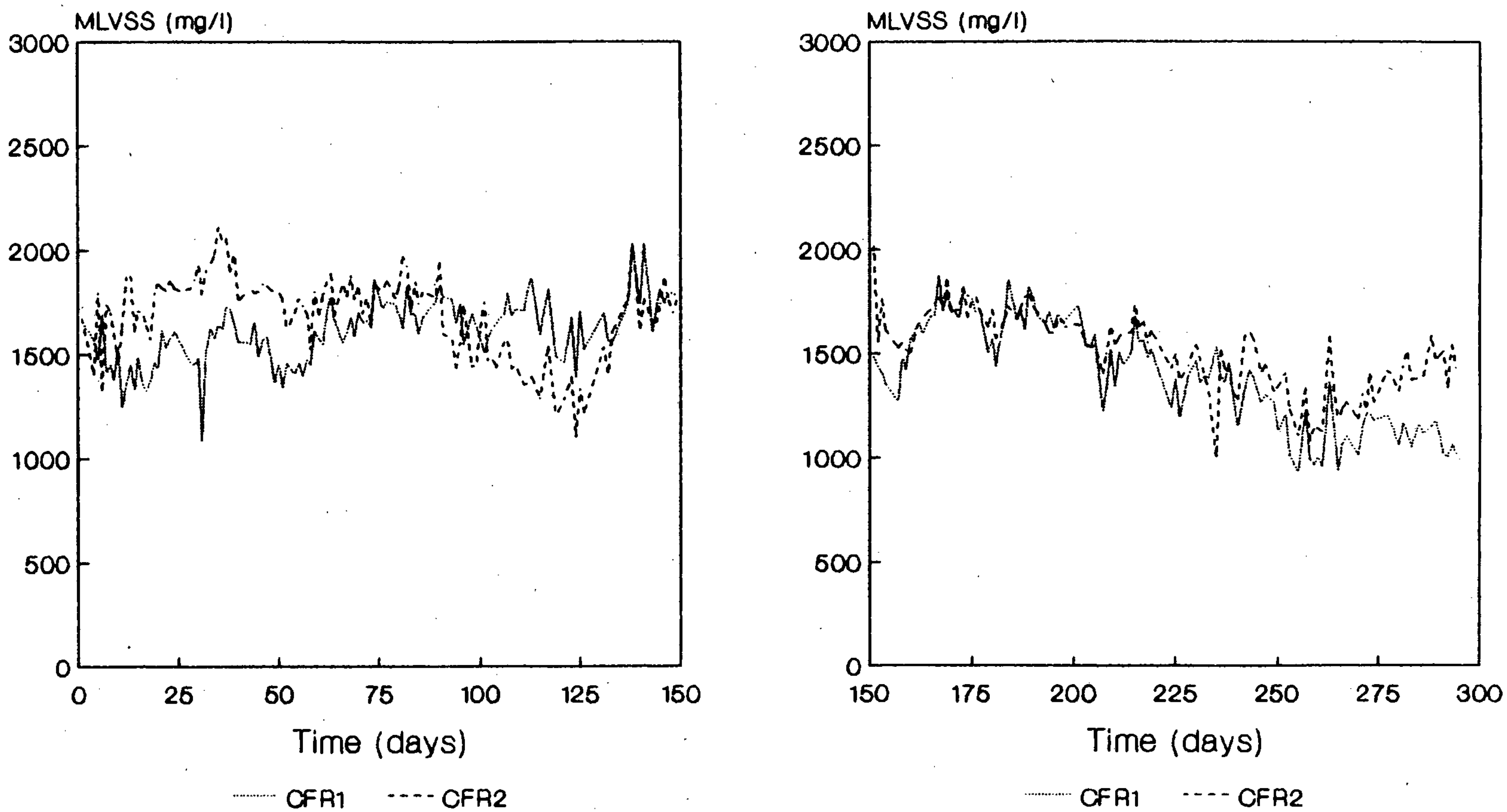


Fig 3.20 Reactor MLVSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation; the VSS is approximately 80-86% of the TSS.

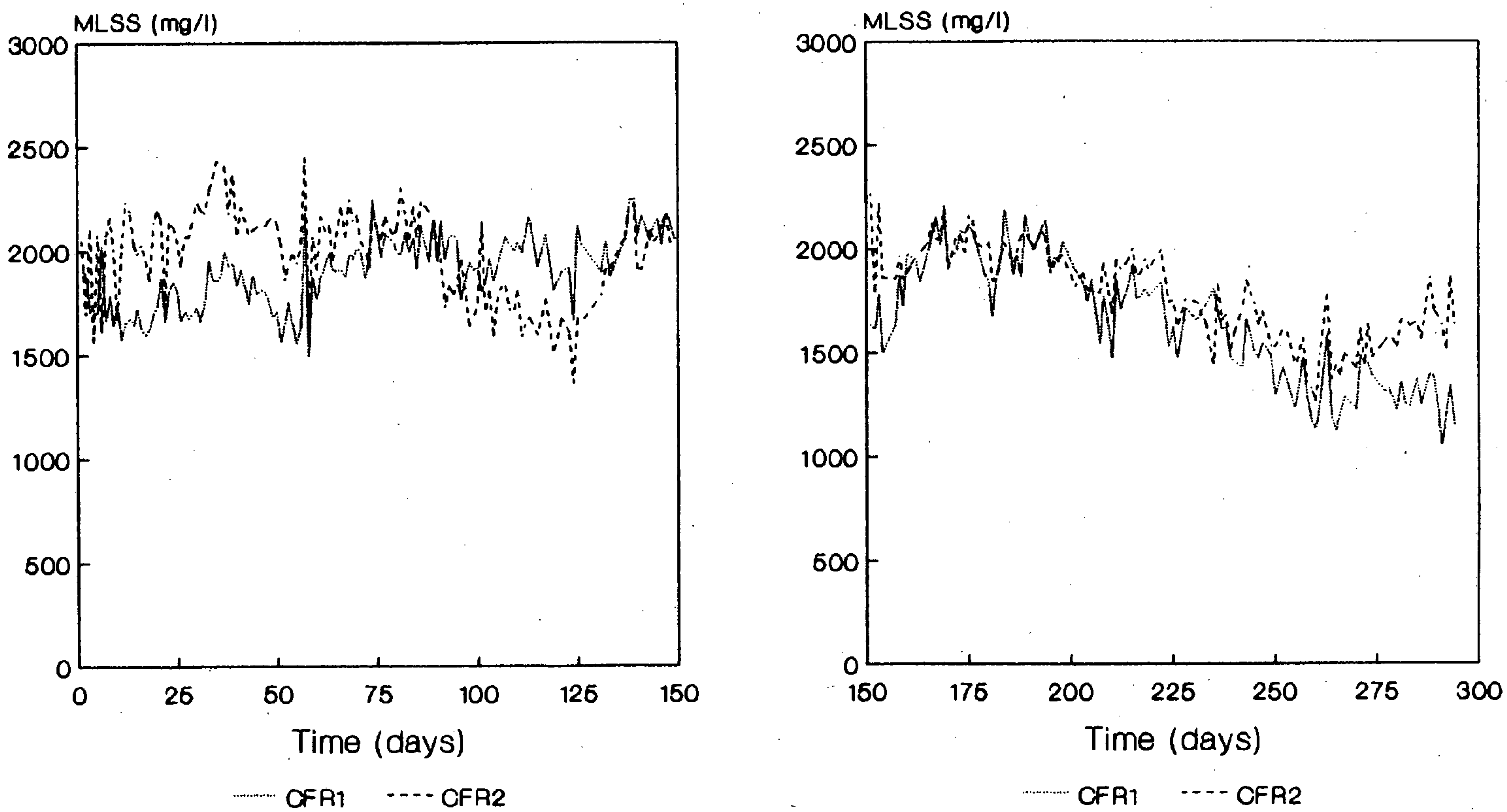
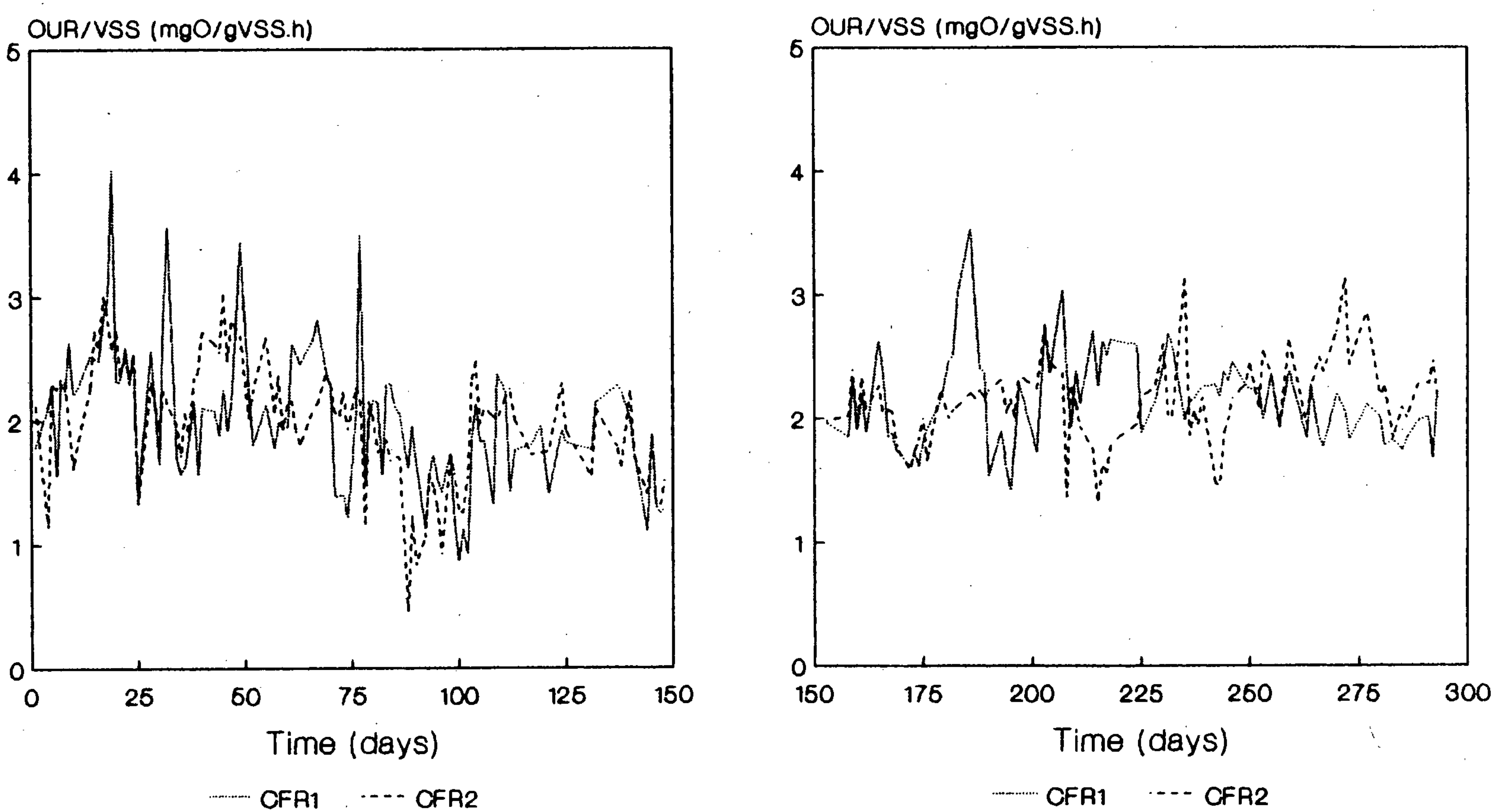


Fig 3.21 Reactor MLSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.



<u>Fig 3.22</u> Oxygen utilization rate per gVSS measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.

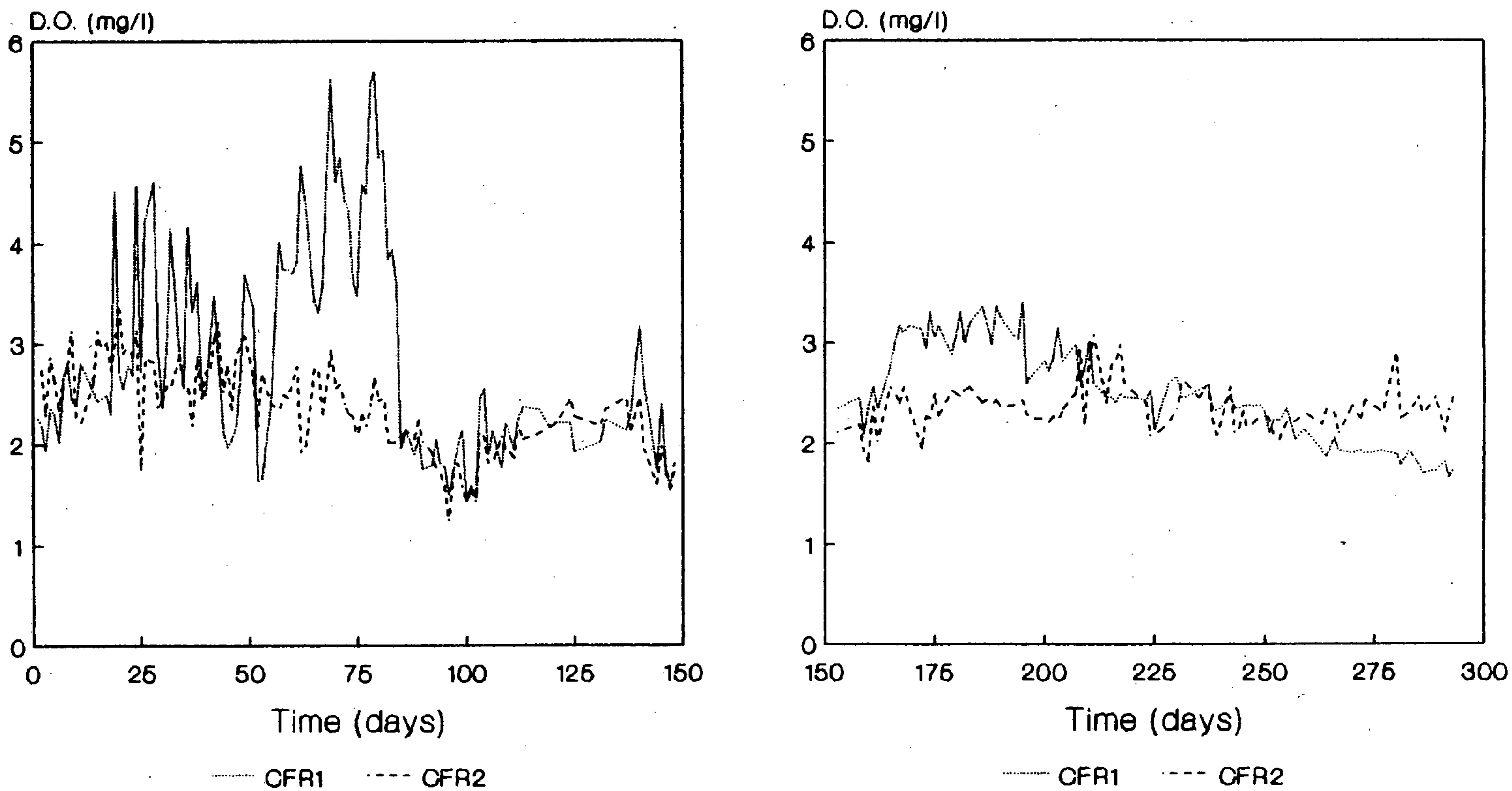


Fig 3.23 Peak dissolved oxygen (DO) concentration during the aeration cycle measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.

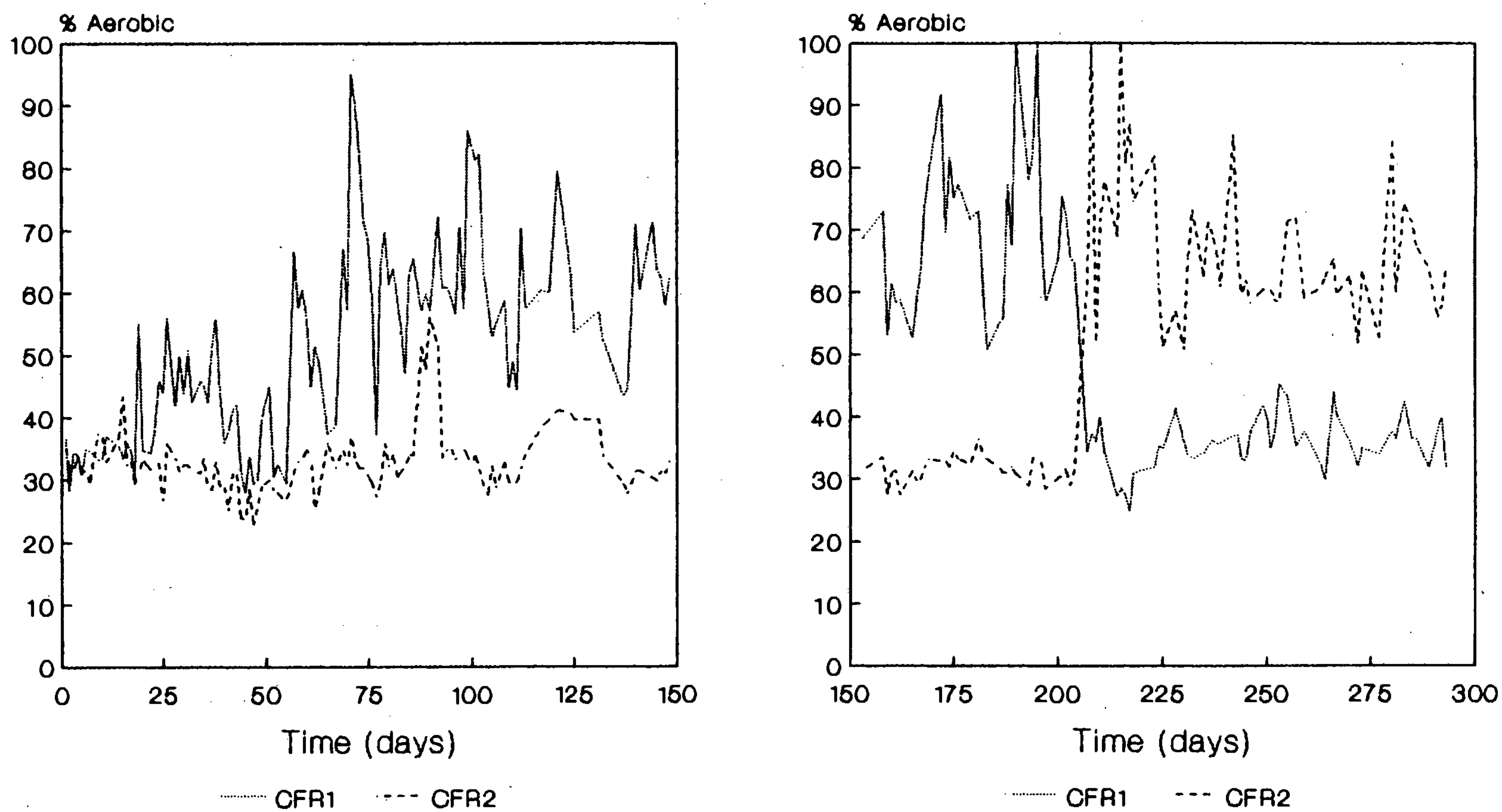
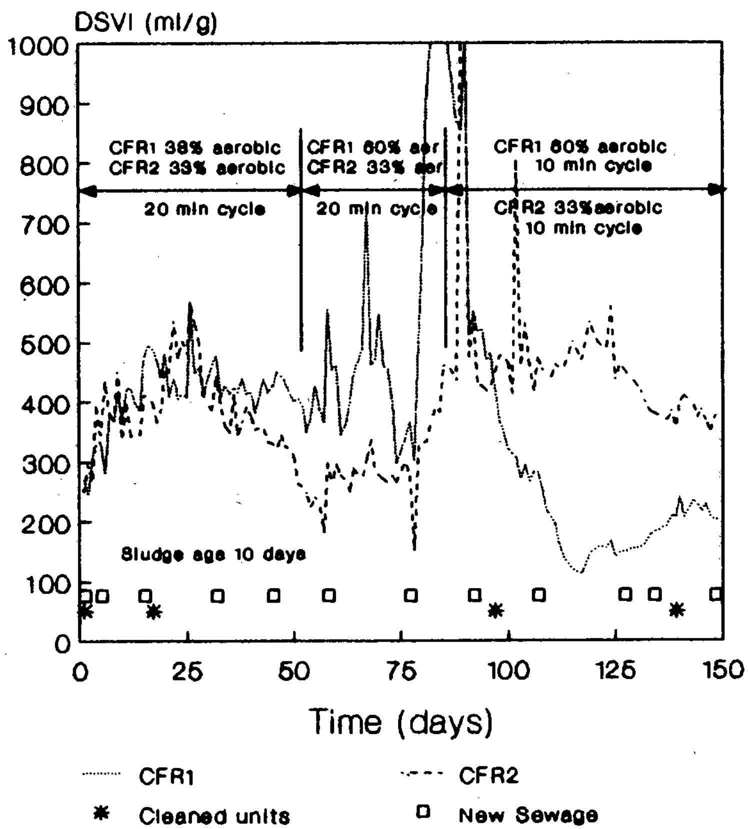


Fig 3.24 Daily measured percentage aerobic mass fraction, that is, the percentage of the intermittent aeration cycle that the dissolved oxygen concentration is > 0,,2 mg/ℓ, measured on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.



Filament Identification.

Day	Unit	Abundance	Dom	Sec	Other
1	CFR1	V.com-AB	M.parv	H.hyd	0041,0092
	CFR2	V.com	M.parv	Nocard	0041,0092 , H.hydrossis
14	CFR1	V.com-AB	M.parv	1851	0092,0041'H.hydrossis
	CFR2	V.com	M.parv	H.hyd	0092,0041,0675
37	CFR1	V.com-AB	M.parv	H.hyd	0041,0092,Flexibacter
	CFR2	Ab	M.parv	0092	0041,1701
70	CFR1	V.com-AB	M.parv	H.hyd	0041,0092,0803,Flex.
	CFR2	C-V.C	M.parv	H.hyd	0092,0803,0041
102	CFR1	V.C	M.parv	0041	H.hyd.,0092,Flexibacter
	CFR2	Ab	M.parv	H.hyd	0092,021N
132	CFR1	C-V.C	M.parv	-	Flex,021N,0041,H.hyd,ThioII
	CFR2	V.com-AB	M.parv	H.hyd.	0041,0092,021N

M.parv. - Microthrix Parvicella
H.hyd. - H.Hydrossis
Flex. - Flexibacter
ThioII - Thiothrix II

C - Common
V.C - Very common
AB - Abundant

<u>Fig 3.25a</u> Daily DSVI data for the period day 1 to day 150 for intermittent aeration systems CFR1 and CFR2 during phase II of the investigation. Also shown on this figure are the filament identifications done every 3 to 4 weeks.

3.2.2.2 System behaviour – Kinetic evaluation

In accordance with the method described in Section 3.2.1.2 in the evaluation of the phase I data, the RBCOD and PBCOD utilization rates (under anoxic and aerobic conditions), and neta values were calculated for each of the steady state periods of the phase II data and are presented in Table 3.8. On examination of Fig 3.26 [in which the PBCOD utilization rates (anoxic and aerobic) are plotted against the % aerobic] and Table 3.8, the following trends can be identified:

(1) The PBCOD utilization rates under both anoxic and aerobic conditions decrease with an increase of the aerobic fraction (Fig 3.26). this tendency is more obvious in the utilization of PBCOD under aerobic conditions. This arises because the utilization rate of PBCOD follows a saturation type kinetic expression (see Dold *et al.*, 1980) the rate of which is reduced by neta under anoxic conditions. Consequently when conditions are predominantly anoxic (low aerobic fraction) the overall (anoxic and aerobic) utilization rate of PBCOD is low (i.e. mainly at $PBCODUR_{anx}$) so that the concentration of unutilized PBCOD builds up in the mixed liquor. Under conditions of high unutilized PBCOD concentration, when the conditions are aerobic (for a short time) or anoxic (for a long time) the $PBCODUR_{aer}$ and $PBCODUR_{anx}$ rates are high.

In contrast, when the conditions are predominantly aerobic the overall rate of PBCOD utilization is high so that the concentration of unutilized PBCOD in the mixed liquor is low. Under conditions of low unutilized PBCOD concentration, when the conditions become aerobic (for a long time) or anoxic (for a short time) the $PBCODUR_{aer}$ and $PBCODUR_{anx}$ rates are low.

(2) The rate of decrease in PBCODUR when the aerobic mass fraction of the system is increased, is faster under aerobic conditions that anoxic conditions. This is evident in the neta values shown in Table 3.8. However it appears that the organisms become acclimatized to increased aerobic mass fractions after a number of sludge ages because the neta value progressively reverts from the higher to the lower value after the step change [evident in system CFR1 periods 4 (neta = 0,598) to 9 (neta = 0,266), Table 3.8].

Table 3.7: COD balance results for phase II experimental data; evaluation of effect of magnitude of aerobic mass fraction and sludge age of 7,5d.

System	Period	Day	to Day	Sludge age (d)	COD Balance (%)	% Aerobic
CFR1	1	1	22	10	89,54	35,0
	2	23	43	10	97,87	45,0
	3	44	55	10	91,38	33,1
	4	56	73	10	97,60	59,4
	5	78	95	10	80,34	61,0
	6	103	138	10	77,20	56,3
	7	139	167	10	76,47	62,5
	8	168	189	10	91,92	70,7
	9	196	204	10	93,21	67,3
	10	207	236	10	74,06	33,6
	11	237	267	7,5	79,86	37,4
	12	268	293	7,5	74,84	36,0
		weighted (by days) average			83,2	
CFR2	1	1	8	10	90,13	32,4
	2	9	15	10	93,13	37,6
	3	16	28	10	98,20	32,1
	4	29	43	10	95,64	30,6
	5	44	55	10	99,92	26,8
	6	57	86	10	95,08	32,3
	7	88	92	10	94,18	51,7
	8	93	101	10	70,89	34,1
	9	102	112	10	74,25	39,3
	10	117	131	10	74,73	39,9
	11	137	204	10	82,97	31,4
	12	207	218	10	82,71	77,6
	13	224	236	10	78,63	61,7
	14	237	293	7,5	78,63	63,9
		weighted (by days) average			84,7	
		overall weighted average			84,0	

Note: The N balance assumed to be 100%. This is a reasonable assumption because on systems (outside this investigation) where N balances could be determined usually better than 95% N balances are achieved in the laboratory. The techniques employed in this investigation were the same as those in which good N balances are achieved.

On analysis of the calculated RBCODUR values (Table 3.8) one can see that the utilization rate increases with a decrease in the sludge age of the system i.e. 7,6 and 8,3 mgCOD./(gAVSS.h) for 10 and 7,5 days sludge age respectively. This happened because the RBCOD is applied onto a decreasing active mass with a reduction in sludge age. As in phase I the RBCOD utilization rate is limited by the RBCOD loading rate and for this reason the phase II RBCOD utilization rates (7,6-8,3 mgRBCOD/[gAVSS.h]) are much lower than the RBCOD utilization rates reported by Gabb *et al.* (1989), (50-150 mgRBCOD/[gAVSS.h]) which are not limited by the RBCOD loading rate.

Inspection of the PBCOD utilization rates in Table 3.8 it can be seen that the PBCODUR rates (under aerobic and anoxic conditions) are in the same order as the RBCOD utilization rates measured by Gabb *et al.* (1988) in batch tests not limited by the RBCOD loading rate. It must be noted that the PBCODUR's in Table 3.8 include the COD utilization rate arising from endogenous respiration i.e. approximately 35 mgCOD/[gAVSS.h] under aerobic conditions and 13,3 mgCOD/[gAVSS.h] under anoxic conditions. Subtraction of 35 mgCOD/[gAVSS.h] from the calculated $PBCODUR_{aer}$ in Table 3.8 brings the rates in the approximate expected ratio with the RBCOD utilization rates not limited by the RBCOD loading rate.

Finally the reduction factor of the PBCOD hydrolysis rate under aerobic conditions for anoxic conditions, neta, ranges between 0,266 and 1,412 with an overall average of 0,457 (CFR1 0,485 and CFR2 0,428) which is reasonably close to the predicted value of Van Haandel *et al.* (1981) of 9,38. From these results in Table 3.8 it was concluded that as far as could be determined the kinetic behaviour of the two systems during this phase of the investigation was normal and not contrary to expectation from the kinetic behaviour as it is understood from the general kinetic model.

3.2.2.3 System performance – COD removal

High removals of COD were obtained throughout this phase of the investigation. Generally a 90% removal was achieved with an influent COD of around 500-550 mg/ℓ being reduced to less than 60 mg/ℓ (see Fig 3.17). this level of performance was maintained even when the sludge age of the systems was reduced from 10 days to 7,5 days (day 236).

Table 3.8: COD utilization rates for phase II experimental data; evaluation of effect of magnitude of aerobic mass fraction and sludge age of 7,5d.

Period	%Aerobic mass fraction	[1]RBCODUR	[1]PBCODUR anoxic	[1]PBCODUR aerobic	neta	Sludge age (d)
CFR1						
1	35,0	7,6	58,1	138,1	0,420	10
2	45,0	7,6	60,9	123,9	0,429	10
3	33,1	7,6	48,7	152,0	0,320	10
4	59,4	7,6	55,4	92,7	0,598	10
5	61,0	7,6	44,7	56,8	0,786	10
6	56,3	7,6	36,3	55,4	0,654	10
7	62,5	7,6	33,8	49,9	0,677	10
8	70,7	7,6	24,4	66,9	0,365	10
9	67,3	7,6	19,4	72,9	0,266	10
10	33,6	7,6	31,0	95,9	0,323	10
11	37,4	8,3	40,6	104,2	0,390	7,5
12	36,0	8,3	[2]34,9	88,1	0,396	7,5
CFR2						
1	32,4	7,6	51,9	149,8	0,346	10
2	37,6	7,6	50,2	131,6	0,382	10
3	32,1	7,6	61,1	179,5	0,341	10
4	30,6	7,6	52,9	179,5	0,295	10
5	26,8	7,6	47,9	220,5	0,217	10
6	32,3	7,6	59,1	165,1	0,358	10
7	51,7	7,6	73,8	81,7	0,903	10
8	34,1	7,6	46,3	68,1	0,680	10
9	30,3	7,6	38,6	103,2	0,383	10
10	39,9	7,6	56,7	76,3	0,743	10
11	31,4	7,6	44,5	123,1	0,361	10
12	77,6	7,6	67,7	48,0	1,412	10
13	61,7	7,6	21,2	54,4	0,389	10
14	63,9	8,3	21,2	64,3	0,329	7,5

Note: At first sight it may seem strange that the PBCODUR under aerobic and anoxic conditions is higher than the RBCODUR rates quoted in the text [50 to 150 mgRBCOD/(gAVSS.h)]. This is because the PBCODUR rates in the Table include the OUR for endogenous respiration, which is equivalent to 35 mgCODS/(gAVSS), so that the actual PBCODUR rates are 35 mgCOD/(gAVSS.h) lower than the rates quoted in the Table above. However, the PBCODUR rates are not adjusted for endogenous respiration because in the general activated sludge model, a death regeneration approach is employed requiring neta to be calculated on unadjusted PBCODUR rates (see Dold *et al.*, 1980, Van Haandel *et al.*, 1981, Dold and Marais, 1986).

1 Units of RBCOD and PBCOD utilization rates are mgCOD/(gAVSS.h).

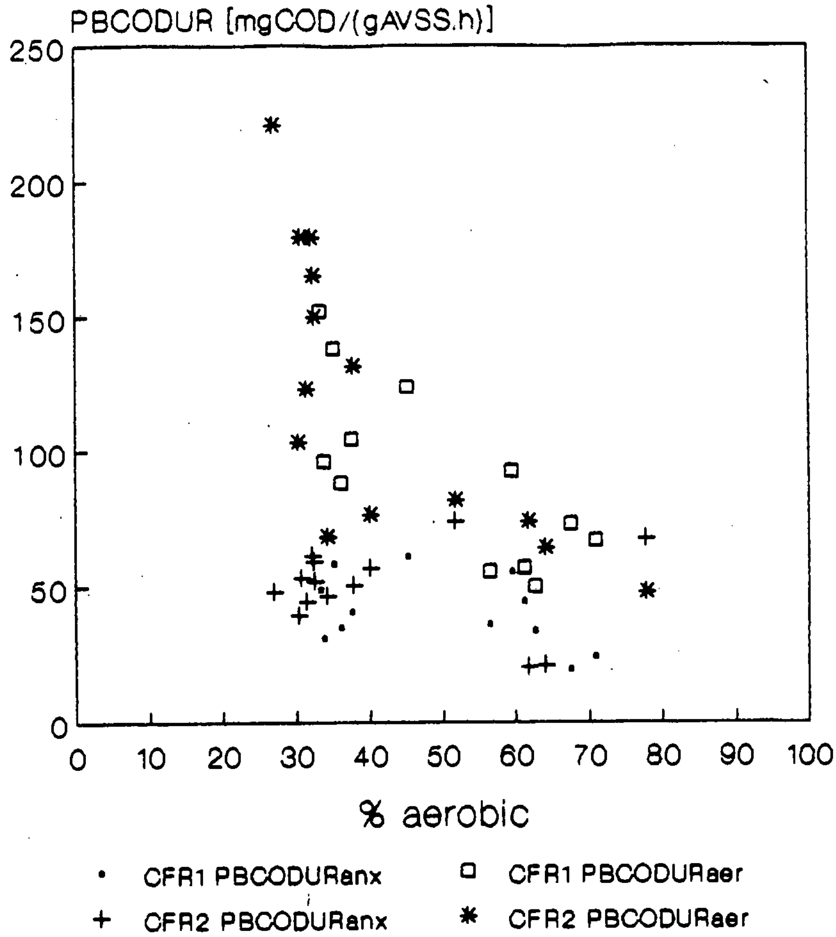


Fig 3.26 PBCOD utilization rates (aerobic and anoxic) plotted against the % aerobic mass fraction calculated from the average data of the steady state periods identified for the intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.

3.2.2.4 System performance – Nitrification

Nitrifiers, being obligate aerobic, can only grow in the aerobic zones of a process, and therefore only during the aerobic period of an intermittently aerated single reactor system. As is evident in Fig 3.27 where nitrate generated by nitrification is plotted against %aerobic, the nitrate generated by nitrification is increased by increasing the aerobic mass fraction of the system. Complete nitrification was achieved at 10 and 7,5 day sludge ages when the aerobic mass fraction exceeded 60% (Fig 3.18 i.e. effluent TKN less than 4 mgN/ℓ) but not when the aerobic mass fraction was around 33% (effluent TKN greater than 4-10 mgN/ℓ).

An estimate of the maximum specific growth rate of the nitrifiers μ_{nmT} can be made for the incomplete nitrification conditions with the aid of the following equation (WRC, 1984):

$$\mu_{nmT} = [(K_n + N_{ae})(b_n + 1/R_s)] / [(1-f_{xt})N_{ae}] \quad (/d)$$

where

K_n = half saturation constant [mg(NH_3-N)/ℓ]
N_{ae} = concentration of ammonia surrounding the organisms [mg(NH_3-N)/ℓ]
b_n = specific endogenous mass loss rate for *Nitrosomonas* (/d)
f_{xt} = unaerated mass fraction
R_s = sludge age

Substituting (1) the estimated effluent ammonia concentration (from the measured effluent TKN concentration minus 4 mgN/ℓ organic nitrogen which was the effluent concentration when nitrification was complete in the 70% aerobic systems), (2) the system sludge age, (3) the anoxic mass fraction (f_{anx}) and (4) the values of the nitrifier kinetic constants at the system temperature 20°C viz. K_n = 1,0 mgN/ℓ, b_n = 0,04/d allows calculation of μ_{nm} at 20°C.

The average specific growth rate calculated using the phase II steady state data where the nitrification was incomplete was 0,44/d (CFR1 0,43/d and CFR2 0,45/d) which compares very favourably with the recommended value for design of 0,45/d (WRC, 1984).

3.2.2.5 System performance – Denitrification

In Fig 3.28, where nitrate denitrified is plotted against %aerobic, it can be seen that denitrification can be increased by increasing the anoxic fraction of the

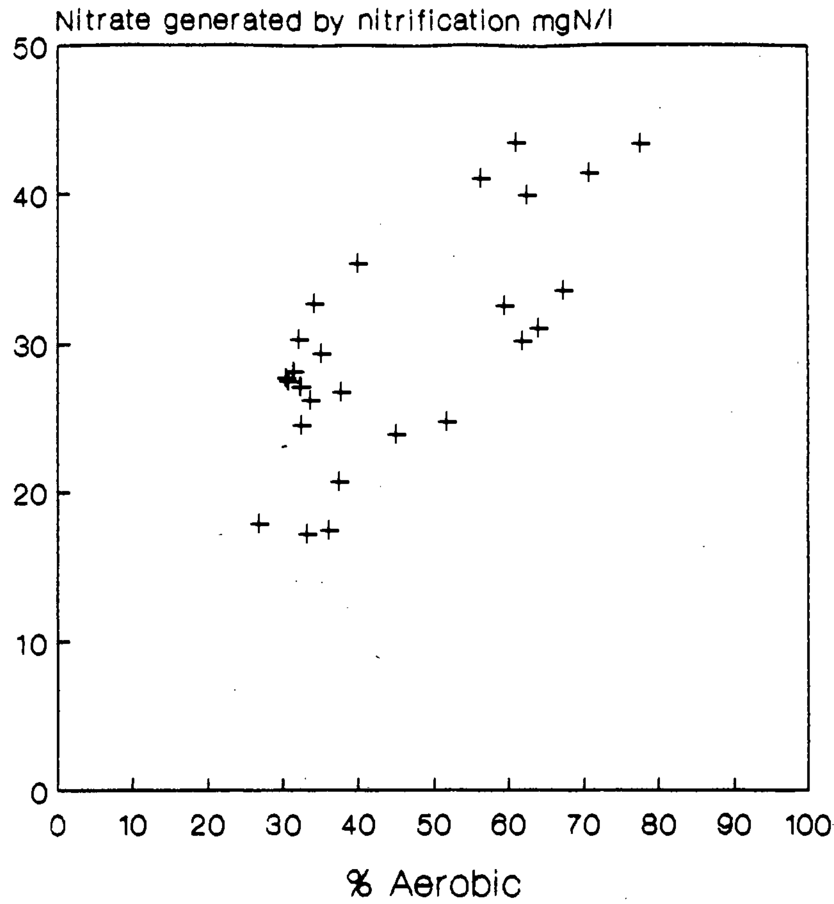


Fig 3.27 Mass nitrate generated per day by nitrification versus the % aerobic mass fraction calculated from the average data of the steady state periods identified for the intermittent aeration systems CFR1 and CFR2 during phase II experimentation. Note that nitrification improves with an increase in the % aerobic mass fraction.

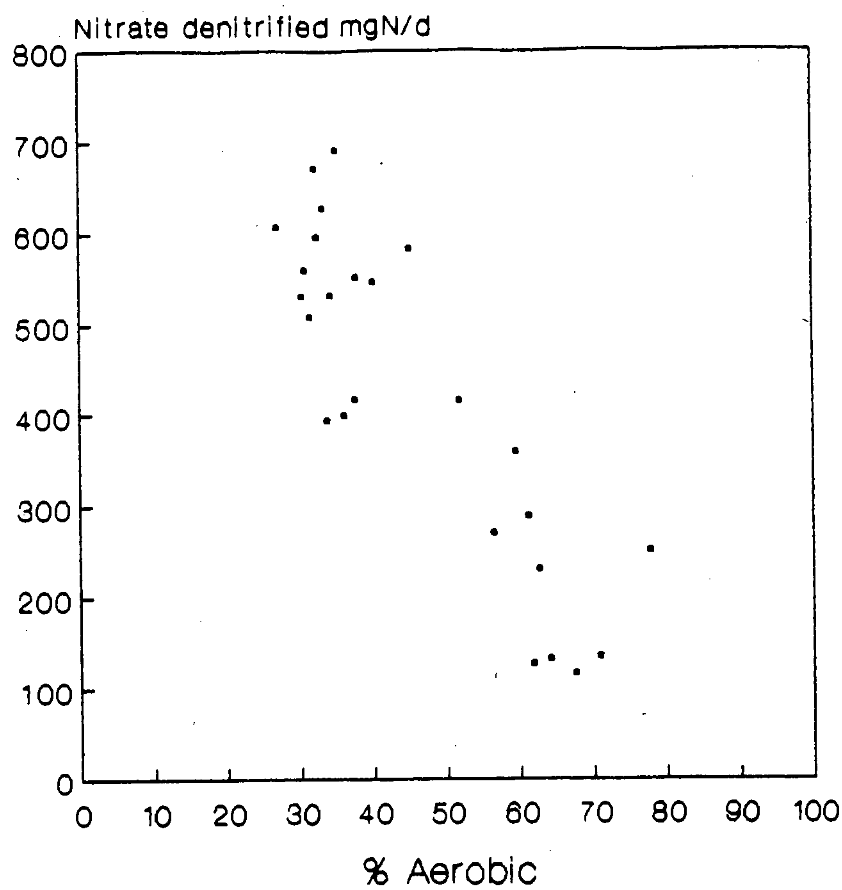


Fig 3.28 Mass nitrate denitrified per day plotted against the % aerobic mass fraction calculated from the average data of the steady state periods identified for the intermittent aeration systems CFR1 and CFR2 during phase II of the investigation; note that as % aerobic mass fraction decreases so denitrification increases.

system. However if the anoxic mass fraction of the system is too large the denitrification will be limited by insufficient nitrate being generated by nitrification during the aerobic period. However because nitrate was dosed into both systems throughout this phase of the investigation, denitrification was never nitrate limited i.e. the effluent nitrate concentrations in both systems was always greater than 4 mgN/ℓ throughout the investigation (Fig 3.19). From Fig 3.28 it can be seen that at 33% and 67% aerobic the systems denitrified 550-650 mgN/d and 100-200 mgN/d respectively which is equivalent to 55-65 mgN/ℓ and 10-20 mgN/ℓ respectively.

Taking account of (1) the TKN in the effluent (~ 4 mgN/ℓ at complete nitrification), (2) the N required for sludge production (~ 20 mgN/ℓ at 10 days sludge age) and (3) 4 mgN/ℓ nitrate in the effluent which the system does not denitrify due to effluent leaving the system during the aerobic period, the concentration of nitrate denitrified would have been generated from influent TKN concentrations of 88 and 44 mgN/ℓ at 33% and 67% aerobic respectively. At an average influent COD concentration of 500 mg/ℓ, the systems with 33% and 67% aerobic (which) have achieved the biological denitrification potentials of 60 and 15 mgN/ℓ at TKN/COD ratios of 0,18 and 0,09 respectively. An evaluation of the denitrification achieved in the systems in the entire investigation is given in Section 3.4.

3.2.2.6 System behaviour – Low F/M filament bulking

Generally from the above evaluation of the experimental data measured on systems CFR1 and CFR2, it is evident that kinetically, the two systems performed as expected in terms of the established kinetic understanding and model of nitrification and denitrification systems. Because the kinetic performance of the two systems was as expected from previous experience, the bulking behaviour of the systems cannot be attributed to an unusual kinetic behaviour.

Throughout this second phase of the investigation when the systems CFR1 and CFR2 were operated with aerobic mass fractions around 30%, low F/M filaments proliferated causing excessive sludge bulking (DSVI > 200 mℓ/g); and when the systems were operated with high aerobic mass fractions (>70%) low F/M filaments did grow but not sufficiently to cause bulking in the activated sludge.

Effect of aerobic mass fraction on low F/M filaments

Over the first two and a half sludge ages, during which the two systems were operated with a 35% aerobic mass fraction, the DSVI in both systems was similar and increased from 300 mℓ/g to 500 mℓ/g (Fig 3.25). Then from day 25 to 56 the DSVI in CFR1 decreased to 400 mℓ/g while that in CFR2 decreased to 300 mℓ/g. In both systems the bulking was caused mainly by *M.parvicella* and *H.hydrossis* but 0092 and 0041 also were present in the mixed liquor. In order to check the effect of the aerobic mass fraction, this parameter needed to be increased on one of the two systems. This was done in two ways viz. by (1) increasing the peak DO or (2) shortening the aeration cycle time. Initially method (1) was adopted for the following reasons:

(a) the number of aerobic-anoxic alternations would remain the same in both systems,

(b) reducing the aeration cycle time increases the number of anoxic-aerobic alternations; it was speculated that this increase might stimulate the proliferation of low F/M filaments and thus nullify the possible inhibiting effect of the increased aerobic fraction.

Accordingly on day 56 the aerobic mass fraction of CFR1 was increased by means of method (1) by increasing the peak DO during the air-on cycle from 2-2,5 to 5-6 mgO/ℓ. System CFR1 was selected because it had the highest DSVI of the two systems; the increase in the aerobic mass fraction was expected to decrease the DSVI and ameliorate the bulking. However, by day 84, after 28 days, (nearly 3 sludge ages) of operation, contrary to expectation, the DSVI was not significantly reduced, fluctuating considerably above 300 mℓ/g (Fig 3.25).

Examination of the results indicated that possibly the DSVI did not decline because of the difficulty of controlling the aerobic mass fraction at 60% (Fig 3.24). The aerobic mass fraction varied considerably between 40% and 80% depending on the OUR. It was speculated that establishing the 60% aerobic mass fraction by reducing the aeration cycle time rather than by increasing the peak DO possibly may lead to a more stable aerobic mass fraction. However, it was realized that the increased number of aerobic-anoxic alternations this would cause, possibly would nullify the suppressing effect of the aerobic fraction on the low F/M filaments. Nevertheless on day 84, the peak DO was reset to 2 to 2,5 mgO/ℓ and the aeration cycle time reduced from 20 to 10 minutes. This change produced the desired result in that the aerobic mass fraction was now less variable. Furthermore the DSVI progressively declined (over 30 days) from over 500 mℓ/g to 120 mℓ/g on day 115. Between days 115 and 207, 9 sludge ages, the DSVI varied between 150 mℓ/g and 300 mℓ/g with dominant filaments *M.parvicella* and *H.hydrossis* and secondary filaments 0092, 0041 and 1851. Over the same period, in the 30% aerobic mass fraction system, CFR2, the DSVI ranged between 400 and 500 mℓ/g caused by the same filament types.

To confirm the effect of the aerobic mass fraction on the low F/M filament proliferation, on day 207 the aerobic mass fraction was interchanged between the two systems. CFR2 was increased from 33 to 70% and CFR1 was decreased from 60 to 30% aerobic mass fraction. This was achieved by interchanging the air supply lines between the two systems. Over the following three sludge ages (to day 236) the DSVI decreased from 400 to 120 mℓ/g in the 70% aerobic mass fraction system, CFR2, and increased from 200 to 350 mℓ/g in the 30% aerobic mass fraction system, CFR1. These results indicate that *aerobic mass fraction has a significant effect on the proliferation of the low F/M filament bulking, and hence the DSVI.* Figure 3.29 which shows DSVI and %aerobic versus time, clearly shows that the higher the aerobic mass fraction the lower the DSVI. This is confirmed in Fig 3.30 which shows DSVI versus %aerobic. It is interesting to note that the suppression influence of the larger aerobic mass fraction was evident even though the sludge was exposed to a greater number (doubled from 72 to 144/d) of aerobic-anoxic alternations.

Effect of sludge age on low F/M filaments

Having established a positive ameliorating influence on low F/M filament bulking at high (70%) aerobic mass fractions, the influence of sludge age less than 10 days was investigated on the two systems. With both systems still operated under the previous conditions i.e. both at 10 days sludge age and with a peak DO of 2-2,5 mgO/ℓ but CFR1 33% aerobic mass fraction with a 20 minute aeration cycle and CFR2 70% aerobic mass fraction with a 10 minute aeration cycle, on day 236 the sludge age of both systems was reduced to 7,5 days. The dominant low F/M filament in both systems was *M.parvicella* (Fig 3.25) and the abundance of filaments was common to very common in CFR1 and common in CFR2 (Jenkins *et al.*, 1984). Secondary and other low F/M filaments identified in CFR1 were 021N, 0803 and 0041 and other low F/M filaments in CFR2 were *H.hydrossis* and 0092.

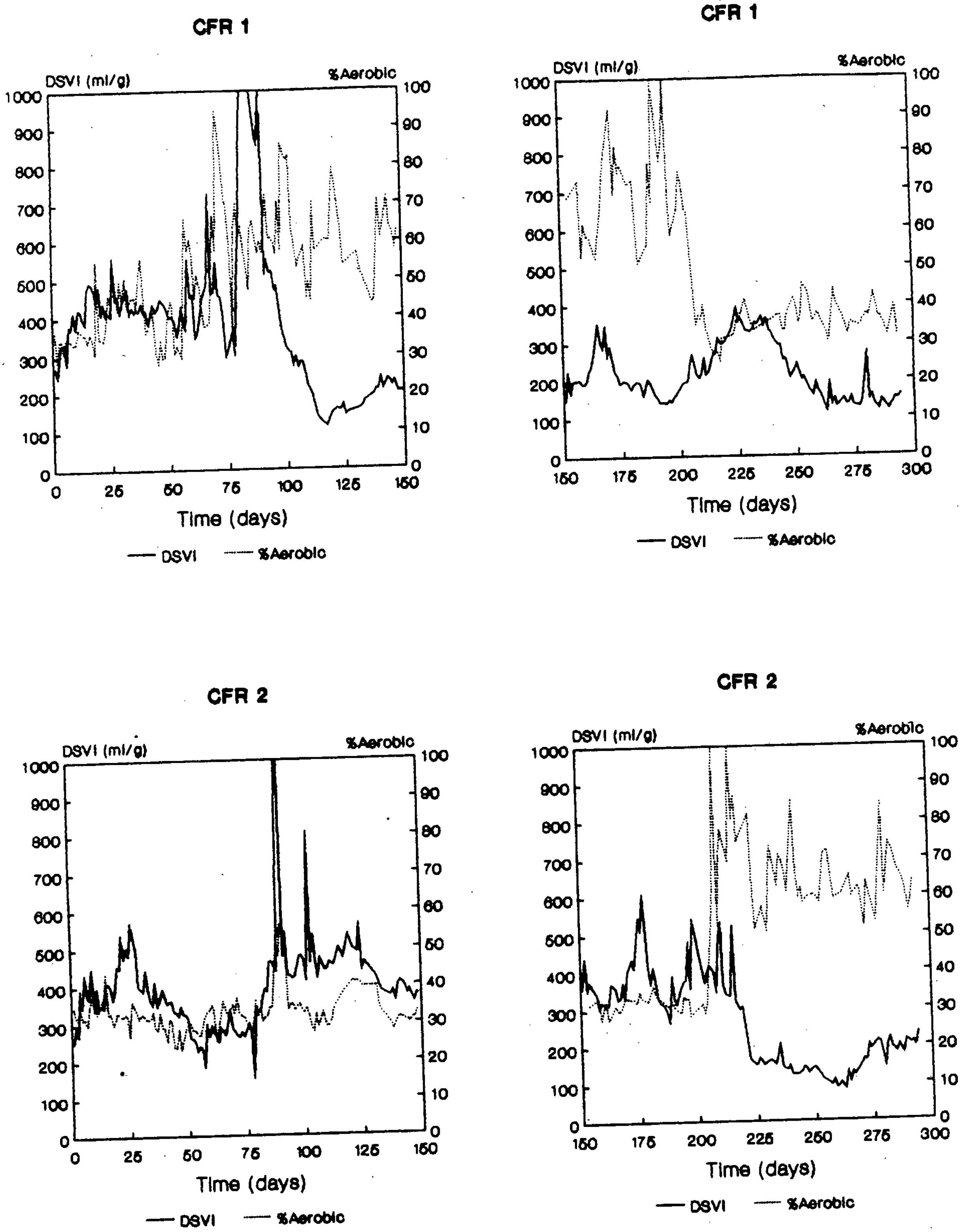


Fig 3.29 DSVI and % aerobic mass fractions measured daily on intermittent aeration systems CFR1 and CFR2 during phase II of the investigation.

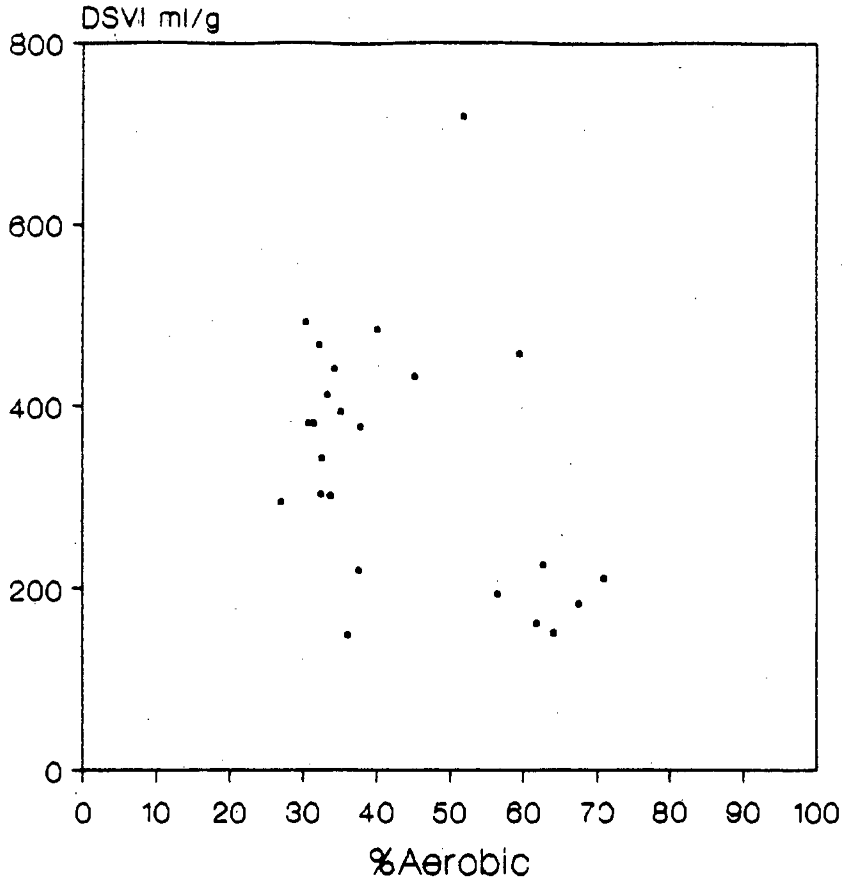


Fig 3.30 DSVI plotted against average % aerobic mass fraction for the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during phase II experimentation; note the DSVI tends to decrease with an increase in the aerobic mass fraction.

However, this ameliorating effect at short sludge age appears relatively weak because in one system (CFR2) the DSVI increased from 120 mℓ/g to 200 mℓ/g. The effect of short sludge age is investigated further in phase III of the investigations.

3.2.3 Phase III: Sludge age less than 10 days

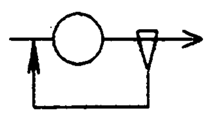
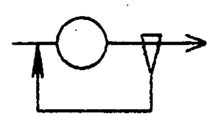
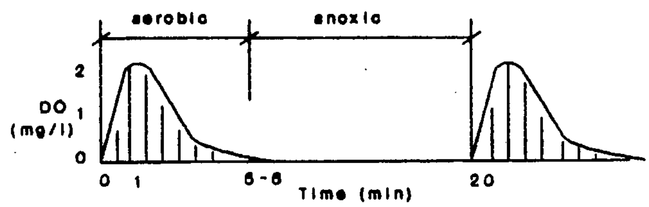
Having established that the low F/M filaments are able to proliferate at 10 days sludge age, it was decided to investigate at which sludge age the low F/M filaments would no longer proliferate to the extent of causing bulking problems. In the latter part of phase II of the investigation, it was found that the low F/M filaments possibly could not proliferate to cause excessive bulking at short sludge ages i.e. at sludge ages below 10 days. In this third phase of the investigation the effects of reducing the sludge age to below 10 days was investigated.

The same two systems CFRl and CFR2 operated in phases I and II and described earlier (see Table 3.1), were started up and operated. Both were intermittently aerated and had an aerobic mass fraction of 30% with a peak DO of 2-2,5 mgO/ℓ in a 20 minute aeration cycle (air on for 1 minute off for 19 minutes) and initially the sludge age was set at 10 days.. To ensure that nitrate never became limiting should nitrification cease by the reduction in sludge age, nitrate was drip fed into both reactors at an equivalent rate of 50 mgN/ℓ influent. The initial operating conditions and parameters for the two systems in this phase of the investigation are set out in Table 3.9.

Intensive monitoring of the systems started on day 1, three sludge ages after the start up. The systems were operated for 120 days during which time the sludge ages between 10 and 5 days were established in the systems. During this period, the systems were intensively monitored by daily measuring parameters such as influent and effluent COD and TKN concentrations, effluent nitrate concentration, reactor MLVSS and MLSS concentrations, the peak DO concentration and oxygen utilization rate (OUR) during the aerobic period, the aerobic fraction, the sludge settleability in DSVI and filament identification. The results of these experimental measurements are presented in the following Figures:

- Fig 3.31 Phase III Influent and effluent COD.
- Fig 3.32 Phase III Influent and effluent TKN.
- Fig 3.33 Phase III Effluent nitrate concentration.

TABLE 3.9 PHASE III INITIAL DESIGN AND OPERATING CONDITIONS.

System	Unit CFR1	Unit CFR2
Operating conditions	continuously fed single reactor	
Graphical representation		
Aeration	Intermittent	Intermittent
DO Concentration (mg/l)	0 - 2,5	0 - 2,5
DO Profile		
Sewage source	Mitchell's Plain Raw	Mitchell's Plain Raw
Mass of COD fed/d (mgCOD/d)	5000	5000
Volume of feed (l/d)	10	10
Concentration (mgCOD/l)	500	500
Influent TKN (mgN/l)	40 - 60	40 - 60
Sludge age (d)	10	10
Temperature (deg C)	20	20
Volume of reactor (l)	7,5	7,5
Hydraulic retention time (h)	18	18
Underflow recycle ratio	1 : 1	1 : 1
pH of mixed liquor	7,3 - 8,2	7,3 - 8,2

Over the 120 day period sludge ages of 10, 8, 7,5, 6 and 5 days were established in the two systems. This was done either progressively by increasing only the sludge wastage rate and letting the MLVSS slowly decrease to the new sludge age or suddenly by changing not only the sludge wastage rate but also wasting a predetermined volume of mixed liquor from the reactor so that the MLVSS concentration conformed also to that estimated for the new sludge age. The changes made to the two experimental systems are outlined in Table 3.10. The behaviour of the two systems is discussed below first before presenting the data regarding the sludge settleability and filament identification.

3.2.3.1 System behaviour – COD mass balance

During this third phase of the investigation, 9 (5 in CFR1 and 4 in CFR2) steady state periods were identified on the basis of sludge age. These periods are shown in Fig 3.31. Following the method and procedures described in Section 3.2.1.1 for the COD balance, an average COD mass balance of 70,7% (CFR1 74,0% and CFR2 67,4%) for the 9 periods was obtained for all of the phase III steady state data; the results of the COD mass balances are shown in Table 3.11 and are plotted versus sludge age in Fig 3.40. Also plotted in Fig 3.40 are the COD mass balances obtained in the earlier two phases of the investigation. From Fig 3.40 it can be seen that the COD mass balances obtained for the phase III steady state data are the poorest (phase I 87,3%, phase II 86,6% and phase III 70,7%) and that generally better COD mass balances are achieved at longer sludge ages (20 days) than at shorter sludge ages (5 days).

A possible reason for the poor COD mass balances at short sludge ages is that short sludge age systems are more sensitive to perturbations than long sludge age systems. Analysis of the experimental data in Figs 3.31 – 3.38 show this to be so in that the process variables such as MLVSS, OUR, % Aerobic and effluent TKN, show considerable day to day variation. Inadvertent or uncontrollable variations in the operating conditions and parameters (i.e. influent COD concentration,

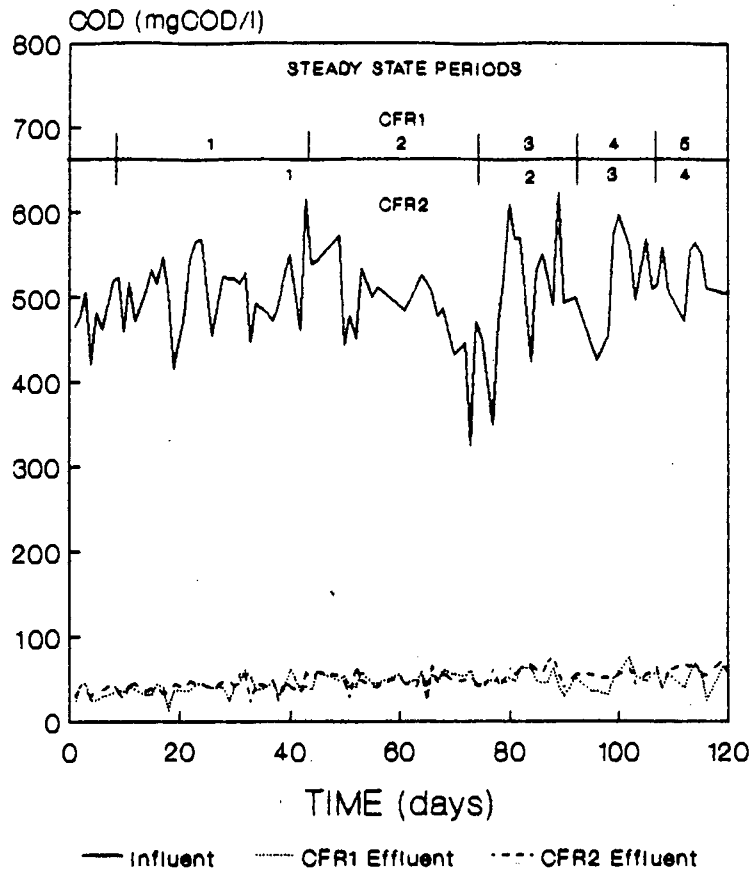


Fig 3.31 Influent and effluent COD concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

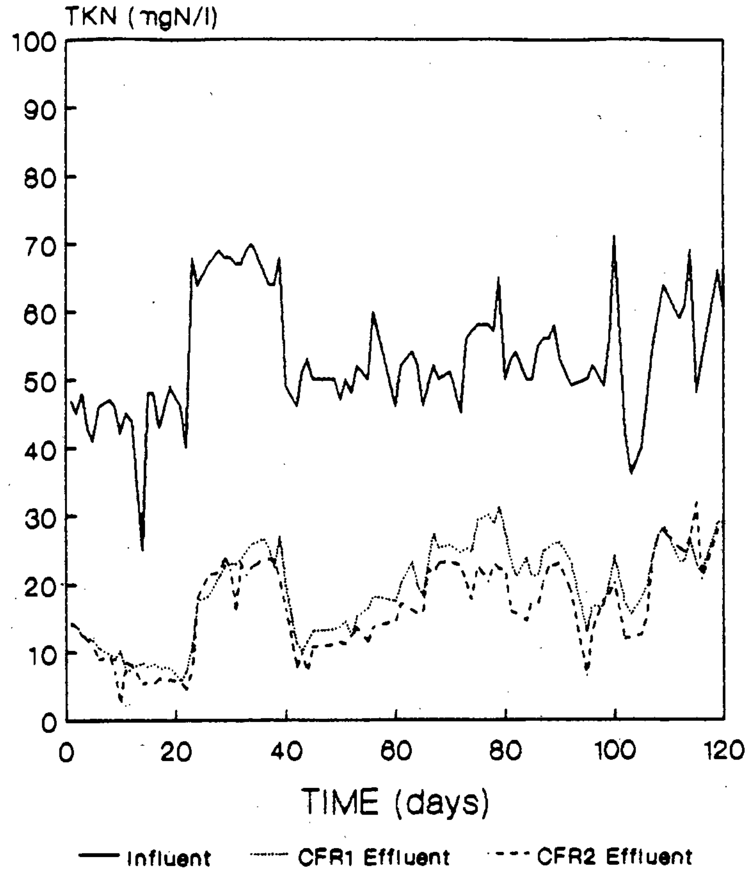


Fig 3.32 Influent and effluent TKN concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

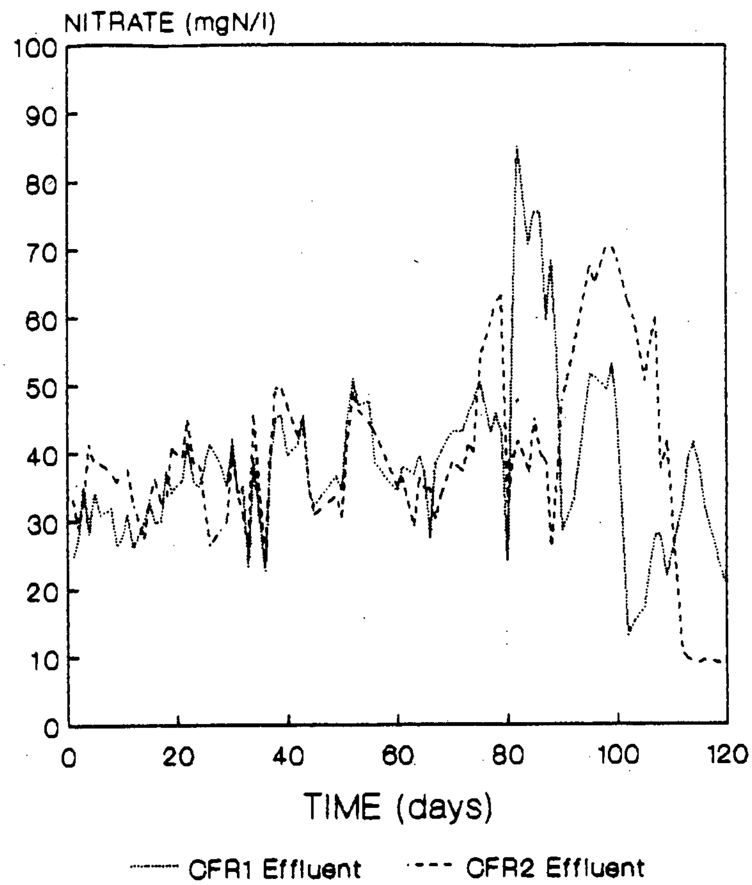


Fig 3.33 Effluent nitrate concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation; note that when there was no nitrate supplementation the effluent nitrate values reduced to around 4 mgN/ℓ indicating complete denitrification of the available nitrate and possibly a nitrate deficiency.

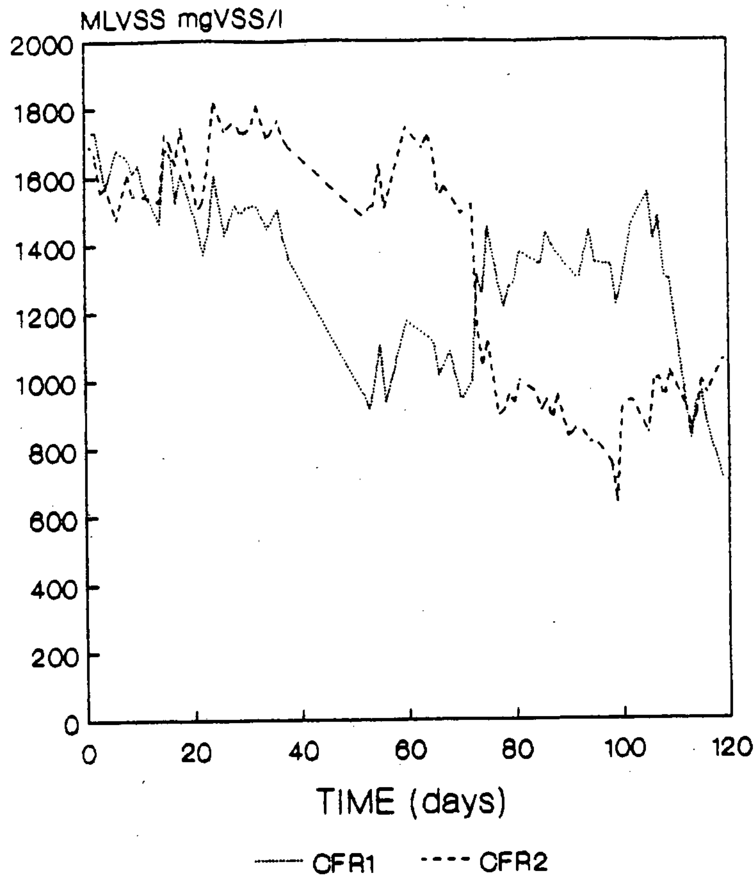


Fig 3.34 Reactor MLVSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation; the VSS is approximately 80-86% of the TSS.

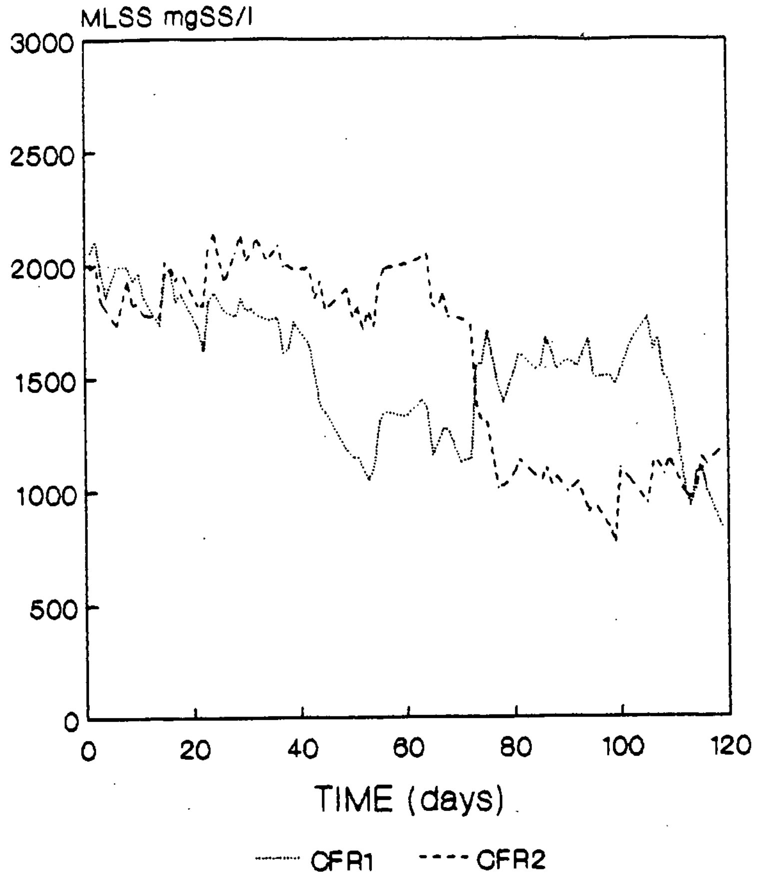


Fig 3.35 Reactor MLSS concentration data measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

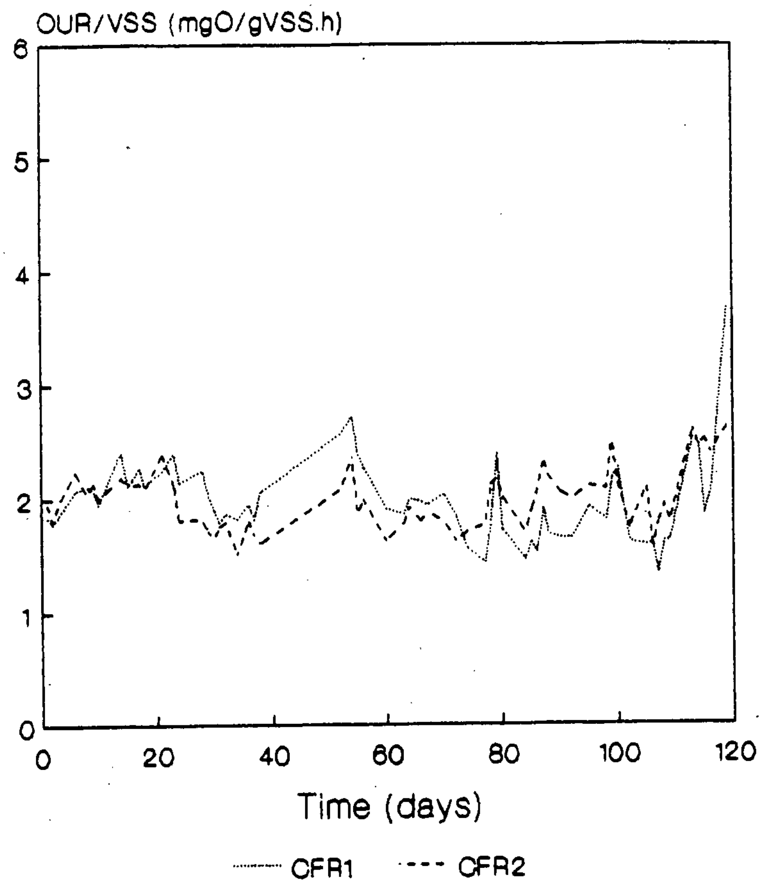


Fig 3.36 Oxygen utilization rate per gVSS measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

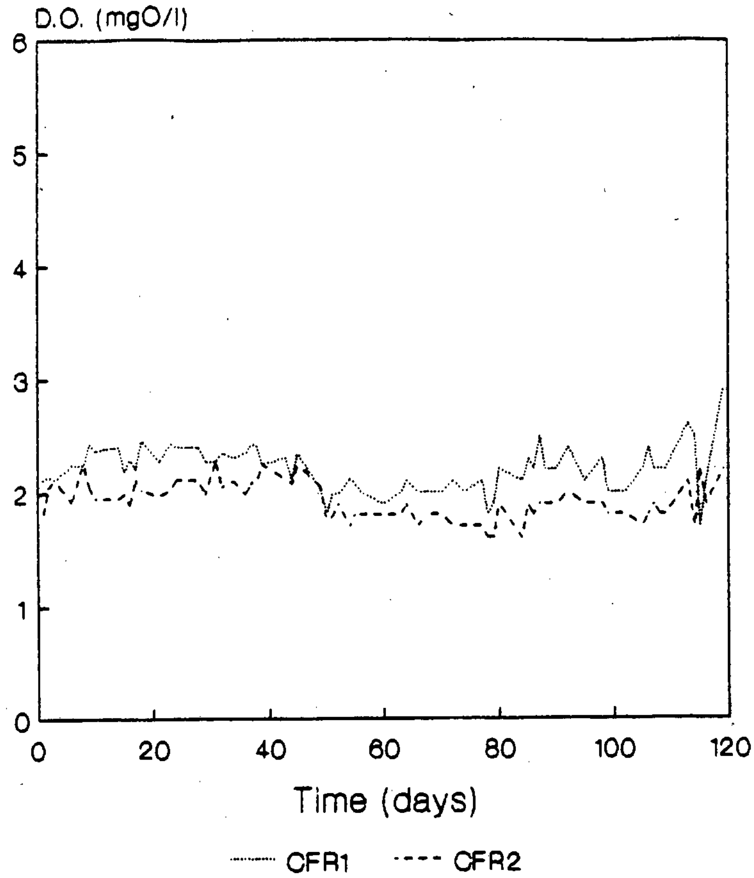


Fig 3.37 Peak dissolved oxygen (DO) concentration during the aeration cycle measured daily on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

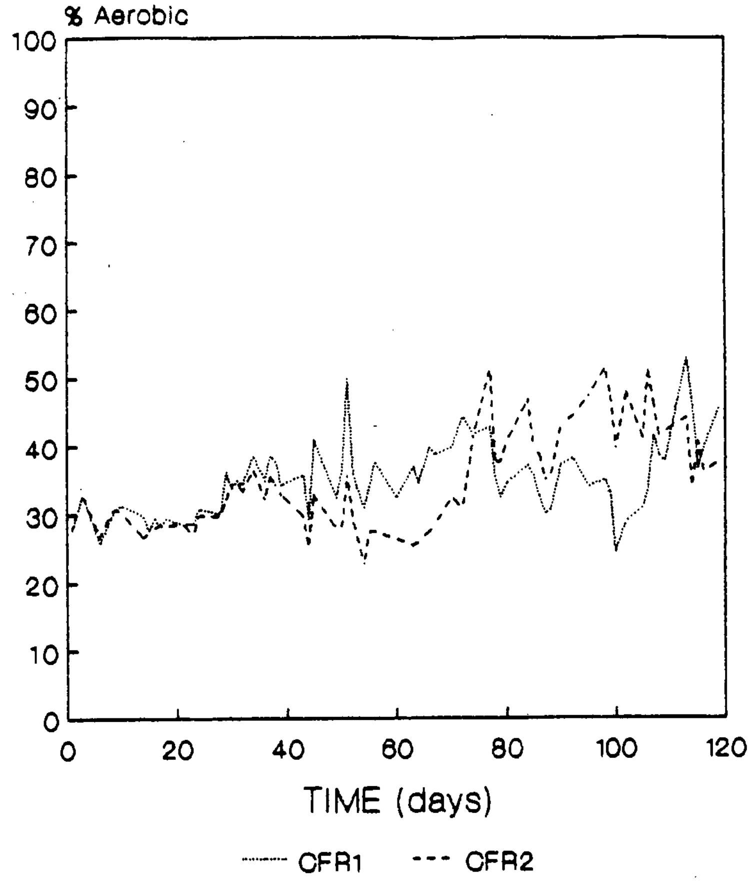
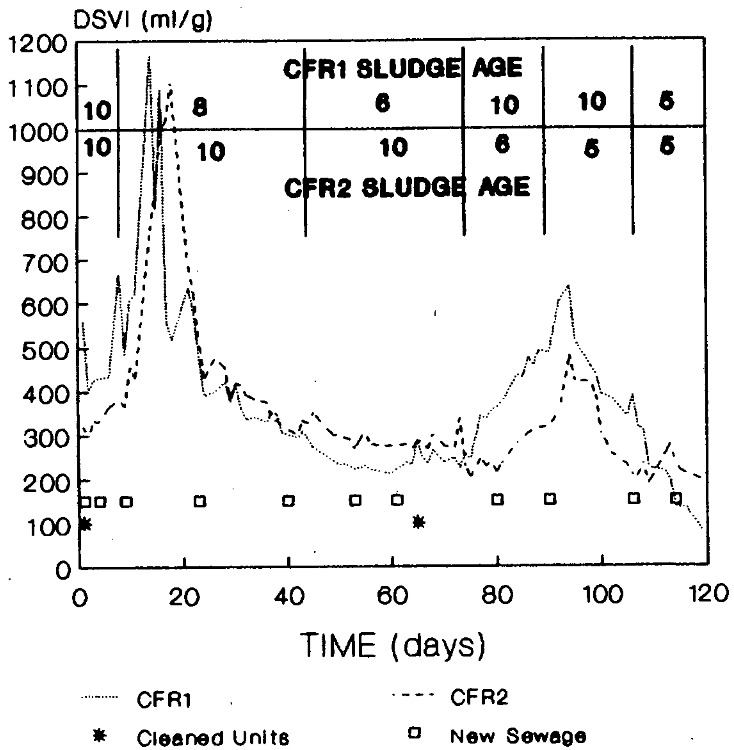


Fig 3.38 Daily measured percentage aerobic mass fraction, that is, the percentage of the intermittent aeration cycle that the dissolved oxygen concentration is > 0,,2 mg/ℓ, measured on intermittent aeration systems CFR1 and CFR2 during phase III of the investigation.

DSVI



Filament Identification.

Day	Unit	Abundance	Dom	Sec	Other
8	CFR1	AB-Exc.	M.parv	0092 H.hyd	021N 0041
	CFR2	AB-Exc	M.parv	0092	H.hyd 0041
35	CFR1	C-V.com	M.parv	0092	H.hyd,0041 021N
	CFR2	AB	M.parv	0092	0041
73	CFR1	AB-Exc	H.hyd	021N	0041,0092 1851
	CFR2	AB	H.hyd	0041 0092	021N
100	CFR1	V.com	H.hyd	021N 0092	0041
	CFR2	AB	H.hyd	0092	0041,021N
120	CFR1	V.com	H.hyd	0092	M.parv
	CFR2	V.com-AB	H.hyd	0041	M.parv 0092,021N

M.parv - Microthrix Parvicella
H.hyd - H.Hydrossis

C - Common
V.com - Very common.
AB - Abundant
Exc - Excessive

<u>Fig 3.39</u> Daily DSVI data for the period day 1 to day 150 for intermittent aeration systems CFR1 and CFR2 during phase III of the investigation. Also shown on this figure are the filament identifications done every 3 to 4 weeks.

Table 3.10: Operational changes made to systems CFR1 and CFR2 during phase III of the investigation; evaluation of the effect of sludge age shorter than 10 days.

Day	Description of change	Reason for change
1	Started monitoring units 20/2/90	
8	Changed CFR1 sludge age to 8 days by increasing sludge wastage.	To investigate the effect of a shorter sludge age on the low F/M filaments.
43	Reduced CFR1 sludge age to 6 days from 8 days.	Little change in the DSVI at 8 day sludge age to that of 10 day sludge age.
74	Increased CFR1 sludge age to 10 days and decreased CFR2 sludge to 6 days and MLSS to 1100 mg/ℓ by wasting an extra 1,8 ℓ.	CFR1 sludge still bulking. Investigate shock reduction in sludge age.
92	Reduced CFR2 sludge age from 6 days to 5 days.	CFR2 still bulking excessively. DSVI > 300 mℓ/g.
93	24 suspension of nitrate feed.	Operator illness.
100	No mixing in CFR1.	Stirrer gearbox seized.
106	Reduced CFR1 sludge age to 5 days from 10 days. Allowed MLSS to decrease through normal sludge wastage only.	To investigate effect of slow reduction in MLSS.
109	Stopped nitrate feed to CFR2.	Note effect of lower nitrate concentration.
120	Terminated experiment.	

Table 3.11: COD mass balance results for phase III experimental data: evaluation of effect of sludge age shorter than 10 days.

System	Period	Day to Day		Sludge age (d)	COD Balance (%)
CFR1	1	1	9	10	83,56
	2	8	43	8	77,65
	3	44	74	6	76,08
	4	75	106	10	55,86
	5	107	120	5	76,85
CFR2	1	1	74	10	73,57
	2	75	92	6	66,68
	3	93	109	5	61,23
	4	110	120	5	68,11

Note: The N balance assumed to be 100%. This is a reasonable assumption because on systems (outside this investigation) where N balances could be determined usually better than 95% N balances are achieved in the laboratory. The techniques employed in this investigation were the same as those in which good N balances are achieved.

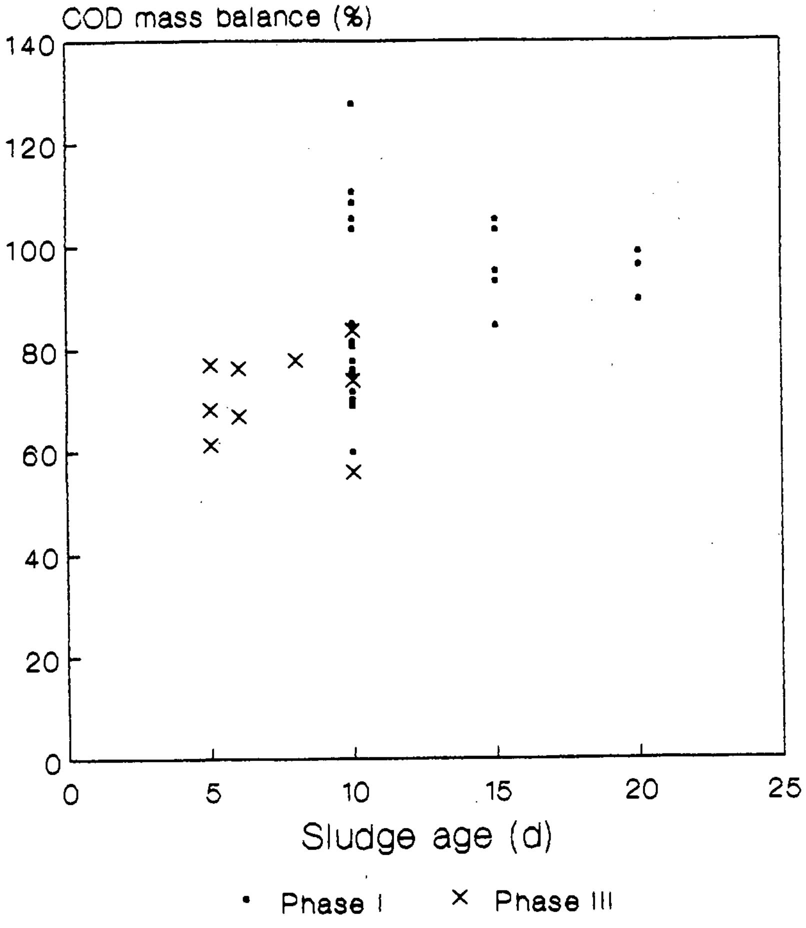


Fig 3.40 Percentage COD mass balances plotted against sludge age calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during all three phases of the investigation; note that the COD balance generally improves with increasing sludge age.

sludge wastage volume, MLSS and MLVSS concentrations etc.) appear to have a more marked effect on systems operating at short sludge ages compared to systems operating at long sludge ages. Because of these daily variations in the operating conditions and parameters (i.e. OUR, peak DO, influent COD concentration, TKN, etc.), steady state conditions are difficult to achieve in the short sludge age systems possibly resulting in low COD mass balances.

3.2.3.2 System behaviour – Kinetic evaluation of results

With the aid of the method described earlier in Section 3.2.1.2 (kinetic evaluation of phase I data) the RBCOD and PBCOD utilization rates and neta values were calculated for each of the 9 steady state periods identified above. The calculated values are shown in Table 3.12.

Inspection of Table 3.12 shows that as before the RBCOD utilization rates under anoxic ($RBCODUR_{anx}$) and aerobic ($RBCODUR_{aer}$) conditions are limited by and equal to the RBCOD loading rates i.e. the RBCOD utilization rates shown in Table 3.12 (7,6-9,8 mgCOD/[gAVSS.h]) are much lower than the RBCOD utilization rates published by Gabb *et al.*, 1988 (50-150 mgCOD/[gAVSS.h]). This is because in the continuously fed systems, the RBCOD utilization rate is limited by the RBCOD loading rate, whereas the RBCOD utilization rates of Gabb *et al.*, 1988 were measured in batch tests where such limitation is absent.

The PBCOD utilization rates as active VSS specific rates i.e. mgPBCOD/(gAVSS.h) under anoxic ($PBCODUR_{anx}$) and aerobic ($PBCODUR_{aer}$) conditions generally decrease with a decrease in the sludge age of the systems; this trend is evident in Fig 3.41 which shows the calculated specific PBCOD utilization rates under anoxic and aerobic conditions and active mass concentration versus sludge age for both the phase III data (i.e. 5-10 day sludge age) and phase I data (10-20 days sludge age). These phase III and I data together clearly show a decrease in the aerobic and anoxic PBCODUR with a decrease in the sludge age. Comparing the PBCODUR (both aerobic and anoxic) with the active organism concentration (X_a) in the reactor, at first sight it may be thought the PBCODUR decreases with sludge age because X_a decreases with sludge age. However, this is not so because the PBCODUR rates are given as active organism specific rates, i.e. mgPBCOD/(gAVSS.h). Therefore any decrease in the PBCODUR as a result of a decrease in X_a is already taken account of in the calculation of the PBCODUR. If the only effect causing a reduction in the

<u>Table 3.12</u>: COD utilization rates for phase III experimental data; evaluation of effect of sludge ages shorter than 10 days.

Period	Sludge age d	[1]RBCODUR	[1]PBCODUR anoxic	[1]PBCODUR aerobic	neta
CFR1					
1	10	7,6	37,8	143,5	0,264
2	8	8,1	40,0	100,4	0,399
3	6	9,0	28,9	81,9	0,355
4	10	7,6	11,6	42,8	0,272
5	5	9,8	42,3	77,0	0,549
CFR2					
1	10	7,6	31,6	98,9	0,319
2	6	9,0	14,0	52,2	0,268
3	5	9,8	10,6	23,8	0,445
4	5	9,8	[2] 0,9	42,5	[2]0,020

Note: At first sight it may seem strange that the PBCODUR under aerobic and anoxic conditions is higher than the RBCODUR rates quoted in the text [50 to 150 mgRBCOD/(gAVSS.h)]. This is because the PBCODUR rates in the Table include the OUR for endogenous respiration, which is equivalent to 35 mgCODS/(gAVSS), so that the actual PBCODUR rates are 35 mgCOD/(gAVSS.h) lower than the rates quoted in the Table above. However, the PBCODUR rates are not adjusted for endogenous respiration because in the general activated sludge model, a death regeneration approach is employed requiring neta to be calculated on unadjusted PBCODUR rates (see Dold *et al.*, 1980, Van Haandel *et al.*, 1981, Dold and Marais, 1986).

1 Units of RBCOD and PBCOD utilization rates are mgCOD/(gAVSS.h).
2 Nitrate deficiency during anoxic period (see Section 3.2.1.5 Denitrification, above).

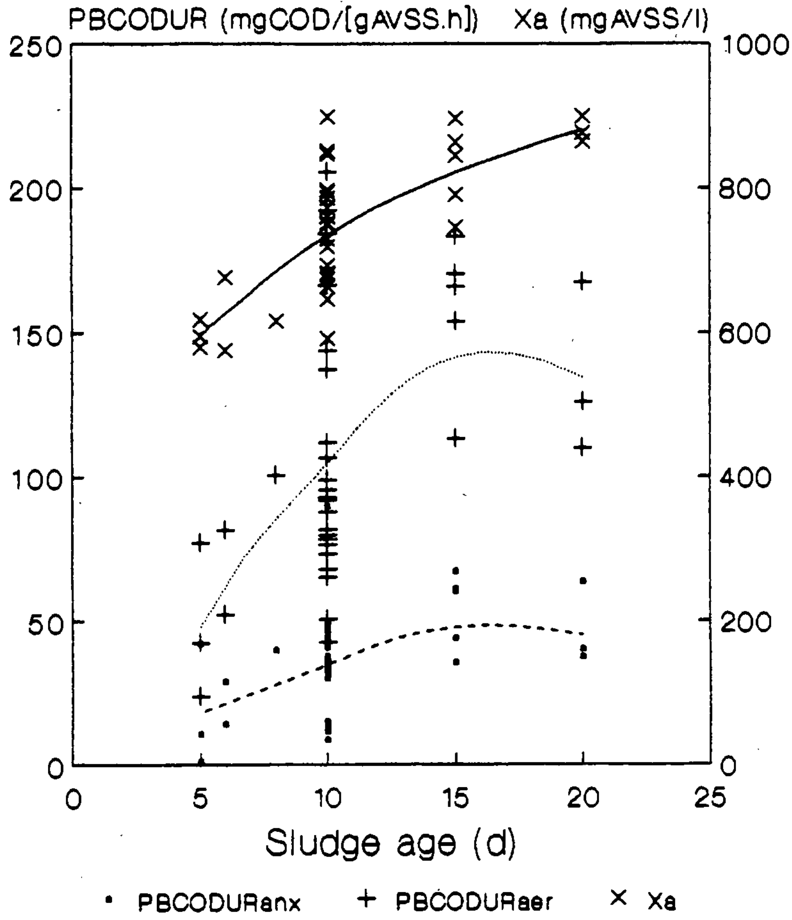


Fig 3.41 PBCOD utilization rates plotted against sludge age calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during for phase I and III of the investigation; note that the PBCOD utilization rate is lower at the shorter sludge ages than at longer sludge ages.

PBCODUR was the reduction in X_a as the sludge age decreases then the aerobic and anoxic active mass specific PBCODUR rates would be constant with sludge age, as was found to be approximately the case with the PBCODUR's for sludge ages longer than 10 days (Phase I data) (see Fig 3.41) and the K_2 and K_3 denitrification rates for sludge ages > 10 days (Van Haandel *et al.*, 1981). Because the PBCODUR, given as active mass specific rate, decreases significantly with a decrease in the sludge age when the sludge age is less than 10 days, there must be another factor that causes this decrease.

It is hypothesized that the net hydrolysis rate decreases as the sludge age decreases. As the sludge age decreases, so the solids retention time decreases. At short sludge ages, and large anoxic mass fractions (remembering that the PBCODUR under anoxic conditions is reduced to 40% of the aerobic value) the PBCOD utilization becomes restricted in that there is now not sufficient time to utilize all the PBCOD enmeshed in the sludge. Aspects of this phenomenon have already been discussed on the phase I data in Section 3.2.1.2 above. If this is the case, then at a fixed sludge age, as the anoxic mass fraction increases so more and more unutilized PBCOD remains in the sludge and is wasted in the waste stream. This unutilized PBCOD increases the VSS concentration in the reactor and reduces the carbonaceous oxygen demand. The steady state activated sludge model that was employed to evaluate the results of this investigation, i.e. WRC, (1984) assumes that all the biodegradable COD (RBCOD & PBCOD) is completely utilized. Consequently, if unutilized PBCOD remains enmeshed in the sludge mass, this would be reflected in the model by an increased unbiodegradable particulate COD fraction f_{up}, when, as was done in this investigation, the measured VSS was set equal to the predicted steady state model VSS. Examining the calculated f_{up} values obtained in this way for the phase I, II and III data the following three points are noted in support of the hypothesis that the PBCODUR is reduced which in the WRC (1984) model reflects as an increased f_{up} value: (1) Taking the 10 day sludge age data, i.e. phase II data, the average f_{up} value for anoxic mass fractions greater than 50% was 0,177 and for anoxic mass fractions less than 50% was 0,126. (2) For the phase I data, all at approximately 40% aerobic mass fraction, f_{up} increases from 0,134 to 0,154 with a reduction in sludge age from 20 days to 15 days; (however reducing the sludge age from 15 days to 10 days did not further increase the f_{up} value). (3) In phase I and III data with nitrate deficiency, i.e. now the PBCODUR is restricted to very low values due to insufficient nitrate (in the general kinetic model, the PBCOD utilization/hydrolysis ratio reduced to zero under anaerobic conditions), very high values of f_{up} were observed i.e. 0,20.

The experimental data cited above supports the hypothesis that the overall PBCODUR reduces as the sludge age decreases below 10 days and the aerobic mass fraction decreases, with the result that not all the PBCOD is utilized and some remains enmeshed in the sludge mass. However not all the data apparently supported this, e.g. the phase III data, all at about 35% aerobic mass fraction and sludge ages 10 to 5 days, do not reflect a consistently increasing f_{up} with a decreasing sludge age. This is probably because the percentage increase in the VSS becomes smaller as the sludge age decreases making increases in f_{up} more difficult to detect.

For the phase III data, the ratio of the anoxic and aerobic PBCOD utilization rates i.e. neta (where neta = $PBCODUR_{anx}/PBCODUR_{aer}$ averaged at 0,36 (CFR1 0,37 and CFR2 0,34) which compares favourably to the kinetic model value of 0,38 of Van Haandel *et al.*, 1981, of 0,38.

Including the interesting observation that the PBCOD utilization rate decreases as the sludge age decreases, it appears that the experimental systems were not behaving in a manner different to that expected from the kinetic model for activated sludge.

3.2.3.3 System performance – COD removal

Generally the COD removal achieved throughout this phase of the investigation was in the order of 80-90% with an influent COD of around 510 mgCOD/ℓ being reduced to 49 mgCOD/ℓ (see Fig 3.31). This level of COD removal was maintained even at the short sludge age of 5 days which confirms the results published in the literature i.e. COD reductions of between 75-90% have been obtained in even very short sludge age systems (less than 5 days).

3.2.3.4 System performance – Nitrification

The effects of sludge age on nitrification are shown in Fig 3.42 which shows the nitrate generated by nitrification plotted against the product of sludge age. Clearly better nitrification is achieved at the longer sludge ages. The mass of nitrifying organisms increases with an increase in the sludge age of the system and the improved nitrification can be attributed to this increase in nitrifier mass. The

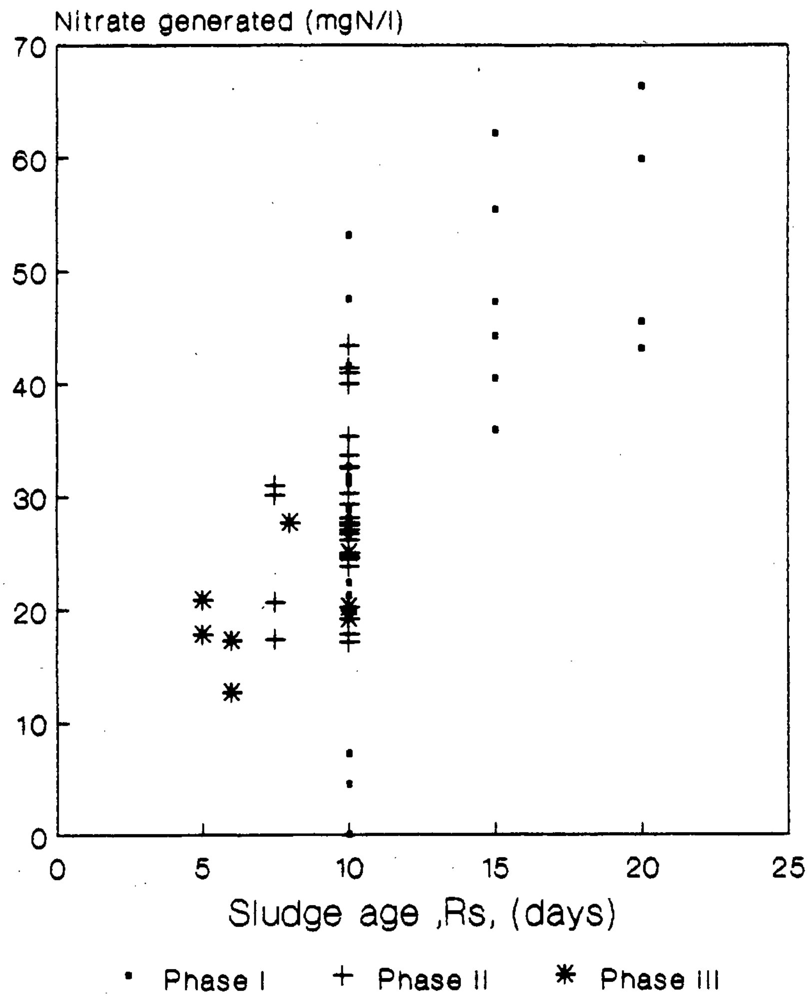


Fig 3.42 Nitrate generated by nitrification versus sludge age calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during phases I and III of the investigation; note that nitrification improves as sludge age increases.

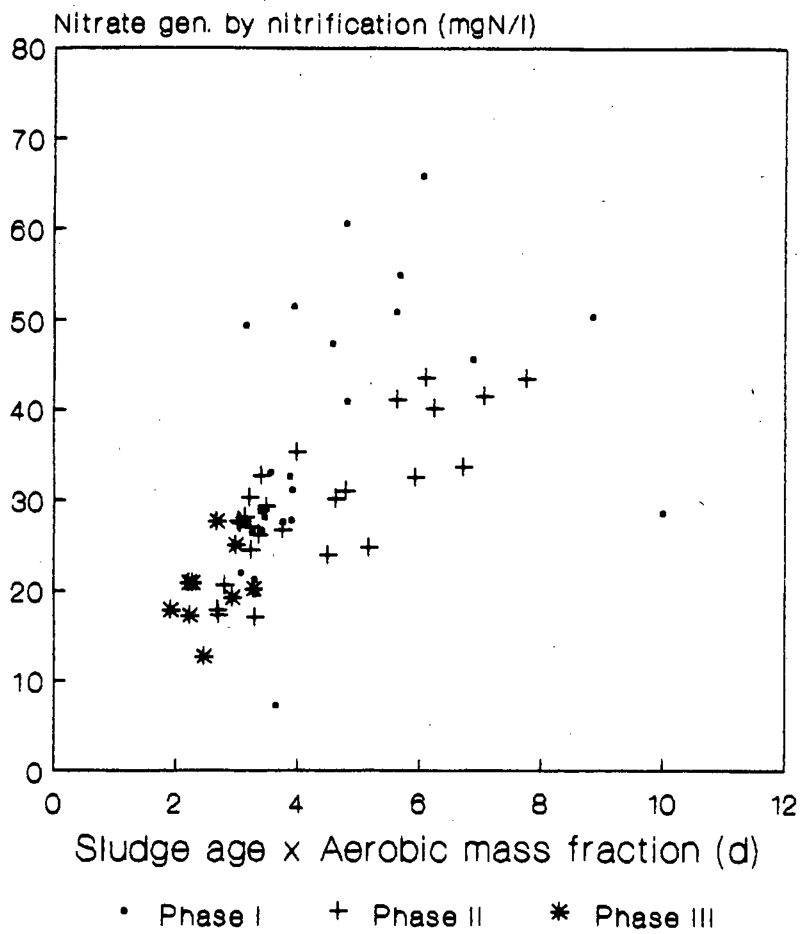


Fig 3.43 Nitrate generated by nitrification plotted against the product of sludge age and aerobic mass fraction calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during phases I, II and III of the investigation; note that the nitrification improves as the product of the sludge age and aerobic mass fraction, i.e. aerobic sludge age, increases.

nitrate generated by nitrification plotted against the product of sludge age and aerobic mass fraction i.e. the aerobic sludge age is presented in Fig 3.43 and shows that the nitrification ability of the system is improved by increasing the aerobic sludge age of the system.

3.2.3.5 System performance – Denitrification

The mass of nitrate denitrified per day ($mgNO_3$-N/d) by the two systems CFR1 and CFR2 is plotted against sludge age in Fig 3.44. Also shown in Fig 3.44 is the mass of nitrate denitrified per day plotted against sludge age for phase I. This is principally because the PBCOD denitrification rate (K_2), by means of which most of the nitrate is denitrified in the system, is directly proportional to the PBCODUR under anoxic conditions – any factor, such as increased sludge age or increased aerobic mass fraction which increases the $PBCODUR_{anx}$, increases also the denitrification. Provided nitrate is not limiting (the data from the one steady state period where this was the case have been omitted from Fig 3.44) it is clearly evident that the denitrification increases by increasing the sludge age of the system. Nitrate deficiency causes a reduction in the overall PBCODUR which causes a build up of unutilized PBCOD in the mixed liquor. This phenomenon is adequately predicted by the general kinetic model; in the steady state model, it has the effect of increasing the unbiodegradable particulate COD fraction f_{up} (see Section 3.2.3.2 above).

3.2.3.6 System performance – Low F/M filament bulking

From the above evaluation of the experimental data measured on systems CFR1 and CFR2, it is evident that kinetically, the two systems performed approximately as expected in terms of the established kinetic understanding of nitrogen removal systems. The overall COD mass balance achieved in the systems of 70,7% and the ratio of the particulate biodegradable utilization rates under anoxic and aerobic conditions, neta, average value of 0,36 (compared to 0,38 established earlier, Van Haandel *et al.*, 1981) indicate that the two systems kinetic behaviour was not very different from that in phases I and II.

Because the kinetic performance of the two systems was not very different to that expected from experience, the bulking behaviour of the systems cannot be attributed to any unusual kinetic behaviour.

Effect of sludge age less than 10 days on low F/M filaments

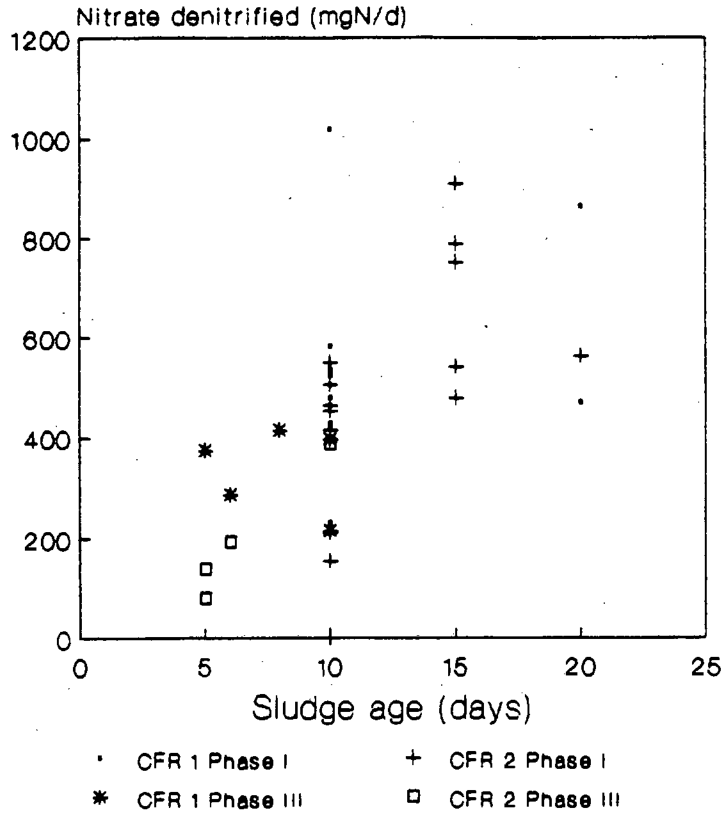


Fig 3.44 Mass of nitrate denitrified per day plotted against sludge age calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during phases I and III of the investigation.

Over the three week period before monitoring commenced, the DSVI in the two systems was above 300 mℓ/g with the bulking caused by the low F/M filaments *Microthrix parvicella*, 0092 and *H.hydrossis*. When monitoring commenced, day 1, the DSVI was 560 mℓ/g in CFR1 and 319 mℓ/g in CFR2 (Fig 3.39). On day 8, about three sludge ages after starting the systems, sludge wastage from CFR1 was increased to establish a sludge age of 8 days. By virtue of the increased sludge wastage, the MLSS concentration (Fig 3.35) progressively reduced over a period of about one sludge age from about 1900 mg/ℓ to around 1700 mg/ℓ, with the result that the reduction in sludge age was not immediate but reduced from 10 days to 8 days progressively over the one sludge age period. Microscopic analysis of sludge samples taken on day 8 indicated that low F/M filaments, *M.parvicella* (dominant) and 0092 (secondary), were present in abundant to excessive quantities in both systems. Other filaments identified were *H.hydrossis*, 0041 and 021N. The DSVI of CFR1 and CFR2 were 480 mℓ/g and 380 mℓ/g respectively. This excessive bulking continued over the next 10 days with the DSVI of CFR1 (8 days sludge age system) peaking at 1169 mℓ/g on day 14, and the DSVI of CFR2 (10 days sludge age) reaching 1104 mℓ/g on day 18. This inordinately severe bulking condition was a direct result of abundant to excessive levels of the low F/M filament *M.parvicella*. After the DSVI reached these very high values, the DSVI in both systems decreased rapidly for no specific reason that could be ascertained, i.e. by day 28, 10 days later the DSVI in CFR1 (8 days sludge age) was 400 mℓ/g and CFR2 (10 days sludge age) was 425 mℓ/g. The DSVI's in both systems continued declining over the next 15 days with the DSVI's in CFR1 and CFR2 falling to 300 mℓ/g and 310 mℓ/g respectively on day 43.

Microscopic analysis of samples taken on day 35 showed that the *M.parvicella* was still the dominant filament in both systems and 0092 remained the secondary filament. In fact no change in the filament population structure was recorded only the abundance level decreased in conformity with the decrease in DSVI i.e. the abundance of filaments in system CFR1 decreased from excessive down to common and those in CFR2 decreased from excessive to abundant.

Because low F/M filament proliferation was still evident in CFR1 at 8 days sludge age it was decided to reduce the sludge age of this system from 8 days to 6 days. Accordingly on day 43 the sludge age of CFR1 was reduced from 8 days to 6 days by increasing sludge wastage from 0,940 ℓ/d to 1,25 ℓ/d. As before the MLSS of the system reduced gradually i.e. from 1700 mgMLSS/ℓ to around 1200 mgMLSS/ℓ in a period of 4 days through the increased sludge wastage, with the result that the sludge age of the system was reduced gradually from 8 days to 6 days over the same period of 4 days. The sludge age of the control system, CFR2, was maintained at 10 days. The DSVI of CFR1 (6 days sludge age system) continued its downward trend over the next 3 sludge ages reaching a low of 213 mℓ/g on day 60 (Fig 3.39). However two sludge ages later the DSVI had again risen and had stabilized at around the 240 mℓ/g level. Over this same period the DSVI of CFR2 (10 day sludge age system) decreased to approximately 280 mℓ/g, and fluctuated in a narrow band (20 mℓ/g) above and below this average value until day 74 when the next system change was introduced. Filament identification performed on samples taken on day 73 showed that *H.hydrossis* had become the dominant filament in both systems and, secondly, that the filament that had dominated both CFR1 and CFR2 throughout the investigation up until this point, i.e. *M.parvicella*, had been *eliminated* from both systems. Because the changes in filament population occurred in both systems this occurrence cannot be ascribed to the shorter sludge age and reasons for the change in filament population must be sought elsewhere. The presence of 021N suggests that the influent sewage may have been septic and that this may have induced the changes in the filament population structure.

On day 74, when the next operational change was made, the DSVI in both systems was high (240 mℓ/g in CFR1, 6 days sludge age, 280 mℓ/g in CFR2, 10 days sludge age) which implied that both systems had bulking sludges and that the filaments could still proliferate and cause bulking even at the short sludge age of 6 days. The gradual reduction of the sludge age from 10 days to 8 days and then from 8 days to 6 days in CFR1 appeared to have no effect on the filament proliferation because the same changes in filaments were observed in the 10 day sludge age system (CFR2). Therefore it was decided to effect a *shock* reduction of sludge age on the low F/M filamentous organisms. Consequently, on day 74, the sludge age of CFR1 was changed back from 6 days to 10 days and the sludge age of CFR2 was reduced from 10 days to 6 days by changing the waste flow accordingly. The *shock* reduction in sludge age to CFR2 was induced by reducing the MLSS concentration (Fig 3.35) of CFR2 from 1800 mgSS/ℓ down to 1000 mgSS/ℓ by wasting an extra 1,8ℓ of sludge from the reactor. On the CFR1 system, sludge wastage was discontinued until the MLSS concentration had reached the expected level for 10 days sludge age, i.e. about 1800 mgSS/ℓ.

Figure 3.39 shows that the DSVI of system CFR1 (sludge age increased from 6 to 10 days) started rapidly increasing from about day 74 from 280 mℓ/g to a peak value of 639 mℓ/g on day 94. On day 100 filament identification indicated that the dominant organism in CFR1 was still *H.hydrossis* so that the high DSVI can be attributed to the excessive levels of this filament.

Considering system CFR2 (sludge age decreased 10 to 6 days), it can be seen in Fig 3.39 that the DSVI decreased rapidly from 350 mℓ/g to 220 mℓ/g within 3 days after implementation of the operational change on day 74 and remained at this level for approximately one sludge age (6 days) to day 80. From day 80, the DSVI sharply increased from 216 mℓ/g to 479 mℓ/g on day 94. Filament identification indicated that *H.hydrossis* was the dominant filament and that a proliferation of this filament was the cause of the sharp rise in DSVI in CFR2. The increase in DSVI in CFR2 indicated that some of the low F/M filaments can proliferate sufficiently in systems with a short sludge age (6 days) to cause bulking and that the ameliorating effect of the shock reduction in sludge age lasted for only a limited period of time, i.e. about one sludge age. On day 92 a further reduction in the sludge age of CFR2 from 6 days to 5 days was implemented to investigate whether the low F/M filament proliferation would continue to proliferate in CFR2 at 5 days sludge age.

The day after the reduction in sludge age in CFR2 to 5 days, on day 93 the supplementary nitrate feeding to both systems inadvertently ceased for 24 hours. This apparently halted the proliferation of the *H.hydrossis*, which can be seen in the progressive decline in DSVI in both systems over the subsequent 10 days. This confirms that the nitrate levels do have some influence on the low F/M filament behaviour. In phase I of the investigation it was shown that the nitrate concentration in the reactors influenced the proliferation of the low F/M filaments, the higher the greater the tendency towards bulking, in particular *M.parvicella*, the dominant low F/M filament in the systems throughout phase I of the investigation.

After the inadvertent cessation of nitrate feeding for 24h on day 94 in both systems, the DSVI in both systems decreased over the next 15 days (to day 109) with CFR1 stabilizing at 380 mℓ/g and CFR2 levelling off at 200 mℓ/g. Microscopic analysis of samples taken from the systems on day 100 indicated *H.hydrossis* still to be the dominant filament in both systems, with 0092 and 021N as secondary filaments in CFR1, and 0092 as the secondary filament in CFR2. Other filaments identified included 0041 in CFR1 and 0041 and 021N in CFR2 (Fig 3.39). Interestingly, *M.parvicella*, the filament that dominated the sludges in the systems during phases I and II was not identified in the 10 or 5 day sludge age systems.

The inadvertent cessation of the nitrate feeding to both systems on day 93 appeared to influence the proliferation of the low F/M filamentous organisms. This observation prompted the final operational change that was made to the systems. On day 109, the sludge age of CFR1 was reduced by the 'shock' method from 10 days to 5 days while supplementary nitrate feeding was continued. System CFR2 was maintained at 5 days sludge age but nitrate feeding was terminated. After reducing the sludge age in CFR1, the DSVI continued its downward trend falling from 380 $m\ell/g$ to a low of 81 $m\ell/g$ on day 120, the final day of the experiment. In CFR2, after cessation of the supplementary nitrate feed, the DSVI increased from 200 $m\ell/g$ over the next 4 days to 272 $m\ell/g$ and then from day 113 declined to 190 $m\ell/g$ by day 120 when the experiment was terminated (Fig 3.39). Filament identification of samples taken on day 120 showed that *H.hydrossis* was still the dominant filament in both systems but levels of abundance in CFR1 and CFR2 had dropped to very common and abundant respectively. Secondary filaments were recorded as 0092 in CFR1 and 0041 in CFR2. It is interesting to note that *M.parvicella* reappeared in both systems at 5 days sludge age as now this filament was again identified in both systems.

Taking an holistic view of the results, shows that the DSVI can be reduced with a reduction in sludge age but not necessarily to below bulking levels. This trend is evident in Fig 3.39 which shows the DSVI's of both experimental systems to be lower at the shorter sludge ages ($<$ 10 days) than at the longer sludge ages ($>$ 10 days). Although the filament abundance estimate in microscopic analysis is quite subjective and can vary considerably it can be seen that the abundance of the low F/M filaments tends to be fewer at the shorter sludge ages A reduction in sludge age therefore holds promise of bringing relief to overloaded clarifiers not only by virtue of the reduction in feed solids concentration this brings about but also by reducing the DSVI which increases the settling velocity of the sludge.

3.2.3.6 Conclusions

The following conclusions can be drawn from the phase III experiments described above:

1. Low F/M filaments do proliferate in systems with sludge ages as short as 5 days. However it would appear that they do not proliferate to excessive quantities in systems with sludge ages less than 10 days.

2. Abundant to excessive amounts of low F/M filaments *M.parvicella* and *H.hydrossis* can proliferate in short sludge age systems and do result in inordinately severe bulking.

3. Generally less severe bulking (lower DSVI's) occurs in intermittent aeration systems at shorter sludge ages (< 10 days) than at longer sludge ages (> 10 days).

4. As found in the phase I experiments the nitrate concentration in the intermittent aeration system seems to have a very weak influence on the low F/M filaments *M.parvicella* and *H.hydrossis*; when nitrate dosing was inadvertently stopped for 24h, the DSVI declined sharply whereas when nitrate dosing was ceased for a long period of time, the DSVI increased.

3.3 Denitrification potential of completely mixed continuously fed intermittently aerated systems (CMCFIA)

The denitrification potential of the completely mixed continuously fed intermittently aerated (CMCFIA) systems cannot be calculated in the same way as that for the Modified Ludzack-Ettinger (MLE) systems. This is because MLE systems have separated anoxic and aerobic reactors of known volume with the result that the anoxic and aerobic mass fractions are known, and the anoxic reactor receives all the influent flow.

In contrast, in the CMCFIA system, the anoxic and aerobic mass fraction is fixed by the aeration cycle and the biological OUR and therefore is less precisely known. Also, because the influent flow is continuous, influent sewage is discharged to the system both under anoxic and aerobic conditions. Whereas all of the influent RBCOD is discharged into the anoxic reactor of the MLE system and utilized for denitrification, in the CMCFIA system only the influent RBCOD discharged to the system under anoxic conditions is utilized for denitrification.

It should be noted that insofar as calculating denitrification potential of Carousel or ditch type plants is concerned, these plants do not classify as CMCFIA systems. The reason is that these plants receive influent at a particular point on the perimeter of the channel which is a fixed distance from the aerator. Because of the high oxygen demand rate of the influent RBCOD, the conditions in the channel immediately after the influent discharge point become anoxic very quickly and will remain so (depending on the availability of nitrate) until the next aerator. If the influent discharge point and aerator are far enough apart, all the influent RBCOD may be utilized before the aerator in which case the plant functions as an MLE system. On the other hand, if the influent is discharged at the aerator some of the RBCOD is utilized aerobically. Clearly with Carousel and ditch type systems the proportion of RBCOD utilized aerobically and anoxically is uncertain making direct application of the denitrification potential equation developed in this section inappropriate.

In the design guide 'Theory, design and operation of nutrient removal activated sludge processes' (WRC, 1984), an equation for calculating the denitrification potential of the primary anoxic reactor in an MLE system is given, viz:

$$D_{p1} = S_{bi}\{f_{bs}(1-f_{cv}Y_h)/2{,}86 + K_2 f_{x1} Y_h R_s/(1+b_h R_s)\} \qquad (3.2)$$

where

D_{p1} = denitrifcation potential of the primary anoxic reactor (mgN/ℓ)
S_{bi} = biodegradable COD concentration of the influent (mgCOD/ℓ)
f_{bs} = readily biodegradable fraction of the influent biodegradable COD
f_{x1} = primary anoxic sludge mass fraction of the MLE system
K_2 = specific denitrification constant (mgN/mgVSS/time)

This equation can be readily modified for calculation of the denitrification potential of CMCFIA systems provided that in these systems the anoxic (or aerobic) mass fraction is known. Knowing the anoxic mass fraction and the fact that only the influent RBCOD that is discharged to the system while it is anoxic contributes to the denitrification, the equation for the denitrification potential of the CMCFIA system can be developed by taking out the anoxic mass fraction term f_{x1} from the second part of Eq (3.2) renaming it f_{xd} for the CMCFIA system, and placing it outside the main bracket as follows:

$$D_p = S_{bi}\, f_{xd}\, [f_{bs}\, (1-f_{cv} Y_h)/2{,}86 + K_2 Y_h R_s/(1+b_h R_s)] \quad (mgN/\ell) \qquad (3.3)$$

where

f_{xd} = anoxic mass fraction of the CMCFIA system

K_2 = specific dentirification rate [$mgNO_3$–N/(mgAVSS.d)]

= PBCOD utilization rate under anoxic conditions $PBCODUR_{anx}$ in mgCOD/(gAVSS.h) times 24/(1000·8,6)

2,86 = oxygen equivalent of nitrate (mgO/$mgNO_3$-N)

By taking the anoxic mass fraction f_{xd} outside the main brackets effectively takes into account of the reduction in the denitrification potential due to influent RBCOD utilization under aerobic conditions.

To calculate the denitrification *potential* of the CMCFIA system, the anoxic mass fraction f_{xd} is defined as 1 minus the aerobic mass fraction, f_{xb}. The aerobic mass fraction is defined as the fraction of time in the total aeration cycle, that DO is present. If in a 20 minute aeration cycle the DO concentration is greater than 0,2 mg/ℓ for 6 minutes, then the aerobic fraction is 6/20 = 0,30 or 30%. Hence the anoxic mass fraction is 1–0,30 = 0,70.

Situations can arise in CMCFIA systems that the denitrification potential is greater than the nitrate available for denitrification. In such cases the nitrate concentration would be reduced to zero before the anoxic period is complete and the nitrate removal performance of the system is less than the denitrification potential. Note that the reduced performance does not change the denitrification potential; if sufficient nitrate were available then more nitrate would be denitrified up to the denitrification potential. Note also that even though the CMCFIA system may be performing below potential due to an insufficiency of nitrate, the effluent nitrate concentration is not zero because with the continuous flow, effluent passes out of the system during the aerobic period when nitrification takes place. So always there will be some nitrate in the effluent (~ 4 mgN/ℓ). The system is only performing at its potential when the effluent nitrate concentration is relatively high, i.e. greater than about 10 mgN/ℓ.

Taking only the steady state periods of this investigation when the nitrate concentration in the effluent was greater than 10 mgN/ℓ, i.e. those where nitrate was dosed into the reactor, the denitrification potential was calculated for steady state periods in phases I to III. The anoxic mass fraction was found from 1 minus the measured aerobic mass fraction, and the influent biodegradable COD S_{bi} was calculated from the measured total influent COD S_{ti} and the calculated values for f_{us} and f_{up} i.e. $S_{bi} = S_{ti}\ (1-f_{us}-f_{up})$ (see Appendix D, E and F). The readily biodegradable COD fraction f_{bs} was obtained from an auxiliary laboratory system treating the same sewage operated specifically for this purpose not only for this investigation but also for others in progress in the laboratory. From twice weekly measurements, an average value 0,24 for the sewage was measured during the investigation.

For the purposes of comparison, the K_2 denitrification rate recommended in the Design Guide (WRC, 1984) of 0,101 $mgNO_3$-N/(mgAVSS.d) was accepted for calculating the predicted denitrification potential. It makes no sense of course to take the K_2 values calculated from the $PBCODUR_{anx}$ determined in this investigation [i.e. K_2 in $mgNO_3$-N/(mgAVSS.d) = $PBCODUR_{anx}$ in mgCOD/(gAVSS.h) times 24/(1000·8,6), see Tables 3.4, 3.8 and 3.12], because the $PBCODUR_{anx}$, and hence K_2, was calculated from the measured denitrification potential.

A comparison of the predicted denitrification potential based on the Design Guide K_2 of 0,101 $mgNO_3$-N/(mgAVSS.d) and the measured denitrification potential (mass NO_3-N denitrified per day divided by the influent flow rate - see Appendix A) for each of the selected steady state periods over the 5 to 20 day sludge age range are given in Fig 3.45.

It can be seen that a reasonable correlation is obtained, but that in general the measured D_p is greater than that predicted. The reason for this is that the average measured K_2 value (excluding the low $PBCODUR_{anx}$ values in phase III) is 0,128 $mgNO_3$-N/(mgAVSS.d) ($PBCODUR_{anx}$ = 46,0 mgCOD/(gAVSS.h), see Tables 3.4, 3.8 and 3.12) compared to 0,101 $mgNO_3$-N/(mgAVSS.d) on which the predictions are based.

The favourable comparison between the predicted and measured denitrification potentials and the Design Guide and measured K_2 denitrification rates not only demonstrates acceptability of Eq (3.3) for calculating the denitrification potential of completely mixed continuously fed intermittent aeration (CMCFIA) systems but also provides further support for the acceptability of the Design Guide K_2 value for estimating the second slow rate of denitrification in primary anoxic (those receiving influent feed) reactors.

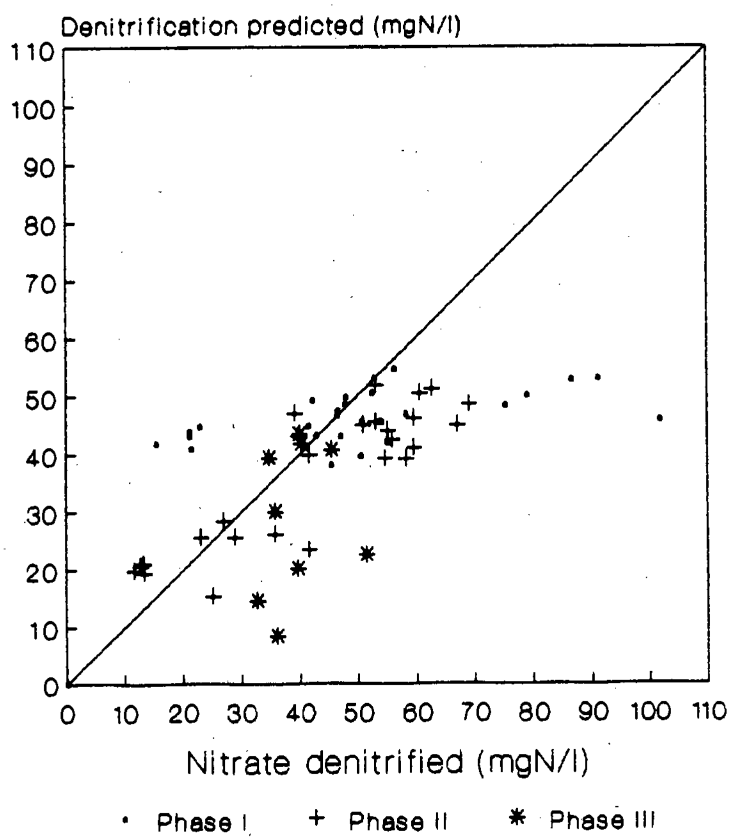


Fig 3.45 The calculated denitrification potential of the intermittent aeration system versus the average actual denitrification achieved by these systems calculated from the average data of the steady state periods identified on intermittent aeration systems CFR1 and CFR2 during phases I and III of the investigation.

CHAPTER 4

CONCLUSIONS

Filamentous bulking, which causes poor activated sludge settleability, is a problem of considerable proportions in South Africa, as indicated by two surveys undertaken in 1985 and 1987 on about 120 activated sludge plants, most of which were either biological N or N & P removal plants. Because the principal filaments causing the bulking are the so-called low F/M filaments, viz. 0092, *Microthrix parvicella*, 0041, 0675, 0914 and 1851, Gabb *et al.* commenced a 4 year research programme, from 1986 to 1989, to evaluate the selector effect, the promoted specific control method for amelioration of low F/M filament bulking. It was found *inter alia* that the selector effect did not control low F/M filament proliferation.

The finding by Gabb *et al.* (1989) that the selector effect, and therefore selector reactors, whether aerobic or anoxic did control bulking by low F/M filaments put research in this area back into an exploratory stage. Since 1989, a wide ranging research programme has been under way to identify the factors that effect low F/M filament proliferation. Completed work has established that the influent COD whether readily biodegradable or particulate were not deciding factors in low F/M filament proliferation, but that aeration and non-aeration does, i.e. the presence of anoxic and aerobic zones or alternating anoxic aerobic conditions in the biological N and N & P removal systems.

The research presented in this thesis forms part of the wide ranging research programme commenced in 1989, and focuses on the effects of

- sludge age
- magnitude of the aerobic mass fraction
- magnitude of the nitrate concentration during the anoxic period

on the low F/M filaments.

The experimental set-up consisted of two intermittently aerated anoxic-aerobic (20 minute cycles, peak DO 2 to 2,5 mgO/ℓ), single reactor completely mixed continuously fed systems. The experimental investigation was chronologically divided into 3 phases and examined the effect of the following conditions on the low F/M filaments:

Phase I

(1) reduction of sludge age from 20 and 10 days on systems having 30% aerobic mass fraction

(2) magnitude of the of nitrate concentration in the anoxic period in systems with 30% aerobic mass fraction. and 10 days sludge age

Phase II

(3) magnitude of the aerobic mass fraction 30% and 70% at 10 days sludge age

(4) 7,5 days sludge age (< 10 days) on systems with 30% and 70% aerobic mass fraction

Phase III

(5) short sludge ages (8,6 and 5 days) on systems with 30% aerobic mass fraction.

In phase I of the investigation, with the aerobic mass fraction fixed at 30%, the sludge ages of the systems were progressively reduced from 20 days to 10 days. It was found that even at 10 days sludge age the low F/M filaments continued to proliferate and caused excessive bulking (DSVI > 300 mℓ/g). It was concluded that the reduction of the sludge age from 20 days to 10 days appeared to have little effect on the low F/M filament proliferation or the filament population types; the commonly occurring low F/M filaments, *M.parvicella* and 0092 but also 0675, 0041 and *H.Hydrossis* could proliferate sufficiently at 10 days sludge age to cause severe bulking problems. On one occasion, while one of the systems was operating at 15 days sludge age, the DSVI increased above 600 mℓ/g due to explosive proliferation of *M.parvicella*, and, in an effort to control this, the system was switched to continuous aeration. This was unsuccessful, so far the only case (out of about 10) in the UCT Water Research Group laboratory where continuous aeration did not ameliorate the bulking.

With the sludge ages of both systems set at 10 days and the aerobic mass fraction set at 30%, the effects of the nitrate concentration during the anoxic period on low F/M filament proliferation and bulking was examined. Initially nitrate was dosed into both systems. To investigate the effect of the nitrate concentration during the anoxic phase the nitrate dosing to one system was terminated but maintained on the second system. Comparing the N removal of the two systems, the system not receiving dosed nitrate was nitrate deficient and could have denitrified 50% (~ 27 mgN/ℓ) more nitrate had this been available. The systems were closely monitored and the effects were recorded over 3 sludge ages. Thereafter the nitrate dosing was interchanged between the two systems a number of times, each time operated for a period of about 3 sludge ages between an interchange of the nitrate feed. The results showed that the system with nitrate deficiency in the anoxic zone tended to suppress filament proliferation, but only weakly and not sufficiently to inhibit bulking. With this proviso, in general the sludges in both systems continued to bulk (DSVI > 150 mℓ/g) with low F/M filaments.

In phase II, maintaining the sludge age in both systems at 10 days the effect of the aerobic mass fraction on low F/M filaments was investigated by changing the aerobic mass fraction from 30% to 70% on one system the other remaining at 30%. Again the systems were run for 3 sludge ages and the aerobic mass fraction interchanged between the two systems a number of times. The results indicated that the 70% aerobic mass fractions appear to have a significant suppressing effect on the proliferation of low F/M filaments *M.parvicella*, *H.Hydrossis*, 0092 and 0041, that is at 70% aerobic mass fraction the DSVI was much lower (120–150 mℓ/g) than at 30% aerobic mass fraction (200–400 mℓ/g).

As a preliminary experiment to investigate the effect of short sludge ages, the sludge ages of both the systems were reduced to 7,5 days. A 70% aerobic mass fraction was maintained in the one system and 30% in the other. The reduction in sludge age had an ameliorating effect on the low F/M filament bulking because the DSVI was reduced in both systems. However rather unexpectedly later in the experiment a rise in the DSVI of the 70% aerobic system was observed but this appeared to be due to a change in the filament population types in that 021N, which is not a low F/M filament, rose to secondary level.

In phase III, to more closely investigate the effect of short sludge ages, the aerobic mass fraction was selected at 30% for both systems, and on the one system a sludge age of 10 days was set while on the other the sludge age was progressively reduced to 8, then 6, then 5 days. After monitoring the effects of the sludge age reductions on the systems the conditions were interchanged between the two systems and the effects of a sudden reduction of sludge age from 10 to 5 days were monitored on the other system. The results indicate that in these systems (intermittent aeration systems), (1) less severe bulking at short sludge ages (< 10 days) than at long sludge age systems (> 10 days) (2) the low F/M filaments can proliferate in systems operated at short sludge ages (5 days) and can result in bulking (DSVI > 150 mℓ/g).

From the investigation it would appear that large aerobic mass fractions (≥ 70%) have the strongest suppressing effect on low F/M filament proliferation, reduction in sludge age less so, and nitrate deficiency in the anoxic zone the least. The lowest DSVI due to low F/M filaments therefore is likely to be obtained at the largest aerobic mass fraction, the shortest sludge age and the lowest nitrate concentration in the anoxic reactor, all factors which mitigate against achieving high N removals by biological denitrification.

Because these filaments appear to be able to proliferate at short sludge ages and generally not under fully aerobic conditions but under anoxic-aerobic conditions it is suggested that their name low F/M filaments is a misnomer and that they should rather be called nitrogen removal filaments.

In the investigation, the kinetic performance of the two systems was evaluated by (1) conducting COD mass balances and (2) calculating the active organism specific particulate biodegradable COD utilization rate under anoxic and aerobic conditions, i.e. $PBCODUR_{anx}$ and $PBCODUR_{aer}$ [mgPBCOD/(gAVSS.h)] respectively, and the PBCODUR reduction factor under anoxic conditions η (neta) which is the ratio of $PBCODUR_{anx}/PBCOD_{aer}$.

In the COD balances, 100% N balance was assumed because for the intermittent aeration systems the nitrate denitrified cannot be directly calculated. This was a reasonable assumption because (1) when one of the systems was fully aerobic an N balance of 98,2% was obtained and (2) on systems outside this investigation on which N balances could be calculated, N balances better than 95% were achieved with the same measurement and laboratory techniques employed on the intermittent aeration systems. Accepting 100% N balance, COD balances averaging 95% were achieved at 20 days and 15 days sludge age, 84% at 10 days sludge age and around 70% at sludge ages below 10 days. The aerobic mass fraction did not influence these results very much. It would therefore appear that as the sludge age decreases so the COD mass balance deteriorates. No explanation for this could be advanced.

With regard to the PBCOD utilization rate under anoxic conditions, this was around 50 mgPBCOD/(gAVSS.h) at 20 and 15 days sludge age, 40 at 10 days sludge age and about 25 at 5 to 6 days sludge age, indicating that the rate, and hence the specific denitrification rate ($mgNO_3$-N/(gAVSS.h) decreases considerably below 10 days sludge age. The reasons for this are not clear. The average $PBCODUR_{anx}$ for sludge ages 10 and longer is 46 mgPBCOD/(gAVSS/h) which converts to a second primary anoxic denitrification rate K_2 of 0,128 $mgNO_3$-N/(gAVSS.h). The rate compares very favourably with the rate established from earlier denitrification work i.e. K_2 = 0,101 $mgNO_3$-N/(gAVSS.d) (see WRC nutrient removal design guide, 1984). The average PBCODUR reduction factor for anoxic conditions neta η (= $PBCODUR_{anx}/PBCODUR_{aer}$) for sludge ages 10 days or longer was measured to be 0,36, which compares very favourably with the earlier value of 0,38 established by van Haandel *et al.* (1981). From the results of the kinetic performance of the systems, it was concluded that the kinetic behaviour of the systems was not contrary to expectation so that the bulking behaviour of the systems could not be attributed to deviant kinetic behaviour.

With regard to design of intermittent aeration systems, the design procedures outlined in the WRC nutrient removal design guide were found adequate for design regarding MLVSS mass accumulation and oxygen demand. Only the denitrification potential equation required modification to take account of the influent RBCOD that is utilized under aerobic conditions. With this modification it was found that the predicted denitrification potential compared very favourably with that measured, the principal reasons being that (1) influent RBCOD concentration for the sewage was measured, and (2) the favourable comparison between the recommended primary anoxic second denitrification rate K_2 (in WRC nutrient removal design guide, 1984) and that measured in the intermittent aeration systems, viz. 0,101 and 0,128 $mgNO_3$-N/(mgAVSS.d) respectively.

It should be noted that insofar as calculating denitrification potential of Carousel or ditch type plants is concerned, these plants do not classify as completely mixed continuously fed intermittent aeration systems like those operated in the investigation. The reason is that these plants receive influent at a particular point on the perimeter of the channel which is a fixed distance from the aerator. Because of the high oxygen demand rate stimulated by the influent RBCOD, the conditions in the channel immediately after the influent discharge point rapidly become anoxic and will remain so (depending on the availability of nitrate) for the time it takes for the sludge to flow to the next aerator. If the influent discharge point and aerator are far enough apart, all the influent RBCOD may be utilized before the aerator in which case the plant functions as a modified Ludzack-Ettinger system i.e. complete utilization of RBCOD in primary anoxic reactor. On the other hand, if the influent is discharged at the aerator some of the RBCOD is utilized aerobically. Clearly with Carousel and ditch type systems the proportion of RBCOD utilized aerobically and anoxically is uncertain making direct application of the denitrification potential equation developed in this investigation for intermittent aeration systems inappropriate. In this respect the laboratory intermittent aeration systems are different to Carousel or ditch type systems in that in the laboratory intermittent aeration systems the proportion of RBCOD utilized aerobic was known and in the same proportion as the aerobic fraction.

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APPENDIX A

Data measured on systems CFR1 and CFR2 during phase I of the investigation

APPENDIX A

Date	day	Influent COD mgCOD /l	Influent TKN mgN /l	CFR1 COD mgCOD /l	TKN mgN /l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO /l	OUR mgO/l /h	%Aer. %	NO3 mgN /l	CFR2 COD mgCOD /l	TKN mgN /l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO /l	OUR mgO/l /h	%Aer. %	NO3 mgN /l
				Effluent and mixed liquor											Effluent and mixed liquor.								
88-02-10	0	552	79	102	11	7.84	4268	3488	172				0.0	70	9	7.74	4112	3368	324				3.6
88-02-11	1	568	100	90	19	7.98	4156	3408	135	2.50	73.00		1.6	49	8	7.71	3992	3300	317				5.6
88-02-12	2	540	128	102	2	7.89	4416	3636	154				1.8	74	11	7.73	3780	3136	317				5.2
88-02-13	3	531	97	98	19	8.12	4380	3648	152				1.6	57	7	8.18	4252	3516	259				9.6
88-02-14	4																						
88-02-15	5	514	89	98	66	8.15	3696	3168	184				0.4	90	36	8.04	3400	2836	235				4.4
88-02-16	6																						
88-02-17	7	497	75	135	0	8.18	3808	3156	152	1.60			0.8	57	56	8.11	3676	3052	239				0.4
88-02-18	8	514	74	122	53	8.16	3520	2940	159				1.5	57	39	7.99	3440	2840	279				7.3
88-02-19	9					8.04	3620	2968	144							7.91	3558	2912	287				
88-02-20	10	530	91	126	58	8.02	3520	2936	145				1.3	61	12	7.66	3776	3128	275				22.0
88-02-21	11	505	99	65	63	7.88							1.6	37	13	7.34							22.5
88-02-22	12	563	97	98	63		3652	2972	148	2.70	24.70	68.30	2.3	41			3708	3036	254	3.0	79.3	32.7	14.9
88-02-23	13	542	97	61	61	7.98	3940	3296	142	2.80	26.20	74.00	2.1	41	7	7.54	3588	2792	268	2.7	71.9	32.5	12.5
88-02-24	14	494	94	92	48	8.04	3724	3064	172	2.40	31.10	55.00	1.9	76	8	7.95	3524	2920	261	2.3	80.5	27.1	8.4
88-02-25	15	514	94	64	43	7.97	3636	3000	171	2.40	31.40	56.00	2.7	58	9	7.96	3658	3042	257	2.4	81.1	28.0	7.3
88-02-26	16	506	93	52	36	7.98		2952	182	2.25	34.10	49.60	4.5	48	8	7.94	3580	2956	263	2.3	82.0	26.8	7.4
88-02-27	17	494	90	48	28	7.78	3732	3156	171	2.45	38.00	48.70	5.0	56	7	7.74	3500	2940	263	2.6	63.2	34.8	6.3
88-02-28	18	534	98	64	19	7.63	3584	2976	189	2.16	42.50	40.50	4.0	56	6	7.44	3520	2948	239	2.3	86.6	26.1	8.4
88-02-29	19	530	96	64	23	7.68	3724	3072	188	2.10	47.10	36.70	4.2	92	10	7.48	3604	3024	222	2.4	83.6	27.4	4.5
88-03- 1	20	526	92	56	26	7.87	3848	3204	182	2.03	47.60	35.50	4.8	56	16	7.84	3740	3092	230	2.4	78.3	28.3	3.2
88-03- 2	21	530	93	48	28	7.96	3560	2844	191	2.00	49.60	34.20	10.1	48	18	8.00	3500	2908	238	2.4	76.0	28.6	6.6
88-03- 3	22	504	93	70	25	8.00	3888	3212	195	2.50	55.40	37.10	5.3	57	50	7.97	3432	2840	268	2.5	82.1	28.6	3.7
88-03- 4	23	492	94	49	16	7.73	3640	2988	203	2.10	62.10	30.30	9.1	57	4	7.83	3280	2724	238	2.8	62.8	36.7	9.6
88-03- 5	24	578	77	67	10	7.70	3816	3156	199	2.10	46.40	37.20	3.0	57	4	7.70	3428	2844	245	2.0	55.0	32.4	3.2
88-03- 6	25	578	80	49	5	7.49	3604		205	2.45	49.30	39.80	3.3	49	3	7.62	3244		240	2.5	61.3	34.7	7.4
88-03- 7	26	500	76	74	3	7.40	3784	3108	199	2.63	51.50	40.60	3.4	36	3	7.40	3292	2748	237	2.8	52.5	41.4	10.1
88-03- 8	27	492	72	61	3	7.54	3596	2976	195	2.10	56.30	32.40	3.5	61	3	7.60	3292	2728	237	2.6	53.5	39.5	6.9
88-03- 9	28	499	74	65	3	7.94	3818	3120	180	2.21	52.40	35.30	3.0	49	2	7.96	3384	2782	213	1.9	60.8	28.6	8.7
88-03-10	29	540	77	70	20	8.00	3628	3004	198	1.35	18.20	27.20	1.3	70	16	7.94	3222	2698	236	1.5	15.0	35.0	1.9
88-03-11	30	519	76	119	43	8.05	3300	2650	194	2.10	17.30	41.40	6.6	98	44	8.08	3084	2580	227	2.0	16.1	41.7	13.9
88-03-12	31	540	80	74	47	8.09	3524	2880	199	1.52	19.30	28.60	7.8	61	52	8.04	3036	2484	237	1.6	24.1	25.0	21.2
88-03-13	32	499	85	65	26	7.78	3580	2904	201	1.64	30.20	21.30	5.1	49	28	7.90	3028	2472	238	1.8	31.6	21.9	21.1
88-03-14	33	533	75	59	26	7.87	3480	2864	218	1.80	37.20	19.50	3.5	43	28	7.83	3228	2712	221	1.7	38.4	18.1	14.5
88-03-15	34	527	72	70	28	7.89	3436	2872	221	1.50	40.10	25.00	17.0	45	36	8.02	3044	2556	237	1.5	37.8	26.0	9.6
88-03-16	35	511	75	70	25	7.85	3388	2788	218	1.50	37.80	33.80	40.0	45	28	7.93	3092	2548	239	1.7	42.5	34.3	23.2
88-03-17	36	500	78	33	24	7.66	3276	2752	238	1.58	35.80	36.50	50.4	28	18	7.71	3128	2596	249	1.9	43.0	36.2	26.4
88-03-18	37	491	75	45	16	7.69	3076	2568	247	1.72	43.10	33.90	15.6	41	23	7.63	3236	2656	241	1.9	46.3	34.6	32.0
88-03-19	38	518	72	26	11	7.56	3364	2820	226	2.00	46.30	35.90	18.4	30	18	7.52	2984	2508	255	2.0	45.4	36.9	42.4
88-03-20	39	528	88	49	13	7.46	3292	2760	237	2.15	36.10	45.70	29.2	45	19	7.51	2968	2460	270	2.1	46.0	37.1	54.0
88-03-21	40	508	88	73	12	7.62	3260	2680	233	2.23	37.80	45.40	29.2	41	8	7.60	2964	2456	270	2.1	49.7	35.1	46.0
88-03-22	41	516	81	61	9	7.68	3388	2824	218	2.40	33.30	53.20	24.4	41	14	7.59	2924	2440	260	2.0	50.1	35.0	27.2
88-03-23	42	520	81	93	9	7.80	2988	2504	234	2.00	31.50	43.00	11.8	69	9	7.58	2920	2468	249	2.0	46.5	37.0	19.8
88-03-24	43	537	79	77	10	7.87	2972	2436	215	2.05	31.90	42.00	23.6	65	[illegible]	7.84	3080	2528	234	2.0	48.8	36.0	35.6
88-03-25	44	512	78	61	13	7.76	2616	2180	214	2.20	36.50	27.30	10.4	37	6	7.61	2944	2488	245	1.9	42.7	24.5	32.8
88-03-26	45	512	77	86	21	7.74	2440	2024	221	2.10	37.00	29.40	9.6	57	21	7.68	2768	2324	260	2.0	43.0	23.0	19.2
88-03-27	46	557	83	74	21	7.74	2328	1940	232	2.15	38.70	28.90	6.8	61	23	7.73	3060	2602	229	2.0	42.0	25.0	21.2
88-03-28	47	541	81	82	19	7.64	2238	1838	232	2.35	37.60	31.70	6.8	53	26	7.72	2676	2226	262	2.2	40.3	26.0	18.4
88-03-29	48	530	83	68	18	7.78	2100	1672	210	2.40	39.40	29.00	4.8	55	26	7.77	2776	2228	238	2.2	40.8	30.0	13.2
88-03-30	49	539	84	63	17	7.52	2074	1740	212	2.55	40.10	30.00	4.0	55	25	7.58	2968	2564	209	2.2	41.2	29.0	15.6
88-03-31	50	518	83	88	19	7.54	2220	1868	195	2.15	41.10	26.00	4.4	59	27	7.56	2988	2356	208	2.3	40.8	30.0	14.4
88-04- 1	51	516	79	90	22	7.52	2150	1758	186	2.30	40.70	27.00	4.4	78	24	7.59	2936	2440	198	2.3	37.7	33.0	12.4
88-04- 2	52	528	84	57	20	7.61	1904	1556	210	2.20	40.60	29.00	6.4	33	29	7.73	2616	2172	216	2.4	38.9	33.0	12.4
88-04- 3	53	492	83	61	32	7.84	2060	1688	210	2.05	39.00	28.00	5.2	49	23	7.90	2816	2316	213	2.5	37.7	34.0	11.2
88-04- 4	54	502	83	68	22	7.78	1992	1656	209	2.50	49.60	27.00	5.2	43	25	7.81	2596	2164	236	2.7	45.5	34.0	10.8
88-04- 5	55	516	81	37	24	7.85	1888	1576	212	2.30	40.50	28.50	6.0	33	29	7.84	2708	2284	222	1.9	39.2	25.0	10.4
88-04- 6	56	528	84	53	19	7.83	1920	1628	217	2.70	49.20	37.00	6.2	53	26	7.84	2732	2276	219	2.1	44.7	35.0	9.8

Date	day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR1 COD mgCOD/l	CFR1 Effluent and mixed liquor TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l	CFR2 COD mgCOD/l	CFR2 Effluent and mixed liquor. TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l
88-04- 7	57	500	82	70	15	7.68	1800	1432	222	2.35	43.20	38.00	6.2	45	20	7.71	2688	2216	123	2.1	42.2	34.5	10.8
88-04- 8	58	537	92	41	18	7.79	1928	1568	207	2.10	49.60	35.00	8.0	37	25	7.86	2748	2236	218	2.5	42.9	35.0	12.2
88-04- 9	59	530	80	66	17	7.56	1940	1660	180	2.30	49.50	33.50	8.2	66	22	7.52	2604	2516	230	2.1	44.6	35.0	7.4
88-04-10	60	506	83	82	20	7.68	2006	1694	224	2.15	51.20	31.00	12.2	37	26	7.60	2588	2152	251	2.0	47.9	31.0	20.2
88-04-11	61	512	84	60	4	7.70	1912	1620	253	2.05	53.30	32.00	10.8	35	20	7.72	2576	2128	271	2.2	52.0	32.0	21.2
88-04-12	62	555	84	54	13	7.62	2020	1668	123	2.25	47.50	35.00	14.4	62	21	7.69	3040	3012	236	1.9	49.1	31.0	18.8
88-04-13	63	543	84	90	20	8.00	2084	1792	208	2.35	47.70	35.00	18.2	66	21	7.84	2856	2420	268	2.1	47.3	32.5	18.0
88-04-14	64	538	79	93	20	7.94	1896	1604	202	2.15	41.80	38.00	20.2	73	21	7.97	2694	2248	284	2.4	48.9	38.5	20.4
88-04-15	65	534	76	77	18	7.78	1860	1576	215	2.40	48.10	38.50	24.0	57	18	7.64	2636	2180	303	2.3	45.3	37.5	28.2
88-04-16	66	514	77	69	21	7.69	1788	1536	214	2.05	37.50	42.00	22.8	23	69	7.47	2572	2188	304	2.2	42.9	42.0	34.6
88-04-17	67	534	83	77	21	7.68	1664	1452	240	2.25	34.50	44.00	23.0	57	10	7.54	2516	2156	318	2.3	47.4	41.0	36.6
88-04-18	68	506	83	61	19	7.68	1624	1320	236	2.10	36.00	47.00	28.0	36	6	7.58	2540	2104	321	2.3	47.5	39.0	39.4
88-04-19	69	506	78	81	0	7.21	1568	1316	255	2.20	36.60	47.00	27.8	28	31	7.21	2600	2160	295	2.1	49.7	37.0	37.4
88-04-20	70	510	80	57	27	7.76	1624	1404	220	2.00	32.00	44.00	15.6	40	22	7.75	2556	2160	346	2.1	48.8	36.0	21.6
88-04-21	71	534	82	65	14	7.82	1340	1140	248	2.70	27.00	74.00	19.2	32	5	7.95	2488	2052	402	2.1	50.4	36.5	19.8
88-04-22	72	497	76	57	5	7.46	1284	1124	239	2.10	25.90	38.50	25.2	21	6	7.49	2472	2116	404	1.9	46.6	44.0	22.4
88-04-23	73	534	76	53	13	7.52	1460	1284	217	2.30	32.90	30.00	47.4	29	7	7.34	2776	2404	374	2.0	51.3	40.0	50.0
88-04-24	74	509	83	66	28	7.83	1348	752	198	2.20	27.50	33.00	21.4	37	9	7.49	2582	2144	397	2.2	50.2	41.0	43.0
88-04-25	75	546	74	62	31	7.61	1228	1064	204	2.40	25.60	35.50	14.4	49	5	7.23	2612	2240	402	2.1	48.1	41.0	42.0
88-04-26	76	511	78	55	37	7.69	1688	1380	172	2.50	28.50	32.00	12.8	47	11	7.17	2712	2244	406	2.0	52.3	38.0	35.8
88-04-27	77	492	80	82	32	7.94	1476	1256	199	2.70	28.30	35.00	16.0	66	11	7.65	2612	2188	421	2.0	52.8	38.0	42.8
88-04-28	78	509	80	86	40	8.11	1284	1116	257	2.45	23.30	38.00	32.0	66	8	7.60	2620	2200	458	2.0	50.7	42.0	54.0
88-04-29	79	496	81	74	38	8.02	1312	1136	254	2.50	29.50	36.00	52.0	82	10	7.57	2416	2016	476	2.0	50.4	41.5	59.6
88-04-30	80	518	80	92	32	7.75	1532	1368	228	2.75	28.50	35.00	29.2	59	5	7.32	2780	2424	432	2.3	52.8	41.0	41.2
88-05- 1	81	582	84	25	39	7.98	1652	1408	212	2.60	26.40	34.50	36.0	16	15	7.48	2860	2452	455	2.0	61.8	38.0	38.4
88-05- 2	82	557	83	37	38	7.72	1640	1400	234	2.35	26.40	33.00	38.4	29	17	7.42	2772	2200	460	2.0	57.8	36.0	29.2
88-05- 3	83	533	89	78	41	7.57				2.40	26.30	33.50	42.0	25	17	7.43	2514	2098	493	2.2	56.8	37.0	25.2
88-05- 4	84	579	86	65	40	7.91	1708	1476	224	2.35	27.50	32.00	46.8	65	16	7.50	2672	2236	478	2.1	57.5	36.0	0.0
88-05- 5	85	514	86	69	41	7.82	1664	1436	240	2.45	27.20	35.00	27.2	41	18	7.52	2860	2456	507	2.1	59.1	35.0	19.2
88-05- 6	86	555	82	90	41	7.77	1512	1336	271	2.35	28.00	35.30	33.2	33	16	7.51	2596	2204	597	1.9	56.7	36.0	20.8
88-05- 7	87	547	84	73	45	7.93	1556	1348	268	2.70	28.60	34.00	28.0	65	71	7.60	2512	2080	567	2.0	55.0	37.0	17.2
88-05- 8	88	538	88	63	43	7.85	1556	1364	268	2.80	25.50	42.00	28.0	26	17	7.51	2722	2354	606	2.0	53.5	38.0	21.6
88-05- 9	89	540	84	65	42	7.83	1562	1320	277	2.35	23.50	39.00	34.4	24	13	7.58	2460	2040	854	2.0	52.2	37.0	19.6
88-05-10	90	573	81	69	29	7.85	1560	1360	295	2.45	24.50	35.00	36.0	36	6	7.49	2540	2116	659			100	44.0
88-05-11	91	532	80	48	32	7.75	1484	1296	319	2.40	21.30	38.00		12	0	7.00	2470	2140	628			100	
88-05-12	92	512	44	57	42	7.70	1584	1380	315	2.50	23.60	36.00	33.6	48	9	6.34	2480	2140	585			100	86.0
88-05-13	93	516	42	52	40	7.84	1540	1308	346	2.50	31.90	29.00	5.6	65	9	7.10	2304	1964	977			100	62.8
88-05-14	94	516	42	57	42	7.84	1728	1466	347	2.35	27.80	33.00	4.4	52	11	7.51	2080	1776	625		28.3	100	62.4
88-05-15	95	482	40	60	43	7.79	1592	1356	414	2.40	23.20	38.00	4.0	27	7	7.02	2140	1736	561		29.9	100	82.0
88-05-16	96	505	44	74	41	7.78	1552	1360	468	2.45	24.80	38.00	6.0	33	8	6.52	2064	1788	569		24.7	100	89.6
88-05-17	97	525	41	46	41	8.06	1568	1368	478	2.35	22.60	41.00	5.2	29	9	6.53	3892	3596	437		29.9	100	92.0
88-05-18	98	526	41	70	41	7.82	1708	1452	429	2.60	36.70	34.00	6.4	37	6	7.14	2016	1716	632		28.6	100	80.8
88-05-19	99	525	42	50	25	7.82	1832	1600	409	2.40	25.70	35.00	6.0	29	8	7.25	2124	1852	600		30.2	100	72.4
88-05-20	100	484	41	83	42	7.84	1752	1484	456	2.40	25.70	35.00	6.0	33	7	7.28	2152	1836	662		30.2	100	74.0
88-05-21	101	532	46	43	45	7.81	1684	1508	465	2.70	22.50	34.00	4.8	43	8	7.24	2224	1920	607		36.3	100	78.8
88-05-22	102	519	46	50	48	7.87	1646	1406	455	3.00	30.50	32.00	5.6	32	8	6.70	2096	1764	608		35.9	100	87.6
88-05-23	103	565	47	71	35	7.85	1796	1500	426	2.80	30.70	26.00	6.4	29	5	7.56	2136	1756	737		33.0	100	78.8
88-05-24	104	525	49	69	46	7.79	1812	1572	404	2.70	33.20	25.00	4.0	35	6	7.49	2172	1916	599		32.7	100	57.2
88-05-25	105	515	47	50	43	7.85	1824	1608	365	3.00	30.40	27.00	15.6	58	5	7.78	2132	1796	586		21.6	100	90.0
88-05-26	106	552	54	62	48	7.88	1872	1800	356	2.90	30.50	26.00	7.2	50	6	7.42	2232	1868	560		31.0	100	74.0
88-05-27	107	494	49	78	48	8.11	2176	1892	321	2.80	27.50	29.00	6.4	45	0	6.86	1984	1744	795		28.6	100	84.0
88-05-28	108	543	52	61	48	7.76	1968	1720	338	2.30	25.80	28.00	6.0	53	2	6.56	2192	1852	935		29.9	100	104.0
88-05-29	109	551	52	57	57	7.80	2108	1880	348	2.50	20.80	34.00	5.2	53	8	6.58	2104	1808	772		25.3	100	98.8
88-05-30	110	518	52	126	27	7.81	1668	1488	569	2.50	21.20	36.00	7.2	98	0	6.33	2056	1808	1034		29.1	100	98.8
88-05-31	111	518	50	65	54	7.79	1752	1524	466	2.50	22.90	37.00	7.2	61	4	6.37	2244	1952	691		30.2	100	102.4
88-06- 1	112	551	52	86	53	7.81	2120	1832	314	2.60	32.40	27.00	6.4	73	2	7.02	2280	1908	789		32.1	100	112.0
88-06- 2	113	541	49	102	53	8.18	2084	1836	320	2.30	30.30	25.00	8.0	81	3	7.57	2212	1892	1198		34.0	100	72.0
88-06- 3	114	528	51	81	51	8.05	2056	1804	337	2.30	28.70	27.00	6.4	73	2	7.16	2124	1856	852		28.6	100	100.0
88-06- 4	115	532	49	118	50	7.74	1968	1704	338	2.60	25.10	33.00	6.0	77	5	7.23	2204	1868	658		28.6	100	100.0

Date	day	Influent COD	Influent TKN	CFR1 COD	Effluent and mixed liquor TKN	pH	MLSS	MLVSS	DSVI	DO	OUR	%Aer.	NO3	CFR2 COD	Effluent and mixed liquor. TKN	pH	MLSS	MLVSS	DSVI	DO	OUR	%Aer.	NO3
		mgCOD /l	mgN /l	mgCOD /l	mgN /l		mg/l	mg/l	ml/g	mgO /l	mgO/l /h	%	mgN /l	mgCOD /l	mgN /l		mg/l	mg/l	ml/g	mgO /l	mgO/l /h	%	mgN /l
88-06- 5	116	510	49	75	50	7.81	2016	1748	339	2.60	26.30	31.00	6.4	59	5	7.54	2228	1908	909		29.1	100	98.4
88-06- 6	117	538	49	83	43	8.12	2128	1792	313	2.70	25.00	32.00	6.0	67	5	7.87	2248	1828	1268		31.8	100	100.0
88-06- 7	118	534	47	96	48	7.83	2248	1708	296	2.60	24.00	37.00	4.0	83	7	7.70	2148	1840	885		26.2	100	100.0
88-06- 8	119	521	48	102	31	8.12				2.70	19.10	46.00	11.2	73	3	7.96					29.1	100	74.4
88-06- 9	120	450	54	75	16	8.01	1868	1500	343	2.00	19.00	40.00	5.8	59	37	8.18	1928	1556	311	2.3	20.0	40.0	11.2
88-06-10	121	489	50	65	46	8.02	1976	1604	344	2.00	19.70	35.00	12.5	86	49	8.18	2276	1880	316	2.1	19.8	37.0	10.0
88-06-11	122	521	50	77	45	8.07	2236	1804	322	2.00	22.60	31.00	6.0	73	5	8.22	2320	1868	324	2.1	23.9	31.0	5.0
88-06-12	123	517	54	61	37	8.03	2368	1904	338	2.35	27.10	32.00	3.5	65	48	8.16	2464	1976	325	2.4	28.5	29.0	2.5
88-06-13	124	511	54	66	34	7.94	2452	2104	343	2.35	23.30	33.50	5.5	74	48	8.14	2540	2160	339	2.4	25.7	33.0	3.0
88-06-14	125	542	53	70	41	7.92	2308	2040	373	2.25	23.40	37.00	9.5	53	49	8.14	2512	2212	350	2.5	21.7	37.0	3.5
88-06-15	126	505	64	57	44	7.96	2244	1964	365	2.25	21.80	39.00	7.5	66	64	8.16	2464	2156	333	2.4	24.2	33.0	4.0
88-06-16	127	484	63	45	43	7.93	2164	1860	370	2.45	23.10	39.00	7.0	37	55	8.10	2376	2024	357	2.4	22.3	38.5	4.5
88-06-17	128	517	65	99	23	7.80	2090	1840	373	2.35	22.60	40.00	19.0	66	46	7.88	2240	1952	420	2.4	20.5	38.0	14.5
88-06-18	129	497	66	57	32	7.96	2040	1708	373	2.35	23.90	38.00	32.5	66	37	8.19	2220	1860	387	2.4	20.7	38.0	28.5
88-06-19	130	520	64	73	30	7.96	2110	1790	332	2.35	27.80	33.50	38.0	45	34	8.16	2256	1940	355	2.4	23.0	36.0	34.0
88-06-20	131	480	66	73	29	7.80	1940	1644	334	2.45	29.00	33.00	30.5	41	32	8.08	2176	1836	377	2.3	24.1	34.0	33.0
88-06-21	132	504	67	85	26	7.78	1948	1654	318	2.50	29.10	34.00	42.0	69	33	8.07	2196	1876	364	2.5	25.4	35.0	33.2
88-06-22	133	488	67	69	29	7.83	1960	1696	306	2.50	26.20	36.00	37.6	41	29	8.04	2128	1852	348	2.3	22.9	38.0	34.4
88-06-23	134	496	64	57	24	7.77	1888	1660	286	2.70	28.60	35.00	45.6	53	28	8.00	2116	1872	321	2.3	26.1	33.0	40.0
88-06-24	135	494	66	59	25	7.76	1820	1464	286	2.45	27.20	34.00	50.0	47	30	8.01	2044	1684	323	2.4	24.2	34.0	34.0
88-06-25	136	536	55	57	19	7.71	1960	1588	269	2.45	28.70	30.00	50.0	53	27	7.98	2268	1872	300	2.4	29.5	27.0	30.4
88-06-26	137	563	56	45	19	7.73	1916	1644	261	2.45	31.70	28.00	46.4	40	23	8.06	2144	1848	280	2.3	28.2	25.0	15.6
88-06-27	138	538	57	85	17	7.71	1800	1584	250	2.55	26.80	31.00	40.8	40	15	8.00	2118	1872	275	2.3	27.5	30.0	10.0
88-06-28	139	514	54	69	16	7.69	1968	1700	228	2.50	27.60	32.00	40.8	57	19	7.96	2276	1968	256	2.8	29.7	29.0	13.2
88-06-29	140	557	59	87	14	7.78	1892	1568	231	2.35	24.60	30.00	43.6	38	20	8.03	2324	1964	244	2.7	28.1	28.0	20.8
88-06-30	141	546	62	81	14	7.76	2008	1652	224	2.15	26.40	30.00	38.4	49	15	8.07	2352	1944	241	2.7	31.4	27.0	21.6
88-07- 1	142	514	53	28	8	7.81	1880	1580	239	2.35	26.70	29.00	36.0	24	20	8.13	2244	1880	252	2.5	31.1	27.0	18.8
88-07- 2	143	524	52	57	13	7.81	1904	1620	213	2.25	29.40	30.00	36.4	49	14	8.04	2300	1952	246	2.4	24.6	29.0	22.8
88-07- 3	144	555	55	47	12	7.81	1860	1608	211	2.45	30.10	29.00	33.2	39	17	8.03	2184	1874	252	2.4	26.4	28.0	24.0
88-07- 4	145	537	54	[illegible]	14	7.78	1856	1596	197	2.35	29.20	30.00	24.4	38	17	7.98	2104	1768	269	2.4	22.9	31.0	20.4
88-07- 5	146	508	56	45	20	8.00	1672	1448	175	2.00	21.20	34.00	17.2	20	23	8.19	2032	1740	246	2.1	20.1	37.0	20.0
88-07- 6	147	500	54	57	10	8.05	1564	1388	198	2.35	21.40	37.00	20.8	41	25	8.23	2024	1864	235	2.0	20.6	35.0	27.6
88-07- 7	148	494	52	43	17	8.10	1604	1324	181	2.15	24.60	34.00	26.0	29	20	8.26	1944	1644	231	1.9	22.5	31.0	39.2
88-07- 8	149	533	55	53	20	8.04	1608	1364	180	2.00	24.60	30.00	28.0	33	20	8.23	1948	1700	221	2.1	22.2	34.0	28.8
88-07- 9	150	554	53	64	11	8.00	1660	1420	181	2.15	21.70	38.00	30.0	39	22	8.22	1912	1620	226	2.0	21.0	32.0	26.8
88-07-10	151	567	55	35	12	7.87	1920		173	1.35	14.20	34.00	35.6	13	26	8.12	1820		238	2.0	21.5	32.0	27.2
88-07-11	152	542	54	57	16	7.76	1860	1596	170	2.00	19.90	37.00	42.8	28	21	8.07	2144	1856	202	2.1	20.1	31.0	30.4
88-07-12	153	498	55	65	13	7.81	1900	1760	193	1.50	14.70	32.00	39.2	53	23	8.03	2228	2040	194	2.1	22.3	30.0	29.2
88-07-13	154	571	57	49	15	7.82	2070	1444	180	2.30	26.70	39.00	36.4	28	20	8.08	2448	1784	177	2.2	24.9	36.0	15.6
88-07-14	155	530	59	57	3	7.76	1928	1600	197	2.00	28.30	35.00	35.2	32	22	7.97	2240	1884	179	2.1	26.5	35.0	5.2
88-07-15	156	540	58	49	23	7.82	2002	1638	200	1.90	26.50	32.00	26.8	41	26	8.01	2288	1920	182	2.0	28.1	31.0	4.0
88-07-16	157	539	57	41	19	7.79	1960	1664	194	2.00	24.50	34.00	25.6	29	23	7.95	2188	1884	192	1.9	23.5	35.0	3.2
88-07-17	158	510	58	61	18	7.77	1976	1624	253	2.20	21.70	41.00	30.0	61	21	7.86	2344	1968	201	2.1	25.5	37.0	2.4
88-07-18	159	502	59	69	16	7.71	2008	1648	224	2.70	25.80	43.00	35.6	33	19	7.86	2354	1986	229	2.3	25.6	37.0	5.6
88-07-19	160	530	55	61	14	7.75	2128	1764	602	2.40	27.40	42.00	34.0	49	2	8.04	2440	2062	291	2.2	26.3	39.0	3.2
88-07-20	161	551	53	53	22	7.88	2008	1728	249	2.20	28.20	39.00	34.4	45	12	8.18	2382	2088	224	2.2	25.9	37.0	4.4
88-07-21	162	535	59	41	14	7.94	1908	1596	297	1.90	25.50	38.00	26.4	37	18	8.23	2424	2068	234	2.1	23.0	42.0	3.2
88-07-22	163	494	55	57	13	7.80	2052	1768	276	2.40	23.80	40.00	33.6	49	18	8.06	2436	2052	232	2.1	21.3	42.0	5.6
88-07-23	164	488	53	45	12	7.81	1984	1656	294	2.40	22.50	41.00	32.0	28	16	8.08	2324	1964	244	2.1	27.7	39.0	4.8
88-07-24	165	484	54	24	12	7.82	2056	1692	308	2.20	20.40	39.00	31.2	33	17	8.09	2344	1964	242	2.2	26.1	45.0	4.8
88-07-25	166	494	52	55	12	7.81	1956	1656	315	2.10	28.30	38.00	34.4	30	15	8.08	2272	1944	235	2.2	23.6	39.0	4.8
88-07-26	167	496	65	41	36	7.79	1980	1688	336	2.00	25.10	35.00	30.0	20	14	7.97	2336	1960	242	2.2	26.3	36.0	5.2
88-07-27	168	524	59	41	10	7.88	1832	1532	391	2.20	29.80	34.00	22.4	33	15	8.11	2264	1926	250	2.1	27.6	34.0	4.8
88-07-28	169	484	57	57	12	7.82	2008	1708	340	1.90	31.40	29.00	22.4	37	17	8.08	2280	1984	241	2.0	29.5	31.0	5.1
88-07-29	170	496	58	33	9	7.80	1796	1508	473	2.20	32.90	30.00	24.4	20	16	8.02	2216	1884	270	2.1	30.3	31.0	5.0
88-07-30	171	484	59	35	12	7.86	1868	1572	669	2.40	31.60	34.00	23.2	18	9	8.00	2156	1820	263	2.1	28.9	33.0	6.4
88-07-31	172	490	49	33	10	7.79	2036	1692	687	1.90	28.10	31.00	23.2	24	6	7.95	2302	1992	260	2.2	28.2	32.0	5.9
88-08- 1	173	514	50	33	6	7.71	1968	1608	389	2.20	33.00	32.00	20.0	29	3	7.86	2188	1888	266	2.2	27.8	33.0	5.4
88-08- 2	174	494	60	33	14	7.62	1944	1628	394	2.20	31.80	29.00	21.6	16	14	7.87	2228	1884	277	2.1	30.3	32.0	5.9

Date	day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR1 COD mgCOD/l	CFR1 Effluent and mixed liquor TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l	CFR2 COD mgCOD/l	CFR2 Effluent and mixed liquor. TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l
88-08- 3	175	508	60	71	14	7.77	1976	1664	497	2.00	31.50	29.00	28.0	51	11	8.05	2316	1976	269	2.2	30.5	33.0	6.3
88-08- 4	176	502	34	37	4	7.80	1948	1616	445	2.20	27.00	36.00	30.8	37	4	8.01	2300	1928	297	2.0	30.9	30.0	5.8
88-08- 5	177	490	33	61	3	7.86	1904	1660	691	2.60	26.50	36.00	28.4	82	2	8.03	2228	1932	314	2.1	29.9	32.0	5.5
88-08- 6	178	486	41	57	4	7.92	1912	1652	409	2.50	32.00	35.00	35.2	20	5	8.17	2212	1920	301	2.2	30.5	33.0	4.8
88-08- 7	179	502	48	37	4	7.84	1848	1572	441	2.10	32.00	31.00	33.6	16	5	8.07	2104	1804	332	2.1	30.6	31.0	4.9
88-08- 8	180	498	50	37	3	7.74	1880	1560	549	2.00	26.40	34.00	32.0	33	4	7.88	2200	1864	288	2.1	30.5	31.0	4.7
88-08- 9	181	502	49	41	3	7.68	1916	1596	445	2.00	26.40	36.00	26.4	24	4	7.82	2208	1908	347	2.2	31.6	30.0	5.2
88-08-10	182	502	48	69	2	7.70	1996	1700	475	2.00	26.50	33.00	24.8	29	1	7.86	2228	1908	366	2.2	29.7	34.0	5.4
88-08-11	183	496	46	80	4	7.82	1972	1636	473			0.00	22.4	27	6	7.96	2250	1916	355			0.0	5.3
88-08-12	184	508	48	49	6	7.83	1906	1636	498	2.12	23.60	33.00	60.0	29	3	8.13	2184	1900	374	2.1	30.7	25.0	0.8
88-08-13	185	510	50	37	6	7.87	1820	1500	640	2.17	23.60	35.00	80.0	33	9	8.07	212	1776	382	1.9	28.9	24.0	0.8
88-08-14	186	508	51	47	6	7.78	1812	1556	515	2.20	21.30	35.00	3.4	47	9	7.98	2220	1960	360	2.3	30.7	27.0	17.2
88-08-15	187	512	44	51	6	7.72	1684	1460	662	2.11	24.80	31.00	10.1	31	4	7.98	2064	1780	565	2.1	30.7	26.0	5.6
88-08-16	188	518	43	37	7	7.64	1912	1620	514	2.14	27.40	27.00	3.6	29	2	8.05	2168	1856	952	2.2	30.7	29.0	7.2
88-08-17	189	490	45	61	6	7.69	2000	1708	450	2.56	31.90	28.00	4.0	37	5	8.06	2132	1812	547	2.4	28.5	30.0	10.0
88-08-18	190	481	46	37	9	7.77	2052	1728	406	2.50	27.20	45.00	3.7	29	3	8.19	2052	1924	511	2.2	27.4	32.0	12.8
88-08-19	191	494	49	57	9	7.76	2160	1840	416	2.43	30.70	25.00	5.1	41	1	8.22	2160	1812	624	2.2	28.5	31.0	25.6
88-08-20	192	502	48	49	1	7.78	2068	1828	419	2.30	29.60	27.00	5.6	53	2	8.14	2094	1856	525	3.0	26.9	34.0	24.0
88-08-21	193	510	50	24	0	7.74	2032	1804	352	2.40	27.40	26.00	5.1	12	0	8.12	2000	1752	558	2.2	24.8	36.0	27.2
88-08-22	194	494	46	49	10	7.67	2108	1828	332	3.04	33.30	32.00	5.1	33	3	7.99	2060	1756	566	2.2	25.9	34.0	31.6
88-08-23	195	494	46	37	8	7.71	2004	1700	407	3.15	30.70	40.00	5.8	12	2	8.09	2090	1754	693	2.3	24.6	37.0	34.8
88-08-24	196	506	46	41	2	8.00	1676	1396	397	2.31	22.10	53.00	3.6	24	2	8.17	1844	1520	704	2.5	22.1	39.0	31.6
88-08-25	197	526	48	54	.15	8.21	1812	1540	368	2.43	17.90	38.00	4.6	34	1	8.37	1934	1632	1016	2.3	24.6	36.0	36.0
88-08-26	198	534	48	63	40	8.04	1872	1640	311	3.01	22.90	43.00	4.1	26	1	8.25	1912	1636	993	2.2	23.7	40.0	36.4
88-08-27	199	524	49	28	13	8.01	1784	1496	299	2.70	20.23	43.00	4.4	36	5	8.22	1872	1560	818	2.6	22.5	48.0	34.8
88-08-28	200	528	47	60	11	7.98	1960	1684	322	2.80	18.50	47.00	4.0	48	2	7.23	1956	1632	596	2.2	21.3	50.0	35.6
88-08-29	201	516	47	85	19	7.79	1904	1684	280	2.70	21.30	39.00	4.5	56	7	7.86	1892	1660	598	2.1	19.5	39.0	40.8
88-08-30	202	532	48	48	3	7.84	1780	1532	309	2.80	18.90	43.00	2.5	40	2	8.16	2052	1736	730	2.2	22.9	43.0	20.4
88-08-31	203	532	53	44	10	7.86	1756	1474	303	2.90	21.30	41.00	5.0	36	8	8.12	1916	1600	530	1.8	20.6	40.0	35.6
88-09- 1	204	520	47	40	11	7.80	1740	1512	335	2.98	25.00	42.00	4.6	73	6	8.19	1908	1628	724	2.2	19.9	43.0	34.4
88-09- 2	205	518	47	47	11	7.78	1620	1400	349	2.18	17.90	40.00	5.8	35	1	7.98	1872	1576	703	2.2	19.2	42.0	32.0
88-09- 3	206	504	46	41	10	7.78	1732	1504	336	2.11	15.00	36.00	7.5	33	1	8.00	2064	1728	839	2.9	20.6	32.0	32.4
88-09- 4	207	516	49	49	5	7.81	1620	1424	401	2.24	20.96	35.00	3.7	49	4	8.10	2066	1768	895	2.4	22.7	36.0	26.0
88-09- 5	208	496	48	41	12	7.83	1540	1284	411	1.95	20.95	31.00	3.7	33	3	8.16	2332	1876	528	2.1	25.9	33.0	25.2
88-09- 6	209	512	49	78	11	7.83	1700	1460	431	2.24	19.20	34.00	4.3	33	4	8.18	2008	1684	813	2.3	23.5	32.0	24.0
88-09- 7	210	532	47	45	4	7.79	1624	1392	441	2.21	21.50	32.00	4.0	33	2	8.10	1932	1616	733	2.3	24.6	32.0	28.8
88-09- 8	211	481	49	43	2	7.81	1616	1432	474	2.59	23.70	35.00	4.3	14	1	8.12	1840	1140	787	2.1	24.1	33.0	30.4
88-09- 9	212	496	48	41	11	7.92	1584	1416	463	2.05	23.30	28.00	4.3	41	7	8.15	1920	1632	559	2.7	28.5	28.0	31.2
88-09-10	213	500	46	39	2	7.86	1564	1348	533	2.24	17.30	40.50	4.7	18	2	8.18	1872	1564	970	2.2	18.4	43.0	31.2
88-09-11	214	506	48	37	1	7.78	1468	1276	601	2.18	15.70	45.00	4.7	20	1	8.10	1936	1640	722	2.4	16.1	53.0	37.2
88-09-12	215	500	48	31	2	7.84	1436	1230	638	2.14	15.50	46.00	4.3	18	1	8.05	2048	1712	870	2.3	13.8	56.0	41.2
88-09-13	216	502	48	37	6	7.90	1416	1208	576	2.08	17.30	43.00	3.5	37	1	8.05	1956	1656	783	2.4	13.7	65.0	47.6
88-09-14	217	530	49	73	5	7.80	1456	1252	663	1.92	18.10	38.00	14.0	33	2	8.15	1920	1636	850	2.1	18.5	42.0	34.0
88-09-15	218	522	52	61	8	7.89	1508	1316	574	1.95	19.20	43.00	21.2	49	6	8.12	2188	1856	738	1.9	21.9	33.0	8.4
88-09-16	219	522	53	45	7	7.92	1444	1232	518	1.82	16.40	41.00	33.6	33	4	8.06	2088	1776	1092	1.9	19.0	40.0	7.6
88-09-17	220	506	51	53	3	7.96	1448	1224	517	1.82	18.20	37.00	53.2	45	4	8.13	2160	1804	678	1.9	20.6	34.0	6.3
88-09-18	221	514	51	32	3	7.92	1464	1236	535	1.73	16.50	37.00	54.0	20	3	8.06	2160	1840	475	1.7	18.7	36.0	7.3
88-09-19	222	518	51	20	4	7.84	1364	1120	525	1.57	16.80	34.00	52.0	28	2	8.04	2168	1780	438	1.5	19.2	32.0	6.8
88-09-20	223	494	50	73	5	7.85	1484	1260	449	1.41	14.90	35.00	43.6	49	12	8.00	2256	1900	384	1.4	16.5	35.0	6.7
88-09-21	224	510	49	20	4	7.88	1388	1168	552	2.53	23.10	34.00	38.8	36	2	8.04	2070	1736	442	2.5	24.4	32.0	5.3
88-09-22	225	510	51	45	5	7.97	1672	1428	378	2.40	25.90	28.00	38.8	24	2	8.13	2188	1840	419	2.4	23.9	32.0	5.6
88-09-23	226	472	46	29	6	8.17	1590	1346	419	2.30	23.50	33.00	34.4	20	6	8.37	2136	1780	499	2.2	25.9	29.0	5.7
88-09-24	227	509	48	65	5	8.08	1686	1416	356	2.11	25.20	30.00	33.6	33	4	8.21	2270	1868	381	2.0	28.7	27.0	6.5
88-09-25	228	501	49	61	7	7.89	1624		349	1.98	27.40	29.00	14.0	29	4	8.05	2192		395	2.1	37.3	28.0	4.7
88-09-26	229	525	52	16	9	7.86	1524	1276	404	2.40	20.60	38.00	15.6	16	3	7.97	2260	1836	368	2.2	26.4	30.0	5.8
88-09-27	230	485	56	61	7	7.87	1568	1356	404	2.38	22.10	36.00	16.4	69	5	7.96	2204	1864	378	2.2	24.8	33.0	6.4
88-09-28	231	511	50	67	8	7.93	1540	1236	363	2.18	19.20	33.00	45.6	75	7	8.05	2298	1888	348	2.3	25.9	33.0	8.5
88-09-29	232	498	50	61	8	7.94	1760	1516	341	2.14	23.30	33.00	40.4	37	4	8.05	2280	1948	380	2.3	25.0	34.0	8.3
88-09-30	233	502	50	45	6	7.94	1680	1384	377	2.24	21.30	35.00	46.0	57	3	8.05	2056	1704	421	2.4	21.9	37.0	8.1

Date	day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR1 COD mgCOD/l	CFR1 TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l	CFR2 COD mgCOD/l	CFR2 TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l
88-10- 1	234	502	46	78	6	7.99	1740		344	3.26	35.40	32.00	53.2	65	1	8.05	1920	1560	425	2.9	34.6	34.0	7.7
88-10- 2	235	498	50	82	7	7.98	1748	1488	343	1.92	30.70	25.00	52.4	45	11	8.06	2148	1796	341	2.1	35.4	24.0	7.7
88-10- 3	236	526	50	73	9	7.88	1820	1488	333	2.38	28.50	30.00	38.4	53	0	7.94	2104	1804	356	2.1	32.9	25.0	7.7
88-10- 4	237	512	53	55	10	7.90	1512	1244	374	3.33	36.80	32.00	37.2	41	8	8.04	1808	1520	368	2.9	44.2	24.0	8.7
88-10- 5	238	521	47	56	11	8.11	1400	1166	381	3.03	31.30	58.00	42.4	56	3	8.28	1856	1576	350	2.4	41.2	22.0	6.0
88-10- 6	239	546	47	53	13	8.00	1476	1216	372	2.30	29.60	28.00	40.0	37	9	8.12	2238	1712	298	2.6	43.1	22.0	6.5
88-10- 7	240	521	50	37	16	7.99	1720	1284	358	2.14	32.60	21.00	44.0	45	13	8.14	2324	1840	294	2.1	43.1	21.0	6.4
88-10- 8	241	527	47	63	18	8.00	1444	1224	323	2.24	22.10	40.00	38.0	47	19	8.16	2088	1824	303	2.5	34.6	26.0	6.4
88-10- 9	242	518	46	59	18	7.93	1556	1356	375	1.82	19.40	30.00	27.2	71	15	8.00	2276	2004	293	2.4	33.3	27.0	4.1
88-10-10	243	531	49	67	16	7.81	1384	1236	445	1.89	19.00	37.00	29.2	75	11	7.91	2056	1940	340	2.3	32.6	26.0	4.0
88-10-11	244	489	51	8	13	7.63	1404	1396	415	2.40	27.40	32.00	55.6	12	7	7.84	2424	2028	302	2.4	13.9	52.0	6.6
88-10-12	245	533	50	41	6	7.69	1496	1300	390	3.04	15.00	67.00	68.0	49	5	7.85	2504	2140	[illegible]	2.1	31.9	24.0	8.0
88-10-13	246	549	52	41	8	7.85	1548	1304	366	2.94	25.90	45.00	47.6	73	5	8.06	2728	2332	256	2.0	33.3	43.0	6.2
88-10-14	247	524	47	57	10	7.93	1416	1148	376	2.05	20.10	33.00	26.0	77	13	8.03	2480	2060	282	2.0	36.9	21.0	2.9
88-10-15	248	553	51	85	12	7.96	1628	1396	358	2.24	19.00	39.00	32.4	81	16	8.02	2512	2160	312	3.8	38.9	29.0	4.9
88-10-16	249	496	49	65	10	7.87	1556	1316	310	2.20	18.50	38.00	36.0	53	17	7.92	2488	2088	268	2.2	25.5	30.0	4.3
88-10-17	250	500	49	49	11	7.80	1526		349	2.53	19.90	42.00	39.6	69	17	7.87	2488		301	2.6	54.6	32.0	4.9
88-10-18	251	544	48	84	7	7.84	1616	1320	350	2.34	19.50	42.00	43.2	72	9	7.96	2440	2060	314	2.4	24.1	34.0	4.5
88-10-19	252	548	50	100	9	7.89	1614		351	2.50	19.40	40.00	52.0	96	11	7.94	2512		331	2.5	23.9	35.0	4.8
88-10-20	253	500	51	24	7	7.95	1696		353	2.50	21.90	39.00	44.0	56	6	8.03	2488		308	2.4	22.5	38.0	5.5
88-10-21	254	504	55	96	13	7.89	1648	1424	394	3.36	20.40	55.00	41.2	60	19	7.96	2484	2152	308	2.6	24.1	35.0	4.0
88-10-22	255	496	50	80	15	7.91	1548	1304	464	3.50	21.30	63.00	34.4	96	6	8.01	2424	2048	316	2.4	23.3	35.0	5.3
88-10-23	256	480	52	72	14	7.89	1632	1548	510	3.33	21.50	58.00	34.4	88	14	7.92	2288	2188	342	2.5	21.1	39.0	5.4
88-10-24	257	522	50	75	14	7.92	1632	1392	459	2.94	20.80	38.00	39.6	67	14	7.91	2332	2004	336	2.5	21.3	39.0	5.0
88-10-25	258	524	51	85	15	7.83	1608	1344	445	3.08	25.02	57.00	34.4	77	2	7.91	2260	1924	317	2.4	26.4	32.0	6.6
88-10-26	259	528	52	77	14	7.90	1632	1404	439	3.30	25.90	70.00	40.8	73	10	8.00	2312	1984	310	2.4	27.2	33.0	6.0
88-10-27	260	488	45	81	3	7.91	1588	1348	419				3.4	94	3	8.02	2244	1928	312				61.2
88-10-28	261	500	48	77	17	7.92	1700	1440	411	2.08	26.40	29.00	6.6	85	16	7.95	2016	1740	330	2.3	54.5	36.0	28.0
88-10-29	262	551	44	86	15	7.87	1756	1496	436	2.24	25.00	33.00	5.8	73	15	8.00	2068	1752	354	2.7	24.1	39.0	34.0
88-10-30	263	535	45	86	11	7.83	1940	1636	403	2.37	23.30	35.00	5.5	78	4	7.88	2112	1796	355	2.7	25.5	38.0	39.2
88-10-31	264	510	47	78	11	7.57	2004	1708	415	2.24	26.40	33.00	4.4	106	3	7.58	2054	1962	373	2.7	25.3	38.0	40.4
88-11- 1	265	539	47	45	6	7.53	2040	1732	384	2.24	25.50	34.00	6.3	3	3	7.70	2116	1788	393	2.4	31.9	35.0	40.4
88-11- 2	266	522	43	82	10	7.59	2020	1700	412				6.5	73	3	7.80	2106	1756	474				43.2
88-11- 3	267	542	49	70	12	7.95	1940		421	1.76	25.00	25.00	1.5	53	5	8.03	2456		346	1.7	17.0	32.0	47.2
88-11- 4	268	556	47	64	12	7.87	1968	1652	440	2.10	22.10	38.00	3.3	55	3	7.95	1960	1660	552	2.3	19.9	45.0	46.0
88-11- 5	269	564	46	96	10	7.90	1948	1634	419	2.10	27.40	28.00	3.2	72	2	7.97	1900	1572	473	2.4	27.9	36.0	50.0
88-11- 6	270	558	47	74	6	7.88	1920	1608	399				2.6	66	4	7.92	1988	1660	443				44.4
88-11- 7	271	484	49	78	6	7.82	2068	1728	362	2.40	28.50	28.00	2.8	70	3	7.92	2100	1740	428	2.3	22.9	33.0	37.2
88-11- 8	272	517	45	74	9	7.84	2032	1748	393	2.64	22.10	48.00	4.5	66	2	7.87	2004	1716	465	2.9	19.9	50.0	34.8
88-11- 9	273	540	48	68	3	7.86	2052	1736	357	2.60	26.20	35.00	4.9	92	3	7.92	2024	1692	469	2.8	22.4	42.0	40.8
88-11-10	274	521	48	70	8	7.93	2052	1728	381	2.10	25.00	30.00	3.8	82	6	7.96	2024	1692	510	2.3	23.7	33.0	34.0
88-11-11	275	513	48	49	6	8.01	2096	1768	365	2.40	30.70	28.00	4.4	62	3	8.09	2060	1704	558	2.2	25.0	30.0	30.0
88-11-12	276	520	47	85	10	8.05	2076	1744	353	2.00	29.60	25.00	2.9	73	73	8.17	2002	1678	516	2.4	30.1	28.0	28.8
88-11-13	277	512	44	102	9	8.02	2148	1820	372	2.10	31.90	44.00	5.3	61	4	8.14	2072	1720	514	2.4	26.4	25.0	34.4
88-11-14	278	484	46	69	7	7.70	2104	1820	380	2.00	28.20	26.00	3.3	69	4	7.87	1968	1668	567	2.4	23.3	33.0	29.6
88-11-15	279	526	46	59	8	7.84	2028	1744	386	2.10	18.50	35.00	4.7	59	0	7.98	1868	1572	670	2.7	22.1	42.0	35.6
88-11-16	280	488	46	33	2	7.98	2136	1808	340	1.90	18.90	34.00	7.4	61	5	8.10	2024	1708	716				46.8
88-11-17	281	504	52	61	8	8.03	2140	1796	339	1.90	21.30	35.00	4.8	77	3	8.13	1944	1620	702	2.6	24.1	38.0	43.2
88-11-18	282	500	52	77	2	8.05	2192	1848	341	2.00	19.50	37.00	6.8	85	2	8.09	2020	1676	618	2.7	26.4	36.0	60.8
88-11-19	283	528	51	69	5	8.03	2156	1816	293	2.00	19.50	35.00	6.4	81	2	8.07	1912	1606	575	2.4	27.4	34.0	52.4
88-11-20	284	514	53	91	2	7.96	2246	1898	289	1.80	24.10	26.00	6.0	91	3	7.97	2004	1652	548	2.3	28.5	27.0	46.0
88-11-21	285	516	51	90	2	7.86	2276	1960	285	2.10	22.10	26.00	6.8	85	2	7.87	2036	1708	490	2.4	26.9	30.0	44.0
88-11-22	286	519	48	57	4	7.85	2212		279				6.1	61	6	7.96	2052	1704	487				42.0
88-11-23	287	505	51	68	0	7.92	2428	2088	302	2.30	22.10	37.00	7.2	68	9	8.01	2008	1696	672	2.7	27.4	32.0	36.6
88-11-24	288	484	52	76	1	7.97	2344	1992	298	2.30	22.90	34.00	6.6	72	7	8.05	2080	1740	488	2.6	28.5	32.0	43.6
88-11-25	289	507	51	115	11	7.90	2284	1944	313	2.70	22.10	41.00	7.6	82	6	7.97	2044	1688	505	2.9	28.5	33.0	57.6
88-11-26	290	519	47	74	15	7.88	2392	2028	317	2.64	22.50	40.00	7.1	86	6	7.99	2052	1740	487	2.7	29.5	31.0	37.2

Date	day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR1 COD mgCOD/l	CFR1 TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l	CFR2 COD mgCOD/l	CFR2 TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l
88-11-27	291	482	50	106	2	7.73	2296	1940	334	2.59	22.30	40.00	7.4	90	2	7.84	2036	1712	458	2.6	28.5	32.0	36.4
88-11-28	292	505	50	80	16	7.80	2396	2008	306	2.92	24.10	44.00	8.5	76	2	7.87	2232	1844	448	2.7	24.8	34.0	40.0
88-11-29	293	509	53	53	3	7.80	2380	2056	308	3.14	23.50	41.00	7.4	45	3	7.90	2060	1728	485	2.9	30.1	35.0	42.4
88-11-30	294	513	52	78	9	8.03	2096	1768	317	2.18	21.70	37.00	4.4	66	9	8.15	2004	1680	449	2.0	23.3	34.0	37.2
88-12- 1	295	529	54	41	20	8.13	2280	1924	329	1.86	19.90	34.00	5.0	62	16	8.18	2004	1700	449	2.0	22.5	33.0	34.4
88-12- 2	296	538	55	33	18	8.06	2224	1856	329				6.0	62	14	8.14	2036	1696	474				40.2
88-12- 3	297	550	48	57	8	8.12	2320	1972	409				9.2	69	13	8.20	2132	1820	500				22.0
88-12- 4	298	525	51	45	3	8.08	2148	1804	372	2.89	25.02	42.30	37.2	110	5	8.15	2024	1684	431	2.6	34.6	29.5	6.2
88-12- 5	299	517	54	45	10	7.93	2064	1716	371	2.22	25.02	34.00	48.4	61	10	7.90	2028	1684	517	2.6	32.8	31.7	7.2
88-12- 6	300	483	55	27	3	7.97	2064	1764	371	2.18	24.57	33.50	37.6	51	10	8.03	2060	1764	590	2.7	34.6	31.0	4.3
88-12- 7	301	527	54	51	15	8.06	2096	1792	350				30.0	75	3	8.08	2156	1832	494				4.5
88-12- 8	302	533	54	49	3	8.04	2200	1844	333	2.85	25.95	35.50	30.4	86	6	8.07	2256	1896	465	2.1	30.1	23.5	4.5
88-12- 9	303	560	54	39	21	8.08	2140	1812	319	2.40	28.83	28.67	16.0	79	10	8.10	2328	1964	458	2.6	40.6	22.3	3.7
88-12-10	304	540	52	45	15	8.11	2040	1744	326	1.94	21.08	33.33	21.2	81	23	8.11	2340	2000	434	2.7	35.1	25.0	3.3
88-12-11	305	528	54	61	3	8.00	2068	1712	322	2.18	20.95	38.33	53.0	81	19	7.99	2456	2060	475	2.5	35.4	26.8	5.6
88-12-12	306	545	51	41	6	7.89	2156	1800	317	2.19	20.23	39.33	68.8	51	7	7.89	2508	2120	445	2.4	29.2	29.0	6.6
88-12-13	307	561	52	45	6	7.92	2060	1732	307	2.90	21.83	39.67	45.6	61	2	7.98	2280	1924	402	2.1	33.3	24.5	6.5
88-12-14	308	541	54	25	9	7.97	2116	1800	293	2.56	20.59	45.00	74.8	57	8	8.02	2356	2016	382	2.7	36.1	24.8	8.9
88-12-15	309	537	52	33	4	7.83	2084	1732	295	2.72	21.70	42.50	76.0	69	13	8.05	2320	1964	359	2.1	34.1	22.5	8.7
88-12-16	310	545	54	29	9	8.06	2108	1772	316	2.61	19.20	46.50	79.2	77	23	8.13	2384	2020	384	2.7	32.8	27.7	10.4
88-12-17	311	532	53	33	4	7.99	1972	1696	346	2.66	19.20	48.50	82.8	81	22	8.02	2416	2068	351	2.6	31.1	28.3	10.4
88-12-18	312	524	50	49	13	7.83	1992	1524	318	2.53	19.11	47.00	76.0	69	22	7.90	2448	2040	347	2.6	31.9	28.5	8.5
88-12-19	313	508	46	45-	11	7.79	2068	1712	290	2.62	18.22	50.83	80.0	73	21	7.86	2552	2148	326	2.4	31.5	27.1	9.0
88-12-20	314	536	53	45	10	7.63	1952	1668	316	2.58	19.65	48.00	82.0	77	20	7.92	2392	2032	341	2.5	33.3	25.5	9.2
88-12-21	315	520	53	49	3	7.99	1948	1672	325	2.69	18.32	50.83	88.8	89	25	8.09	2416	2084	331	2.7	32.6	27.5	8.1
88-12-22	316	537	52	33	3	8.00	1912	1588	340	2.56	19.31	46.17	86.0	77	22	8.03	2440	2068	341	2.4	31.1	26.2	11.0
88-12-23	317	488	52	29	3	8.00	1844	1496	361	2.34	18.22	45.00	72.4	85	21	8.07	2456	2060	353	2.4	32.4	26.2	7.9
88-12-24	318	557	47	37	15	7.85	1920	1568	364	2.87	22.88	47.33	57.2	69	21	7.84	2632	2184	316	2.3	37.1	24.3	7.1
88-12-25	319	532	48	33	5	7.95	1804	1544	388	2.49	18.54	47.50	46.4	29	19	7.96	2452	2096	333	2.6	26.4	33.5	5.6
88-12-26	320	496	49	53	53	7.90	1824	1496	392	2.54	19.20	48.50	45.2	81	17	7.87	2376	1980	350	2.6	24.1	37.0	5.9
88-12-27	321	537	50	41	5	7.82	1936	1568	361	2.51	19.88	46.12	39.2	81	7	7.85	2484	1996	308	2.6	26.4	37.0	5.6
88-12-28	322	532	48	29	6	7.92	1916	1546	365	2.44	20.59	43.00	44.0	81	2	7.96	2484	2012	295	2.6	27.1	33.5	6.6
88-12-29	323	537	48	53	2	7.72	1948	1572	342	2.51	22.88	40.25	38.0	89	14	7.72	2488	2076	288	2.6	29.0	30.7	4.3
88-12-30	324	567	50	20	2	7.78	1896	1576	378	2.65	23.29	38.50	30.0	36	19	7.77	2444	2064	286	2.6	31.9	30.3	4.3
88-12-31	325	524	48	29	2	7.80	1828	1476	383	2.29	19.54	42.50	22.8	73	16	7.78	2436	2024	273	2.3	28.2	29.8	4.1
89-01- 1	326	537	49	57	2	7.81	1916	1572	382	2.29	22.10	38.00	26.0	33	14	7.83	2600	2092	282	2.4	28.5	30.0	3.8
89-01- 2	327	528	49	22	3	7.82	1872	1528	365	2.40	20.20	44.00	20.0	79	13	7.88	2516	2084	265	2.4	26.7	32.0	3.6
89-01- 3	328	524	47	81	7	7.84	1928	1580	345	2.40	21.90	38.00	23.2	37	17	7.84	2580	2160	271	2.6	24.4	38.0	3.9
89-01- 4	329	491	48	37	2	7.71	2060	1640	380	2.43	22.70	39.00	19.2	81	18	7.77	2604	2148	294	2.6	21.3	44.0	3.5
89-01- 5	330	505	51	75	1	7.75	1972	1620	372	2.85	23.70	43.00	22.4	79	18	7.81	2560	2172	280	2.8	28.5	34.0	4.1
89-01- 6	331	523	48	45	45	7.71	1892	1772	378	2.72	24.60	41.00	19.2	97	16	7.73	2464	2072	284	2.7	26.4	35.0	3.8
89-01- 7	332	491	48	45	2	7.76	1988	1612	352	2.66	25.00	39.00	22.0	93	19	7.84	2468	2028	304	2.6	29.0	31.0	4.1
89-01- 8	333	523	48	61	1	7.74	1912	1764	357	2.72	24.40	40.00	19.2	57	18	7.85	2496	2096	314	2.6	29.6	31.0	4.6
89-01- 9	334	537	48	51	51	7.79	1960	1592	323	2.50	24.40	38.00	22.8	99	10	7.84	2368	2008	309	2.6	30.4	30.0	4.8
89-01-10	335	517	50	71	71	7.93	1916	1576	322	2.50	23.30	38.00	11.2	116	20	7.99	2316	1956	316	2.6	23.3	38.0	2.4
89-01-11	336	552	52	45	3	7.84	1832	1548	382	2.34	24.60	34.00	12.8	73	20	7.93	2288	1960	306	2.5	26.2	32.0	2.2
89-01-12	337	507	51	37	13	7.89	1840	1592	371	2.67	23.30	40.00	22.0	73	24	7.97	2284	2000	313	2.7	26.2	35.0	3.1
89-01-13	338	548	54	53	16	7.91	1772	1444	404	2.56	23.50	40.00	24.4	53	24	8.01	2304	1920	318	2.6	27.2	33.0	3.3
89-01-14	339	469	52	29	11	7.85	1916	1596	382	2.88	25.90	38.00	26.8	45	17	7.96	2472	2108	310	2.5	26.4	33.0	4.5
89-01-15	340	512	47	57	6	7.83	1876	1564	355	2.78	22.30	42.00	39.2	57	21	7.92	2204	1844	298	3.0	20.9	47.0	6.6
89-01-16	341	500	47	33	1	7.95	1812	1556	349	2.74	22.90	42.00	41.2	37	13	8.00	2260	1988	295	2.7	24.1	39.0	6.5
89-01-17	342	545	55	41	5	7.93	1864	1552	339	2.59	26.70	35.00	38.4	65	20	8.00	2416	2064	289	2.7	23.7	39.0	6.7
89-01-18	343	496	55	49	4	7.96	1916	1604	365	2.82	22.10	41.00	29.6	61	22	8.02	2416	2048	296	2.9	21.3	42.0	7.2
89-01-19	344	504	54	41	6	7.62	1856	1524	341	2.72	24.10	37.00	34.4	77	20	7.93	2368	2004	288	2.8	24.1	39.0	6.7
89-01-20	345	520	57	49	12	7.97	1812	1496	368	2.64	25.70	37.00	35.2	69	16	8.01	2332	1968	286	2.9	22.9	42.0	7.0
89-01-21	346	528	58	73	2	7.88	2032	1668	328	2.62	27.90	34.00	30.8	20	7	7.95	2476	2008	289	2.8	26.4	37.0	6.3
89-01-22	347	524	60	57	57	7.87	2004	1616	332	2.66	25.90	37.00	32.0	73	25	7.93	2404	2008	305	2.8	26.4	35.0	7.0

Date	day	Influent COD mgCOD/l	TKN mgN/l	CFR1 COD mgCOD/l	Effluent and mixed liquor TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l	CFR2 COD mgCOD/l	Effluent and mixed liquor. TKN mgN/l	pH	MLSS mg/l	MLVSS mg/l	DSVI [illegible]	DO mgO/l	OUR mgO/l/h	%Aer. %	NO3 mgN/l
89-01-23	348	509	56	49	8	7.91	1976	1588	329	2.72	26.70	37.00	29.6	77	21	7.97	2404	2008	291	2.7	27.4	34.0	5.7
89-01-24	349	535	50	53	4	7.95	2000	1628	333	2.43	26.40	34.00	30.8	78	22	8.01	2380	1996	294	2.8	25.0	35.0	7.9
89-01-25	350	490	57	29	4	7.96	2094	1756	334	2.59	28.50	33.00	34.0	78	19	8.05	2484	2112	282	2.6	28.7	32.0	7.3
89-01-26	351	526	52	37	9	7.97	1984	1652	327	2.78	26.40	38.00	38.0	65	20	8.02	2360	2016	282	2.9	24.6	40.0	7.9
89-01-27	352	526	52	29	20	7.89	2012	1680	323	2.60	27.40	34.00	38.8	16	20	7.95	2456	2088	285	2.7	26.4	36.0	6.2
89-01-28	353	535	65	33	17	7.85	1938	1714	326	2.60	27.70	35.00	34.0	73	10	7.91	2316	1796	289	2.7	25.5	38.0	7.3
89-01-29	354	547	48	41	5	7.91	2076	1764	313	2.70	29.80	33.00	28.4	90	17	7.95	2496	2144	267	3.0	29.6	35.0	6.0
89-01-30	355	559	48	53	2	7.86	2076	1752	321	2.62	30.70	32.00	27.2	78	20	8.01	2332	2032	278	2.7	29.0	34.0	5.0
89-01-31	356	514	48	69	69	7.97	1952	1640	350	2.66	31.00	32.00	35.2	69	14	8.07	2332	2000	300	2.9	29.0	37.0	5.4
89-02- 1	357	498	43	29	9	8.01	2036	1652	327	2.62	31.00	34.00	34.4	41	10	8.06	2366	196	298	2.8	28.5	35.0	5.5
89-02- 2	358	528	48	32	1	7.98	1972	1536	321	2.56	28.50	33.00	32.4	69	3	8.01	2336	1916	278	2.9	27.9	37.0	5.7
89-02- 3	359	498	47	42	2	7.88	1988	1620	302	2.43	28.50	33.00	39.6	32	3	8.01	2272	1876	300	2.8	31.0	34.0	7.0
89-02- 4	360	504	51	32	5	7.81	1852	1692	324	2.43	27.90	33.00	44.4	52	7	7.84	2276	2060	278	2.8	30.7	34.0	7.5
89-02- 5	361	492	49	36	8	7.87	1748	1528	343	2.60	28.50	35.00	33.8	34	6	7.93	2188	1932	289	2.9	29.6	37.0	5.8
89-02- 6	362	480	48	48	8	7.98	1920	1616	295	2.34	28.50	30.00	20.0	20	6	8.02	2376	2024	266	2.4	32.6	28.0	4.6
89-02- 7	363	363																					
89-02- 8	364	471	48	49	7	7.78	1932	1624	276	1.73	20.40	33.00	17.9	45	8	7.83	2236	1888	238	1.7	22.1	30.0	4.2
89-02- 9	365																						
89-02-10	366																						
89-02-11	367																						
89-02-12	368																						
89-02-13	369																						
89-02-14	370																						
89-02-15	371	447	49	53	7	8.11	1680	1400	317	2.14	20.20	40.00		14.8	92	7	8.21	1888	1608	256	2.5	23.7	
89-02-16	372	525	48	37	4	8.12	1696	1472	304	1.98	20.60	35.00		33.9	61	7	8.37	1888	1636	265	2.1	17.3	
89-02-17	373	493	49	20	2	7.97	1832		273	2.08	15.50	37.00		39.3	33	8	7.80	2056		227	2.6	17.3	
89-02-18	374	496	50	37	2	7.88				2.50	19.90	45.00		45.0	45	6	8.05				2.9	21.3	

PHASE I
STEADY STATE PERIOD DATA.

CFR1

day	Sti mgCOD/l	Nti mgN/l	Ste mgCOD/l	Nte mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	peak DO mgO/l	OUR mgO/l/h	OUR/VSS mgO/gVSS.h	%AEROBIC	Nne mgN/l
1-28	523	91	77	29	7.88	3778	3123	173	2.29	45.48	1.95	44.19	3.3
29-41	518	79	63	23	7.78	3384	2797	219	1.81	33.27	1.59	34.42	19.1
42-58	523	82	69	19	7.72	2213	1827	214	2.26	40.36	3.06	31.58	7.6
59-76	523	80	68	18	7.68	1685	1410	214	2.25	37.95	3.59	39.44	20.3
77-92	536	81	67	38	7.84	1539	1333	257	2.51	26.15	2.63	35.71	34.2
93-118	525	47	72	45	7.87	1854	1604	389	2.57	27.16	2.29	31.88	6.2
120-129	503	57	67	36	7.96	2175	1833	354	2.24	22.65	1.65	36.45	10.9
130-145	523	59	63	19	7.78	1919	1628	262	2.43	28.07	2.30	31.53	39.6
146-154	530	55	52	15	7.94	1762	1468	181	1.98	21.00	2.02	35.00	30.7
155-188	508	52	48	11	7.79	1942	1624	415	2.11	26.35	2.23	33.89	29.2
191-215	511	48	47	9	7.85	1766	1525	397	2.48	22.03	1.92	37.66	4.6
217-259	514	50	58	9	7.91	1563	1317	412	2.41	22.76	2.28	39.19	38.8
260-297	518	48	72	8	7.89	2113	1791	359	2.24	24.01	1.79	34.22	5.4
298-373	518	51	43	11	7.90	1954	1633	340	2.53	23.61	1.94	39.04	52.7

CFR2

day	Sti mgCOD/l	Nti mgN/l	Ste mgCOD/l	Nte mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	peak DO mgO/l	OUR mgO/l/h	OUR/VSS mgO/gVSS.h	%AEROBIC	Nne mgN/l
1-17	522	94	57	17	7.84	3674	3029	270	2.56	76.33	3.45	30.32	9.6
18-28	524	86	56	11	7.71	3429	2864	237	2.43	68.41	3.20	32.03	6.6
29-41	518	79	49	25	7.79	3072	2551	245	1.83	37.38	1.96	32.07	25.6
43-59	523	82	51	23	7.74	2819	2339	221	2.20	41.78	2.39	30.44	16.3
60-76	523	80	43	18	7.57	2636	2242	328	2.13	48.57	2.91	37.53	30.0
77-89	535	84	46	18	7.51	2646	2227	523	2.05	55.16	3.31	37.88	29.9
90-119	526	49	51	6	7.11	2251	1929	739		29.83	2.13	100.00	85.1
120-129	503	57	64	44	8.13	2334	1964	346	2.31	22.73	1.55	35.45	8.7
130-145	523	59	45	23	8.04	2202	1875	294	2.40	26.57	1.89	30.69	25.4
146-154	530	55	32	22	8.16	2056	1781	219	2.08	21.69	1.63	33.11	27.2
155-188	506	52	34	11	8.01	2203	1928	302	2.13	28.12	1.89	32.50	5.1
191-215	511	48	34	3	8.09	1983	1659	724	2.33	22.61	1.83	38.80	31.5
217-259	514	50	53	8	8.03	2253	1892	394	2.30	28.43	1.99	31.84	6.8
260-297	518	48	71	7	7.98	2048	1717	491	2.50	26.39	2.09	34.71	40.6
298-373	518	51	41	13	7.92	2129	1179	190	13.49	29.82	2.17	19.63	7.3

APPENDIX B

Experimental data measured on systems CFR1 and CFR2 during phase II of the investigation

APPENDIX B

date	Day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR 1 Effluent and mixed liquor. COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	Peak DO mgO/l	OUR mgO/l/h	%Aer.	Nne mgN/l	CFR 2 Effluent and mixed liquor. COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	Peak DO mgO/l	OUR mgO/l/h	%Aer	Nne mgN/l
21-2-89	1	461	46.5	17.4	0.0	7.9	1906	1660	271	2.3	22.2	37		40.5	1.7	8.1	2048	1672	252	2.7	27.0	35	
22-2-89	2	489	42.6	85.0	6.9	8.1	1900		246	2.2	26.8	29		80.5	7.8	8.3	1700		294	2.7	31.8	32	
23-2-89	3	518	46.8	29.6	1.7	8.0	1712		312	1.9	21.7	35		28.3	10.9	8.2	2108		269	2.3	25.2	31	
24-2-89	4	552	47.3	42.5	2.0	8.2	1718	1566	330	2.4	24.7	34		44.1	10.9	8.3	1566	1406	394	2.9	12.1	34	
25-2-89	5	506	42.6	47.0	1.3	8.2	1694	1476	335	2.3	25.4	31		43.7	9.5	8.2	2074	1796	346	2.7	30.9	31	
26-2-89	6	542	43.1	41.7	7.8	8.7	2026	1690	280	2.0	19.7	35		40.5	6.0	8.9	1614	1320	434	2.3	22.3	32	
27-2-89	7	520	41.4	45.5	7.5	8.0	1668	1416	380	2.6	24.5	35		45.1	4.2	8.1	2072	1744	378	2.7	30.6	30	
28-2-89	8	519	45.4	62.5	4.9	8.0	1790	1450	372	2.8	24.4	34		52.4	7.6	8.2	2168	1704	369	2.8	29.6	34	
1-3-89	9	539	50.0	48.4	9.7	8.2	1646	1380	415	2.5	27.2	33	18	42.3	6.7	8.2	2002		450	3.1	35.7	37	26.9
2-3-89	10	648	53.5	62.5	7.9	8.1	1748	1536	372	2.4	25.4	34	20	66.2	7.1	8.2	1676	1472	338	2.2	17.9	38	33.5
3-3-89	11	539	46.1	58.7	8.4	8.1	1574	1242	424	2.8	21.2	37	19	56.6	7.0	8.2	2020	1634	396	2.2	22.6	33	35.7
4-3-89	12	529		45.1		8.0	1654	1360	423				26	63.9		8.1	2234	1874	343				20.2
5-3-89	13	462		84.9		7.9	1674	1454	398				22	72.3		8.1	2190	1898	350				37.8
6-3-89	14	524		49.9		7.9	1648	1326	384	2.5	25.1	36	40	54.5		8.2	2028	1614	345	2.6	27.4	37	27.2
7-3-89	15	503	42.1	40.6	0.0	8.0	1726	1484	473	2.4	27.9	34	33	50.7	10.5	8.2	1986	1708	411	3.1	34.9	44	41.2
8-3-89	16	450	59.8	46.1	8.7	8.0	1616	1364	495	2.5	25.5	36	29	43.3	14.1	8.2	2032	1708	410	2.9	33.0	33	37.3
9-3-89	17	549		58.4	12.2	8.1	1596	1326	491	2.5	28.2	35	28	56.3	1.7	8.2	1958	1644	400	3.0	37.2	33	30.7
10-3-89	18	547	63.0	50.3	18.6	8.1	1630	1372	470	2.3	30.8	30	22	46.3	0.0	8.2	1864	1576	367	2.7	33.1	30	15.4
11-3-89	19	558	61.0	53.3	21.4	7.8	1706	1464	440	4.5	44.2	55	8.8	50.5	21.3	7.8	2140	1798	389	3.0	34.6	31	17.2
12-3-89	20	535	57.5	48.3	23.9	7.8	1724	1432	483	2.7	24.7	35	2.8	52.3	23.7	7.7	2198	1846	455	3.4	37.8	34	12.8
13-3-89	21	521	60.3	54.3	29.8	8.0	1874	1620	409	2.6	28.3	35	3.2	43.5	20.4	8.1	2150	1820	450	2.9	32.4	33	12.4
14-3-89	22	527	72.8	31.1	24.2	8.0	1666	1530	440	2.8	29.7	34	3.2	35.1	24.4	8	1736	1810	538	3.0	33.9	32	14.8
15-3-89	23	540	61.0	38.1	22.9	8.0	1808	1578	406	2.7	27.2	38	11	36.5	25.1	8	2140	1860	475	2.9	33.0	33	19.2
16-3-89	24	536	58.1	40.2	22.4	8.0	1854	1608	414	4.6	30.7	46	20	44.2	20.3	8.2	2118	1820	504	3.1	34.4	33	24.0
17-3-89	25	497	57.1	31.1	20.3	8.0	1808	1572	406	2.7	16.3	44	33	37.1	19.3	7.9	2047	1810	482	1.8	18.1	27	31.2
18-3-89	26	526	59.9	64.3	0.0	8.1	1666		560	4.2	27.3	56	42	58.2	13.5	8.1	1930		570	2.9	30.5	36	34.8
19-3-89	27	535	57.4	49.2	21.4	8.0	1710		448				46	49.2	14.7	8	2068		532				34.4
20-3-89	28	493	60.6	61.2	17.7	8.0	1680	1462	456	4.6	28.1	42	38	61.2	14.7	8.1	2066	1814	500	2.8	31.3	34	13.6
21-3-89	29	515	59.6	52.9	22.1	7.9	1702	1448	411	2.9	23.0	50	23	44.8	13.0	8	2162	1858	401	2.4	29.6	32	12.0
22-3-89	30	405	57.1	63.1	24.3	7.8	1730	1486	443	2.4	18.3	44	24	44.8	24.5	7.9	2238	1934	395	2.4	27.9	33	17.6
23-3-89	31	558	54.5	68.1	24.4	8.1	1664	1082	461	2.9	22.8	51	27	54	16.1	8.1	2198	1790	387	2.6	30.1	33	32.8
24-3-89	32	658	59.6	52.9	22.7	8.2	1740	1516	479	4.2	40.6	43	24	36.6	12.0	8.2	2184	1910	443	2.6	30.5	32	26.8
25-3-89	33	527	53.8	61.1	22.9	7.9	1952	1626	410				20	44.8	13.4	8	2278	1928	395				41.6
27-3-89	34	550	58.5	48.9	26.2	7.9	1864	1578	429	2.9	20.2	46	15	44	14.1	7.8	2358	1982	360	2.9	29.4	31	38.4
28-3-89	35	520	49.8	59.6	20.6	8.2	1854	1640	414	2.6	19.3	45	21	33.6	8.1	8.2	2432	2116	350	2.6	27.3	34	31.6
29-3-89	36	560	54.6	64.0	19.7	8.0	1892	1620	423	4.2	19.8	43	22	43.5	12.9	8	2426	2038	412	2.6	31.5	29	40.4
30-3-89	37	563	57.4	48.8	19.9	8.0	2002	1728	416	3.3	24.0	51	17	41.5	7.9	8	2410	2056	346	2.2	28.8	29	43.2
31-3-89	38	510	55.2	37.8	20.4	8.1	1930	1718	440	3.6	27.9	56	18	36.9	8.1	8.1	2180	1902	367	2.9	33.5	33	43.6
1-4-89	39	485	44.1	35.9	18.3		1942	1644	412	2.6	19.4	44	27	21.6	7.4		2372	1988	393	2.5	35.6	29	44.0
2-4-89	40	468	49.8	52.1	17.6		1834	1560	418	2.5	24.6	36	26	56.1			2074	1758	378	2.7	35.9	29	37.2
3-4-89	41	501	49.1	49.3	14.6	7.9	1914		383	3.0	28.9	38	23	36.9	8.7	8	2216		353	2.7	41.9	25	15.6
4-4-89	42	466	49.7	55.4	10.1					3.5	24.5	41	28	51.3	1.3					3.0	34.5	31	18.0
5-4-89	43	527	53.8	56.0	15.6	7.8	1752	1552	438	2.9	24.2	42	32	52	8.1	7.8	2082	1818	360	3.2	35.8	31	34.8
6-4-89	44	482	56.0	51.6	18.6	7.8	1880	1660	417	2.1	23.4	32	31	70.6	8.0	7.8	2100	1798	333	2.5	34.4	24	37.2
7-4-89	45	516	39.5	72.6	15.5	8.1	1798	1490	426	2.0	25.2	28	20	84.7	6.4	8.2	2114	1802	331	2.8	41.0	24	36.8
8-4-89	46	537	42.3	47.4	10.4	8.2	1814	1568	450	2.1	22.7	34	19	45.4	5.6	8.3	2140	1840	319	2.4	34.3	29	27.2
9-4-89	47	579	38.9	48.6	8.4	8.3	1806	1582	443	2.2	25.6	30	17	32.5	6.8	8.4	2122	1830	346	2.9	38.7	23	22.4
10-4-89	48	491	39.3	48.2	12.9	8.3	1760	1498	436	2.6	30.4	30	14	47.4	7.6	8.5	2146	1816	326				12.8
11-4-89	49	560	42.3	53.3	12.2		1682	1364	416	3.7	35.1	40	15	43.3	8.7		2166	1796	323	3.1	36.1	29	18.0
12-4-89	50	550	40.0	52.5	7.6	7.6	1706	1452	401				16	57.3	14.6	7.7	2136	1802	312				12.0
13-4-89	51	543		50.9	8.5	7.8	1562	1346	405	3.3	22.8	45	12	61	9.2	7.8	2034	1768	262	2.7	26.8	30	15.2
14-4-89	52	564	43.5	49.3	9.3	7.9	1658	1456	392	1.6	19.7	31	16	44.5	8.9	7.9	1864	1616	259	2.2	27.0	29	13.2
15-4-89	53	534	25.3	54.5		8.0	1756		351	1.7	18.9	33	2.8	53.3	10.8	7.9	1944		248	2.7	35.8	28	3.6
16-4-89	54	551	42.3	47.7	10.4		1652	1402	373				6	50.9	13.2		1988	1702	226				4.0
17-4-89	55	533	41.9	49.9	21.0	7.7	1552	1456	430	2.4	23.2	30	3.6	48.3	8.8	7.7	1940	1768	241	2.4	35.4	27	4.4
18-4-89	56	520	39.2	49.1	9.3	7.7	1630	1396	389				8.4	51.2	11.2	7.6	2022	1734	231				6.4
19-4-89	57	535	38.6	47.1	9.8	7.6	2178	1474	367	4.0	19.5	67	20	55.3	8.8	7.6	2452	1700	184	2.3	26.4	32	14.8
20-4-89	58	542	57.4	45.1	9.5	7.6	1500	1454	556	3.7	21.8	58	32	53.3	15.3	7.7	1672	1526	299	2.5	27.1	33	21.6
21-4-89	59	414	48.2	49.1	10.5	7.7	1872	1614	454	3.7	23.5	61	40	55.3	15.8	7.7	2072	1800	265	2.5	26.1	34	26.0
22-4-89	60	502	51.8	53.3	9.1	7.7	1774	1570	460	3.7	22.9	56	41	47.1	16.6	7.8	1914	1688	296	2.6	27.1	35	26.8

		Influent		CFR 1 Effluent and mixed liquor.										CFR 2 Effluent and mixed liquor.									
date	Day	COD	TKN	COD	TKN	pH	MLSS	MLVSS	DSVI	Peak DO	OUR	%Aer.	Nne	COD	TKN	pH	MLSS	MLVSS	DSVI	Peak DO	OUR	%Aer	Nne
		mgCOD /l	mgN /l	mgCOD /l	mgN /l		mgSS /l	mgVSS /l	ml/g	mgO/l	mgO /l/h		mgN /l	mgCOD /l	mgN /l		mgSS /l	mgVSS /l	ml/g	mgO/l	mgO /l/h		mgN /l
25-4-89	62	513	57.0	42.6	10.8	7.8	1934	1712	362	4.8	32.7	52	46	44.6	18.6	7.9	2096	1860	270	1.9	26.7	26	17.2
26-4-89	63	519	58.7	32.5	19.9		1994	1778	401	4.5	32.7	49	54	48.7	9.0		2124	1894	251	1.9	25.7	29	21.6
27-4-89	64	530	58.0	47.1	5.0	7.9	1906	1668	446				60	45.1	16.7	8	1958	1688	289				26.9
28-4-89	65	501	60.9	52.4	0.0					3.4	32.6	38	48	44.2	15.8					2.8	28.8	36	22.4
29-4-89	66	519	57.4	56.5	7.8		1908	1556	489	3.3	31.1	38	44	17.6	14.3		2218	1844	270	2.8	29.1	34	17.2
30-4-89	67	538	58.2	48.5	9.2	7.8	1880	1608	727	3.6	33.9	39	48	43.6	16.2	7.9	2066	1780	307	2.3	28.5	32	38.8
1-5-89	68	530	52.4	46.5	7.1	7.7	1988	1686	461				65	50.6		7.8	2246	1880	337				2.2
2-5-89	69	513	62.2	43.2	5.3		1962	1584	467	5.6	28.7	67	****	41.2	12.3		2146	1770	287	2.9	31.5	35	67.3
3-5-89	70	538	60.6	37.9	6.9	7.8	2014	1702	546	4.6	28.8	58	108	46.1	13.3	7.9	2170	1828	277	2.6	31.4	33	79.2
4-5-89	71	334	50.1	43.4	3.9	7.7	1992	1654	460	4.9	17.1	95	110	43.4	11.2	7.8	2038	1696	270	2.6	26.3	37	86.0
5-5-89	72	494	49.3	32.8	5.3	7.6	1874	1662	454	4.5	17.4	90	104	41	5.9	7.8	2016	1778	265	2.4	26.9	33	67.6
6-5-89	73	475	45.1	41.0	5.0	7.7	1960	1632	400	4.3	17.1	82	70	47.1	10.6	7.8	1922	1640	277	2.3	27.5	32	31.6
7-5-89	74	471	49.0	34.8	5.9	7.7	2248	1860	297	3.6	17.0	71	55	34.8	7.4	7.8	2192	1830	266	2.3	26.5	32	16.8
8-5-89	75	479	50.1	49.0	2.4	7.8				3.5	16.0	69	64	67.3	8.7	7.8				2.1	25.3	31	16.0
9-5-89	76	488	46.8	51.0	4.2	8.0	1968	1722	339	4.6	26.8	59	61	38.8	19.5	8	2044	1810	302	2.3	30.7	30	7.6
10-5-89	77	600	69.4	42.8	7.4	7.9	2082	1750	368	4.5	45.9	37	0.1	44.9	11.1	8	2164	1856	277	2.2	29.8	27	0.1
11-5-89	78	519	61.5	37.7	4.9	7.7	2986	2712	301	5.5	30.0	64	104	37.7	11.8	7.9	4114	3726	154	2.4	32.3	30	12.8
12-5-89	79	532	61.3	30.2	2.5	7.7	2042	1740	498	5.7	26.2	70	112	46.4	14.0	7.8	2066	1768	331	2.7	28.5	36	37.2
13-5-89	80	475	55.7	31.3	4.9	7.6	1996	1696	635	4.8	27.4	61	112	29.2	16.4	7.8	2108	1814	332	2.4	27.4	32	80.0
15-5-89	81	515	59.4	41.3	6.9		1982	1626	899	4.9	26.1	64	112	43.3	17.1		2302	1972	333	2.5	25.8	34	94.0
16-5-89	82	550	60.1	46.4	0.0	7.7	2086	1824	1039	3.8	21.4	59	112	46.4	12.0	7.9	2180	1924	367	2.0	24.8	31	95.2
17-5-89	83	573	64.7	40.3	5.6		1994	1694	1354	3.9	29.0	54	112	44.4	20.2		2048	1722	391	2.0	23.9	32	97.6
18-5-89	84	558	67.5	42.3	2.9	7.7	2068	1692	1378	3.6	29.2	47	112	50.4	21.3	7.9	2216	1850	384	2.0	23.3	32	89.2
19-5-89	85	566	56.3	56.8	4.9	7.6	1916	1596	1026	1.9	25.4	63	112	54.8	21.1	8	2066	1742	460	2.1	22.4	34	86.0
20-5-89	86	544	63.0	44.6	3.1	7.6	2124	1678	1271	2.1	25.9	66	112	56.8	23.0	7.9	2232	1800	463	2.1	23.0	34	80.0
21-5-89	87	484	62.1	43.6	4.2								112	51.7	22.8								82.0
22-5-89	88	480	62.2	55.8	4.8	7.6	1950	1730	872	1.9	20.9	57	112	51.7	19.9	7.8	5072	4042	437	2.0	14.1	51	88.0
23-5-89	89	499	64.4	39.1	2.0	7.6	2150	1748	853	2.1	25.6	60	38	55.4	17.5	7.8	2168	1774	999	2.2	16.3	48	81.0
24-5-89	90	496	59.6	36.6	3.2	7.6	1948	1834	1531	1.8	22.9	57	73	61	17.9	7.7	2012	1948	****	2.0	12.3	56	46.5
25-5-89	91	494	63.3	44.1	2.8	7.6	2148	1778	512				60	66.7	22.5	7.7	1958	1596	476				46.0
26-5-89	92	504	55.7	46.2	2.5	7.5	1964	1768	552	1.8	15.0	72	94	79	17.2	7.6	1728	1584	540	1.9	12.7	51	38.0
27-5-89	93	564	64.4	45.1	5.6	7.6	2062	1770	517	2.0	20.9	61	56	71.8	14.6	7.7	1832	1582	428	1.8	18.4	34	38.0
28-5-89	94	539	56.8	38.0	4.5	7.7	2074	1646	522	1.8	21.4	61	56	54.4	14.8	7.8	1794	1434	427	1.7	15.8	35	30.5
29-5-89	95	511	67.0	43.1	3.6	7.5	2052	1744	471	1.8	19.7	59	57	59.5	12.5	7.8	1832	1560	418	1.6	15.1	35	28.0
30-5-89	96	538	60.2	43.1	3.4	7.5	1764	1546	482	1.5	16.5	57	57	80	14.6	7.7	1978	1738	421	1.3	12.1	33	22.5
31-5-89	97	514	54.6	37.7	3.7					1.8	15.7	70	64	70.2	15.3					1.8	18.9	35	21.5
1-6-89	98	494	58.2	35.6	5.9	7.6	1948	1700	368	2.0	22.2	58	68	54	15.7	7.6	1640	1442	478	1.8	18.6	35	28.0
2-6-89	99	497	56.6	52.9	2.8	7.5	1904	1634	350	2.1	14.5	86	72	61.1	11.1	7.7	1672	1444	478	1.6	17.0	34	27.5
3-6-89	100	438	51.5	36.6	3.6	7.5	1920	1566	321	1.4	10.3	83	77	48.9	11.4	7.7	1750	1624	467	1.4	15.7	33	28.7
4-6-89	101	517	57.7	55.0	4.9		1808	1510	313	1.6	12.7	81	79	67.2	11.3		2136	1754	414	1.5	16.5	34	39.5
5-6-89	102	531	55.4	34.6	2.5	7.5	1848	1572	307	1.5	11.0	82	90	48.9	8.7	7.7	1694	1470	807	1.4	17.1	32	39.5
6-6-89	103	511	58.0	38.7	3.5		1970	1626	271	2.4	22.4	63	84	55	11.5		1810	1486	460	2.1	25.7	29	36.0
7-6-89	104	503	56.3	38.7	1.4	7.6	1850	1642	297	2.6	26.4	58	74	59	9.5	7.8	1594	1434	533	2.1	26.6	28	34.5
8-6-89	105	483	49.0	47.3	4.2	7.7	1932	1676	267	1.9	23.0	53	64	55.5	13.2	7.8	1778	1506	459	1.8	22.3	32	30.0
9-6-89	106	498	57.7	37.0	9.0	7.8	2006	1692	282	2.1	23.3	55	47	49.3	16.0	7.9	1830	1558	419	1.8	24.6	29	19.0
10-6-89	107	551	54.0	45.2	6.4	7.7	2068	1790	282				48	55.5	14.4	7.9	1830	1562	474				19.0
11-6-89	108	547	51.8	53.5	3.9	7.7	2032	1686	254	1.8	16.7	59	56	49.3	9.9	7.9	1722	1430	455	2.1	21.8	33	16.5
12-6-89	109	536	48.4	37.0	1.7	7.7	1996	1716	217	2.2	30.6	45	66	55.5	6.4	7.9	1698	1444	442	1.9	21.7	30	18.5
13-6-89	110	525	48.7	40.1	2.4	7.8	2040		209	2.1	27.2	49	63	62.7	9.0	7.9	1814		441	1.9	22.2	29	24.0
14-6-89	111	533	47.3	35.0	1.0		1992	1710	192	1.9	28.5	44	66	47.3	33.9		1588	1350	462	1.9	22.1	30	16.0
15-6-89	112	537	49.6	34.8	0.0		2072	1806	161	2.2	19.2	70	64	61.4	13.2		1644	1360	456	2.2	23.0	32	16.5
16-6-89	113	520	47.6	79.9	2.9	7.7	2168	1870	138	2.4	24.7	57	74	59.4	11.9	7.8	1684	1396	455	2.0	21.0	34	24.0
17-6-89	114	504	52.6	49.1	2.4								69	57.3	7.2								29.5

		Influent		CFR 1	Effluent and mixed liquor.									CFR 2	Effluent and mixed liquor.								
date	Day	COD	TKN	COD	TKN	pH	MLSS	MLVSS	DSVI	Peak DO	OUR	%Aer.	Nne	COD	TKN	pH	MLSS	MLVSS	DSVI	Peak DO	OUR	%Aer	Nne
		mgCOD /l	mgN /l	mgCOD /l	mgN /l		mgSS /l	mgVSS /l	ml/g	mgO/l	mgO /l/h		mgN /l	mgCOD /l	mgN /l		mgSS /l	mgVSS /l	ml/g	mgO/l	mgO /l/h		mgN /l
18-6-89	115	549	58.0	57.3	3.5	7.5	1922	1592	121				70	53.3	8.8	7.7	1596	1288	501				22.5
19-6-89	116																						
20-6-89	117	508	50.4	57.3	4.5	7.5	2080	1816	112	2.3	24.6	60	66	65.5	11.6	7.8	1770	1540	471	2.1	19.9	38	28.5
21-6-89	118	495	56.6	40.9	2.9								65	53.1	12.1								22.0
22-6-89	119	495	56.8	42.9	6.3	7.5	1812	1486	147	2.2	21.7	60	49	45	15.4	7.7	1498	1202	534				14.5
23-6-89	120	460	44.2	67.5	3.5								50	55.2	9.4								27.0
24-6-89	121	427	59.9	47.0	4.8	7.4	1898	1460	158	2.2	15.5	79	70	55.2	11.3	7.7	1670	1284	499	2.2	16.8	41	34.5
25-6-89	122																						
26-6-89	123	247.3	48.2	38.8	3.1	7.4	1922	1676	156				60	42.9	6.9	7.7	1606	1396	488				34.5
27-6-89	124	495	45.1	45.0	7.0	7.4	1666	1388	170	2.2	20.0	64	77	47	10.6	7.7	1364	1102	562	2.5	19.0	41	36.5
28-6-89	125	538	69.4	34.8	2.8	7.5	2120	1706	142	1.9	23.3	54	76	40.9	9.2	7.7	1674	1334	438	2.3	19.2	40	37.0
29-6-89	126	536	62.4	28.6	4.9	7.6	2026	1524	148				74	45	11.8	7.8	1658	1218	462				31.5
30-6-89	127	509	76.4	31.4	4.3								75	51.6	15.5								33.5
1-7-89	128	404	66.8	41.5	7.8								72	41.5	18.6								33.0
2-7-89	129																						
3-7-89	130																						
4-7-89	131						1900	1692	158	2.0	22.3	57	62			7.7	1786	1536	420	2.2	17.7	40	32.5
5-7-89	132	523	77.8	32.7	4.1	7.4	2052	1560	162	2.2	25.0	52	74	51.1	23.3	7.8	1918	1400	400	2.3	21.9	34	29.5
6-7-89	133	552	79.5	47.0	4.8	7.4	1874	1558	178				70	45	24.4	7.8	1908	1608	384				24.5
7-7-89	134	540	79.8	47.0	0.0								74	49.1	24.5								29.5
8-7-89	135	523		57.2									70	45	22.7								24.5
9-7-89	136	578	69.4										58	49.1									22.5
10-7-89	137	529	56.3	34.8	5.3	7.6	2058	1748	194	2.1	29.9	44	54	30.7	19.0	7.9	2074	1768	370	2.5	23.8	30	18.5
11-7-89	138	536	65.8	45.0	5.7		2238	2034	209	2.3	34.1	45	54	75.6	18.6		2244	2024	386	2.1	24.7	28	12.5
12-7-89	139	589	58.7	51.1	5.9	7.5	2250	1870	207				62	53.1	18.6	7.9	2246	1848	356				13.0
13-7-89	140	611	67.5	61.3	5.3	7.4	2066	1744	242	3.2	26.3	71	73	71.5	20.4	7.8	1916	1622	400	2.5	27.1	31	12.5
14-7-89	141	527	64.3	48.0	6.4	7.5	2166	2028	208	2.6	26.2	61	74	52	21.7	7.8	1910	1766	410	1.9	22.5	31	13.5
15-7-89	142	437	60.2	20.4	4.2								76	49	20.2								15.5
16-7-89	143	542	65.2	35.7	2.9	7.4	2050	1610	236				82	52	18.5	7.8	2098	1648	397				17.5
17-7-89	144	521	60.8	39.8	5.7	7.4	2124	1740	228	1.8	14.6	72	84	43.9	18.5	7.8	2044	1656	375	1.6	17.5	30	18.0
18-7-89	145	708	56.1	32.6	5.7	7.4	2154	1816	217	2.4	25.6	64	75	40.8	20.3	7.8	2064	1744	388	2.0	23.6	30	19.5
19-7-89	146	499	62.2	49.1	2.9	7.4	2030	1748	230	1.7	17.0	62	1.5	45	19.6	7.7	2122	1870	369	1.8	18.7	31	22.5
20-7-89	147	487	58.5	49.1	3.9	7.3	2182	1802	207	1.6	16.9	58	72	57.2	19.5	7.8	2174	1758	353	1.5	17.4	31	23.5
21-7-89	148	515	56.6	42.9	5.0		2136	1790	203	1.7	17.3	63	67	45	16.5		2038	1700	376	1.8	19.2	33	26.5
22-7-89	149	462	54.9	40.9	2.5	7.4	2056	1780	203				74	40.9		7.7	2044	1770	375				25.5
23-7-89	150																						
24-7-89	151	495	58.2	40.9	9.8	7.4	1636	1480	153				87	40.9	16.9	7.8	2268	2022	360				25.5
25-7-89	152	505	56.3	26.6	4.5	7.3	1612	1434	227				82	47	10.6	7.7	1782	1558	440				19.3
26-7-89	153	505	56.3	38.9	9.1	7.3	1786	1406	168	2.3	20.7	69	71	43	13.0	7.7	2222	1764	353	2.1	26.2	31	19.5
27-7-89	154	519	53.8	51.8	2.8	7.2	1494	1356	201				74	49.8		7.7	1864	1614	376				26.0
28-7-89	155																						
29-7-89	156	486	61.9	50.8	5.5								74	63	30.4								22.5
30-7-89	157	500	54.5	56.9	4.2		1636	1268	204				74	61	18.6		1860	1528	341				29.5
31-7-89	158	553	58.8	61.0	2.7	7.5	1882	1474	195	2.5	20.5	73	71	69.1	16.2	7.8	1966	1552	305	2.2	23.5	34	32.5
1-8-89	159	494	51.8	56.9	9.9	7.5	1728	1416	193	2.1	24.6	53	60	54:9	14.4	7.8	1862	1516	322	1.9	27.3	28	33.5
2-8-89	160	501	53.2	43.7	6.3		1976	1566	202	2.3	22.4	62	59	29.5	15.4		1886	1498	318	1.8	21.7	31	27.0
3-8-89	161	498	58.0	42.7	4.5	7.3	1964	1604	231	2.6	26.2	58	58	46.7	14.7	7.7	1930	1578	320	2.4	27.5	32	27.6
4-8-89	162	519	59.4	44.6	7.3	7.3	1950	1656	239	2.3	23.4	59	66	52.7	16.8	7.7	1964	1656	314	2.0	25.8	28	29.0
5-8-89	163	511	57.7	30.4	2.9		1842	1596	271				66	46.6	14.3		1985	1676	370				29.0
6-8-89	164																						
7-8-89	165	464	56.8	40.6	3.1	7.3	1978	1680	354	2.8	33.1	53	67	34.5	13.6	7.7	2028	1712	362	2.6	29.1	31	27.0
8-8-89	166	507	58.0	32.5	5.5	7.4	2066	1686	307	3.0	29.8	59	63	60.8	15.1	7.8	2126	1746	329	2.5	26.6	30	20.5
9-8-89	167	535	50.4	44.6	2.9	7.3	2154	1878	286	3.2	26.1	65	69	48.7	15.7	7.7	2050	1770	333	2.4	27.5	30	20.5

		Influent		CFR 1 Effluent and mixed liquor.										CFR 2 Effluent and mixed liquor.									
date	Day	COD mgCOD /l	TKN mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	Peak DO mgO/l	OUR mgO /l/h	%Aer.	Nne mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	Peak DO mgO/l	OUR mgO /l/h	%Aer	Nne mgN /l
10-8-89	168	537	53.9	41.0	3.4	7.3	2016	1708	347	3.1	24.1	74	76	49.1	17.5	7.8	2050	1732	374	2.6	26.6	32	17.5
11-8-89	169	524	55.7	49.1	3.2	7.3	2154	1808	263	3.2	23.5	79	78	57.3	14.1	7.8	2212	1868	332	2.4	24.9	33	22.5
12-8-89	170	479	56.8	43.0	3.4		1946	1726	291				63	49.1	16.1		1906	1700	402				24.5
13-8-89	171																						
14-8-89	172	504	56.0	41.0	3.5	7.4	1990	1668	226	3.1	20.1	92	93	41	14.4	7.7	2062	1714	436	1.9	20.4	33	42.0
15-8-89	173	481	53.2	38.9	3.1	7.3	2090	1800	215	2.9	23.3	69	74	34.9	11.6	7.7	2066	1826	411	2.3	23.8	33	29.5
16-8-89	174	477	59.6	56.0	5.0	7.3	2076	1780	193	3.3	21.6	82	78	45.7	13.8	7.7	1984	1674	487	2.2	22.9	32	33.5
17-8-89	175	523	55.7	54.0	3.4	7.2	2116	1762	197	3.0	24.0	75	83	85.1	14.4	7.8	2166	1770	546	2.5	26.6	35	35.5
18-8-89	176	542	55.2	54.0	2.7	7.2	2088	1704	200	3.2	24.5	77	78	62.3	16.3	7.7	2154	1788	511	2.3	22.4	33	38.0
19-8-89	177	492	54.3	43.6	1.3	7.3	2020	1720	198				78	54.8	12.7	7.8	2026	1708	609				29.5
20-8-89	178																						
21-8-89	179	500	54.3	39.4	0.0	7.5	1874	1508	178	2.9	24.2	72	75	56	15.7	7.8	2002	1630	416	2.5	27.2	32	34.0
22-8-89	180	544	54.6	45.7	4.8	7.5	1838	1572	190				82	49.8	14.7	7.8	2032	1710	369				39.0
23-8-89	181	504	63.0	53.5	1.5	7.4	1682	1440	198	3.3	26.7	73	90	74	14.4	7.8	1852	1576	414	2.5	23.7	37	37.0
24-8-89	182	487	61.0	47.3	4.3	7.2	1866	1568	197	3.0	29.6	60	84	51.4	16.4	7.7	1860	1598	376	2.5	24.8	34	45.5
25-8-89	183	504	61.9	51.4	4.1	7.1	1946	1658	188	3.2	37.5	51	83	47.3	16.5	7.6	1968	1668	339	2.6	26.3	33	46.0
26-8-89	184	526	65.1	43.2	5.7	7.2	2188	1860	160				77	51.4	18.5	7.6	2028	1726	321				46.0
27-8-89	185																						
28-8-89	186	553	65.4	47.3	3.9	7.4	1882	1658	204	3.4	43.9	55	74	53.5	18.9	7.8	1928	1676	311	2.4	27.7	32	38.5
29-8-89	187	545	64.7	43.2	5.3	7.4	1970	1714	195	3.2	38.0	56	78	51.4	18.5	7.8	1986	1722	294	2.4	27.9	31	37.5
30-8-89	188	577	64.1	49.1	1.1	7.3	1864	1618	179	3.0	29.1	77	89	59.4	19.0	7.8	2064	1772	266	2.4	29.6	31	29.1
31-8-89	189	477	50.9	47.1	5.2	7.3	2160	1822	162	3.4	32.4	68	89	51.2	20.4	7.8	2084	1796	392	2.4	29.3	32	26.3
1-9-89	190	479	55.7	41.0	0.0	7.2	2042	1770	155	3.3	20.4	100	88	53.3	15.7	7.8	2040	1726	335	2.4	28.8	31	26.7
2-9-89	191	491	50.4	20.5	4.5	7.5	1992	1680	142				90	36.9	13.4	7.7	2014	1702	314				27.1
3-9-89	192																						
4-9-89	193	522	53.5	28.7	2.8	7.4	2108	1648	142	3.1	23.5	78	77	32.8	10.4	7.8	2086	1648	360	2.4	28.6	29	18.8
5-9-89	194	504	49.3	41.0	6.1		2136	1702	140	3.0	20.4	83	65	59.4	9.5		2050	1598	374	2.4	24.5	34	21.7
6-9-89	195	520	54.8	36.9	3.2	7.7	1898	1626	149	3.4	17.3	100	74	53.3	6.3	7.8	1886	1598	380	2.4	25.9	33	25.2
7-9-89	196	504	52.1	53.3	4.3	7.5	1964	1692	144	2.6	22.8	69	71	57.3	10.8	7.7	1938	1666	482	2.3	25.1	33	30.0
8-9-89	197	512	51.5	45.1	2.4	7.5	1936	1642	155	2.7	28.2	58	70	49.1	7.0	7.8	1958	1664	358	2.2	29.3	29	30.0
9-9-89	198	469	47.6	38.9	4.9	7.5	2036	1662	164				77	45.1	9.1	7.7	1970	1630	541				19.3
10-9-89	199																						
11-9-89	200	469	51.9	38.9	5.5	7.5				2.8	27.1	65	74	41	11.9	7.7				2.2	29.3	30	25.2
12-9-89	201	479	49.6	41.0	3.4	7.4	1898	1738	193	2.7	22.6	75	74	28.7	4.9	7.7	1824	1644	439	2.2	27.6	31	29.6
13-9-89	202	453	53.8	44.9	2.1					2.9	23.8	72	70	44.9	6.4					2.3	27.9	32	34.2
14-9-89	203	483.5	48.4	34.7	3.5	7.4	1840	1534	199	3.1	31.5	65	78	42.8	6.6	7.6	1892	1548	370	2.2	32.0	29	38.0
15-9-89	204	484.5	48.7	43.9	5.7	7.4	1752	1532	238	2.8	27.3	65	78	43.9	8.7	7.6	1804	1532	397	2.3	27.9	32	35.6
16-9-89	205						1852	1590	270								1796	1534	418				
17-9-89	206																						
18-9-89	207	491.6	50.7	53.0	2.9	7.4	1546	1218	216	3.0	27.8	35	123	55.1	7.7	7.8	1792	1406	400	2.5	25.1	62	34.6
19-9-89	208	483.5	51.8	30.6	3.8	7.5	1776	1330	206	2.6	23.7	37	82	38.8	4.5	7.5	1930	1498	345	2.9	15.4	100	50.8
20-9-89	209	459.4	47.6	32.4	10.9	7.6	1660	1520	221	2.7	22.0	36	52	46.5	2.2	7.3	1818	1640	495	2.2	28.2	52	70.8
21-9-89	210	530.3	69.2	60.7	6.6	7.5	1476	1346	260	3.0	24.1	40	80	48.6	5.6	7.4	1690	1546	533	2.8	24.6	72	74.0
22-9-89	211	518.1	69.4	44.5	13.7	7.6	1854	1510	216	2.6	24.1	34	84	50.6	3.1	7.3	1954	1580	367	3.1	22.9	78	64.3
23-9-89	212	412.9	97.2	24.3	23.5	7.7	1716	1446	223				55	32.4	4.6	7.3	1906	1600	341				80.5
24-9-89	213																						
25-9-89	214	453.4	61.0	30.4	32.2	7.8	1822	1498	265	2.5	30.4	27	31	24.3	7.1	7.3	1944	1598	334	2.4	20.9	69	87.7
26-9-89	215	585.2	52.8	52.8	29.7	7.8	1922	1674	269	2.5	28.3	29	26	40.6	4.9	7.4	2002	1742	524	2.8	17.3	100	75.1
27-9-89	216	538.5	51.5	42.7	21.8	7.8	1762	1548	312	2.4	30.5	28	22	42.7	3.4	7.3	1866	1628	322	2.8	19.8	81	78.0
28-9-89	217	569	54.6	48.8	20.9		1776	1568	300	2.5	29.5	25	19	65	4.3		1892	1652	308	3.0	19.4	87	73.5
29-9-89	218	589.3		44.7		7.8	1808	1480	295	2.5	29.3	31	20	46.7		7.3	1952	1552	299	2.6	21.0	75	76.8
30-9-89	219	591.3	51.0	38.6	19.0	7.7	1772	1520	301				19	46.7	4.6	7.3	1906	1614	307				71.3
1-10-89	220																						

date	Day	Influent COD mgCOD /l	Influent TKN mgN /l	CFR 1 COD mgCOD /l	CFR 1 TKN mgN /l	CFR 1 pH	CFR 1 MLSS mgSS /l	CFR 1 MLVSS mgVSS /l	CFR 1 DSVI ml/g	CFR 1 Peak DO mgO/l	CFR 1 OUR mgO /l/h	CFR 1 %Aer.	CFR 1 Nne mgN /l	CFR 2 COD mgCOD /l	CFR 2 TKN mgN /l	CFR 2 pH	CFR 2 MLSS mgSS /l	CFR 2 MLVSS mgVSS /l	CFR 2 DSVI ml/g	CFR 2 Peak DO mgO/l	CFR 2 OUR mgO /l/h	CFR 2 %Aer	CFR 2 Nne mgN /l
2-10-89	221																						
3-10-89	222	485.6	53.9	44.7	17.8		1842		335				25	26.4	3.5		1994		167				82.7
4-10-89	223	512.1	49.8	44.7	17.4	7.7				2.4	23.6	32	29	32.5	3.4	7.4				2.4	17.6	82	98.7
5-10-89	224	551.6		48.8			1530	1240	392	2.5	24.1	36	19	36.5			1742	1432	155	2.1	21.0	61	76.8
6-10-89	225	543.5	51.0	66.9	20.3	7.5	1626	1374	359	2.1	19.4	35	16	54.8	3.9	7.2	1756	1500	152	2.1	24.4	51	58.0
7-10-89	226	454.3	49.6	77.1	18.9	7.6	1472	1194	362				25	77.1	5.9	7.3	1624	1372	170				69.2
8-10-89	227																						
9-10-89	228	494.8	50.5	73.0	20.6	7.6	1714	1390	331	2.6	22.2	41	33	52.7	1.5	7.3	1762	1446	151	2.2	24.4	57	72.3
10-10-8	229	473.5	51.1	43.6	17.5								20	43.6	1.6								72.3
11-10-8	230	473.5	51.2	41.6	17.8	7.6	1676	1464	328	2.7	26.6	36	26	47.7	9.8	7.3	1748	1546	162	2.3	30.2	51	69.2
12-10-8	231	482.7	51.8	36.5	17.8	7.6	1654	1360	333	2.5	27.4	34	29	48.7	3.6	7.2	1744	1474	162	2.6	22.5	65	67.2
13-10-8	232	455.4	44.5	36.4	15.7	7.6	1702	1390	353	2.5	27.1	33	27	56.7	2.7	7.4	1682	1398	159	2.6	21.2	73	71.2
14-10-8	233	437.2	44.2	12.1	13.9		1728	1380	347				23	40.5	2.8		1646	1322	152				71.7
15-10-8	234																						
16-10-8	235	506	46.2	50.6	14.2	7.7	1806	1526	369	2.5	22.8	34	28	46.5	2.9	7.4	1442	1000	208	2.5	23.5	63	66.2
17-10-8	236	477.7	48.2	36.4	12.7	7.7	1700	1390	343	2.6	22.3	35	24	30.4	3.9	7.4	1834	1526	145	2.5	21.3	71	69.2
18-10-8	237	441.2	43.4	24.3	13.0	7.6	1606	1364	363	2.6	22.1	36	30	24.3	4.9	7.3	1656	1428	141	2.5	22.0	69	72.3
19-10-8	238	534.5	50.1	49.0	14.1	7.6	1622	1456	329	2.3	24.1	36	30	44.9	4.5	7.3	1684	1416	139	2.2	20.7	67	72.3
20-10-8	239	499.8	50.4	22.4	13.3	7.6	1476	1300	327	2.3	22.0	36	27	26.5	2.7	7.3	1508	1314	150	2.1	21.4	61	72.3
21-10-8	240	493.7	45.4	32.6	13.7	7.7	1456	1150	309				29	40.8	4.8	7.4	1602	1280	125				75.5
22-10-8	[illegible]																						
23-10-8	242	493.7	49.6	32.6	14.4	7.7	1428	1336	292	2.5	22.7	37	28	32.6	3.2	7.5	1712	1596	127	2.6	17.6	85	78.8
24-10-8	243	605.9	47.3	46.9	12.3	7.6	1660	1424	291	2.4	23.2	37	26	36.7	2.9	7.4	1852	1606	126	2.1	17.6	66	77.7
25-10-8	244	587.5	44.5	32.6	12.2	7.7	1580	1382	253	2.3	24.6	33	28	44.9	4.3	7.3	1788	1572	131	2.1	22.2	60	71.2
26-10-8	245	579.4	49.6	49.0	11.5	7.6	1498	1308	256	2.4	22.6	33	26	44.9	2.7	7.3	1734	1482	144	2.3	22.2	62	66.2
27-10-8	246	514.1	46.5	28.6	10.9	7.6	1474	1262	237	2.4	23.2	38	27	36.7	4.2	7.3	1634	1402	143	2.1	22.8	58	62.5
28-10-8	247	495.7	39.5	38.8	13.2	7.6	1546	1300	205				30	51	5.2	7.3	1698	1448	128				62.5
29-10-8	248																						
30-10-8	249	471.2	44.8	55.1	9.2	7.6	1486	1266	224	2.4	21.5	42	33	47	3.1	7.3	1530	1320	142	2.3	22.5	60	66.2
31-10-8	250	487.6	39.8	42.8	10.6	7.6	1296	1126	244	2.3	18.9	40	32	34.7	5.6	7.3	1528	1340	142	2.3	24.5	60	66.0
1-11-89	251	501.8	42.8	49.0	12.2	7.6				2.1	19.9	35	31	36.7	5.7	7.3				2.2	23.0	60	63.2
2-11-89	252	510	45.4	49.0	14.1		1422	1210	199	2.2	20.3	38	28	32.6	4.1		1614	1408	124	2.0	22.2	59	58.5
3-11-89	253	489.6	45.1	36.7	12.9	7.7	1368	1012	207	2.2	15.1	45	29	28.6	5.7	7.4	1604	1232	114	2.0	23.5	58	60.6
4-11-89	254	452.9	42.0	36.7	12.9								31	51	5.9								60.7
5-11-89	255	489.6	46.8	57.1	12.3	7.7	1228	926	176	2.3	16.4	43	37	32.6	1.8	7.5	1430	1106	105	2.2	19.6	71	62.3
6-11-89	256																						
7-11-89	257	469.2	43.1	40.8		7.6	1482	1232	157	2.0	17.8	35	35	32.6	3.1	7.4	1570	1336	96	2.2	19.3	72	63.2
8-11-89	258	491.2	49.8	18.6	5.2	7.7	1282	990	195				36	33	11.5	7.3	1358	1080	110				67.4
9-11-89	259	478.9	41.2	61.9	7.1		1178	968	170	2.1	17.4	38	27	33	14.7		1328	1140	88	2.3	22.5	59	67.4
10-11-8	260	497.4	47.0	41.3	14.8	7.9	1130	1004	162				26	37.1	3.2	7.8	1266	1138	92				66.0
11-11-8	261	466.5	48.4	37.1	15.7	7.8	1254	952	146				32	49.5	3.4	7.4	1490	1126	101				72.3
12-11-8	262																						
13-11-8	263	466.5	45.9	45.4	16.9	7.7	1590	1370	115	1.9	18.9	32	23	31.4	3.2	7.3	1790	1584	84	2.2	23.1	61	71.3
14-11-8	264	454.1	52.6	33.0	18.8	7.7	1198	1158	195	1.9	19.7	30	22	49.5	4.3	7.3	1370	1330	134	2.3	22.4	63	73.9
15-11-8	265	463.3	46.2	34.5	17.5	7.7	1126	934	133				32	56.9	2.7	7.2	1442	1182	104				68.8
16-11-8	266	512.1	56.6	52.8	17.1	7.7	1216	1064	151	2.0	14.7	44	23	40.6	4.3	7.2	1392	1232	132	2.3	23.1	65	72.3
17-11-8	267	489.2	55.4	35.1	24.9	7.7	1288	1102	129	1.9	14.6	40	36	47.5	7.0	7.3	1494	1270	123	2.1	22.7	60	76.5
18-11-8	268	471.4	58.2	44.7	26.9								36	36.6	7.8								70.3
19-11-8	269																						
20-11-8	270	402.3	57.7	56.9	29.8	7.7	1224	1012	150	1.9	16.7	36	32	40.6	11.2	7	1422	1186	152	2.4	24.1	63	69.3
21-11-8	271	496.7	62.7	42.9	30.2	7.8	1484	1136	135				25	40.9	6.6	7.3	1616	1304	165				76.5
22-11-8	272	558	61.0	32.7	30.1	7.9	1454	1210	138	1.9	18.7	32	30	30.7	7.4	7.7	1444	1224	162	2.2	28.8	52	72.3
23-11-8	273	519.2	61.3	61.3	28.3	7.9	1450	1206	156	1.9	16.5	35	29	61.3	11.3	7.5	1640	1404	205	2.4	25.6	64	57.6

date	Day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR 1 Effluent and mixed liquor. COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	Peak DO mgO/l	OUR mgO/l/h	%Aer.	Nne mgN/l	CFR 2 Effluent and mixed liquor. COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	Peak DO mgO/l	OUR mgO/l/h	%Aer	Nne mgN/l
24-11-8	274	425.1	55.7	65.4	28.6	7.9	1386	1178	132				29	49.1	1.1	7.5	1476	1264	192				76.5
25-11-8	275																						
26-11-8	276																						
27-11-8	277	474.2	54.1	49.1	28.1	7.9	1310	1202	127	1.9	19.0	34	30	45	3.8	7.6	1556	1416	214	2.3	30.5	53	72.3
28-11-8	278	537.6	58.8	49.3	29.3	7.9	1328	1164	151				24	49.3	3.9	7.5	1594	1400	209				62.8
29-11-8	279	451.4	55.4	57.5	26.7								25	45.1	3.9								67.4
30-11-8	280	562.3	56.8	49.3	26.2		1220	1064	273	1.9	16.1	38	30	49.3	4.1		1526	1320	142	2.9	21.5	84	78.2
01-12-8	281	607.4	57.7	45.1	27.6	7.8	1364	1160	147	1.8	15.4	37	28	45.1	3.6	7.6	1662	1436	201	2.2	24.3	60	77.7
02-12-8	282	556.1	49.8	47.2	24.2	7.8	1254	1118	159				26	39	10.4	7.5	1664	1516	220				71.2
03-12-8	283	424.8	56.0	59.5	26.5	7.9	1242	1054	134	1.9	14.4	43	22	43.1	6.3	7.4	1630	1372	194	2.3	19.0	74	62.4
04-12-8	284																						
05-12-8	285	504.8	50.7	36.9	22.7	7.9	1378	1162	121	1.8	15.2	37	44	28.7	5.2	7.5	1650	1380	182	2.5	21.6	71	98.2
06-12-8	286	513	50.4	43.1	22.5	7.9	1248	1114	147	1.7	15.4	36	33	36.9	7.8	7.5	1562	1382	203	2.3	20.8	68	77.7
07-12-8	287	525.3	53.5	52.9	22.5								32	48.9	6.0								73.8
08-12-8	288	537.5	56.6	57.0	23.9	8.1	1394	1152	132				30	48.9	5.2	8	1868	1588	178				75.5
09-12-8	289	435.7	49.3	61.1	22.8		1386	1180	120	1.7	17.6	32	29	44.8	5.6		1706	1466	215	2.5	25.3	64	65.2
10-12-8	290																						
11-12-8	291	574.1	53.2	48.9	24.4	7.9	1054	1012	142	1.8	15.3	38	24	40.7	3.6	7.5	1638	1514	204	2.1	25.8	56	59.8
12-12-8	292	513.1	53.5	61.1	25.2	8.1	1206	1002	152	1.7	12.7	40	21	65.2	6.7	7.5	1514	1338	209	2.3	24.7	58	65.2
13-12-8	293	480.5	59.4	69.2	30.1	8.0	1342	1062	149	1.7	17.6	32	21	48.9	5.7	7.7	1870	1544	196	2.5	25.3	64	67.2
14-12-8	294	559.9	57.4	38.7	26.9	8.0	1148	1020	160				29	34.6	4.3	7.7	1640	1430	234				68.2

PHASE II STEADY STATE DATA.

CFR1 Day	Sti mgCOD/l	Nti mgN/l	Ste mgCOD/l	Nte mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	PeakDO mgO/l/h	OUR mgO/l	%Aer.	NO3ad mgN/l	Nne mgN/l.
1-22	524	51	50.1	10.4	8.0	1723	1457	393	2.5	26.4	35	600	19.7
23-43	521	55	51.9	19.2	8.0	1815	1554	433	3.3	24.6	45	600	25.6
44-55	537	41	52.2	12.2	8.0	1719	1479	412	2.4	24.7	33	600	14.3
56-73	496	53	44.8	8.0	7.7	1897	1606	458	4.2	26.0	59	600	57.9
78-95	522	61	42.4	3.8	7.6	2091	1781	837	3.1	24.2	61	750	92.0
103-138	506	58	44.4	3.9	7.6	1987	1672	193	2.2	24.1	56	500	65.2
139-167	519	58	43.6	5.1	7.4	1955	1643	225	2.4	23.2	62	500	68.4
168-189	515	58	46.7	3.4	7.3	1988	1689	210	3.1	28.2	71	500	79.9
196-204	482	50	42.6	4.0	7.5	1904	1633	182	2.8	26.2	67	500	74.0
207-236	503	54	44.6	16.9	7.6	1710	1426	302	2.6	25.5	34	500	37.4
237-267	498	47	40.1	13.5	7.7	1396	1184	219	2.2	20.0	37	500	29.4
270-293	505	56	52.3	26.5	7.9	1318	1122	148	1.8	16.2	36	500	28.1
CFR2													
1-8	513	44	46.9	7.3	8.3	1919	1607	342	2.6	26.2	32	600	25.0
9-15	535	48	58.1	7.8	8.2	2019	1700	376	2.7	27.7	38	600	31.8
16-28	524	61	47.2	16.4	8.0	2034	1773	467	2.9	32.4	32	600	22.9
29-43	521	54	42.8	11.1	8.0	2258	1929	381	2.7	32.3	31	600	31.8
44-55	537	41	53.2	9.1	8.0	2058	1776	294	2.6	34.4	27	600	17.2
57-86	510	56	45.4	14.4	7.9	2179	1856	303	2.4	27.2	32	750	43.3
88-92	495	61	62.7	19.0	7.7	2588	2189	719	2.1	13.8	52	750	59.9
93-101	512	59	63.0	13.5	7.7	1829	1572	441	1.6	16.4	34	500	29.4
102-112	523	52	54.5	13.2	7.8	1727	1460	492	1.9	22.7	30	500	24.5
117-131	465	58	49.4	12.0	7.7	1628	1327	484	2.2	18.5	40	500	30.4
137-204	512	57	50.3	15.2	7.7	2012	1696	381	2.2	25.5	31	500	27.3
207-218	512	61	44.7	4.7	7.4	1886	1586	388	2.7	21.5	78	500	69.6
224-236	486	49	48.6	3.9	7.3	1698	1402	162	2.4	23.6	62	500	69.4
236-293	500	51	41.6	5.3	7.4	1584	1359	151	2.3	22.8	64	500	69.7

APPENDIX C
Experimental data measured on systems CFR1 and CFR2 during phase III of the investigation

APPENDIX C

		Influent		CFR 1 EFFLUENT AND MIXED LIQUOR										CFR2 EFFLUENT AND MIXED LIQUOR.									
Date	Day	COD mgCOD /l	TKN mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	DO mgO /l	OUR mgO /l/h	%aer	Nne mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	DO mgO /l	OUR mgO /l/h	%aer	Nne mgN /l
FEB 20	1	465	47	22	14	7.8	2052	1726	560	2.1	24	28	25	30	14	8	1986	1692	319	1.8	25	27.9	33
21	2	477	45	43	14	7.9	2110	1734	402	2.1	23	30	27	41	14	8	2004	1662	299	2.0	22	31.3	29
22	3	506	48	45	13	7.8	1964	1648	424	2.1	23	33	35	37	13	8	1846	1556	334	2.1	23	32.7	33
23	4	421	43	25		7.8	1860	1566	430				28	29		8	1804	1570	332				41
24	5	482	41	25	12								34	41	11								38
25	6	462	46	29	11	7.8	1996	1680	434	2.2	26	26	31	37	9	8	1734	1476	365	1.9	25	26.8	38
26	7																						
27	8	519	47	33	10	7.8	1988	1654	670	2.2	26	29	32	45	9	8	1926	1612	381	2.3	25	30.3	37
28	9	523	46	37	9	7.9	1926	1612	484	2.4	25	31	26	33	7	8	1824	1544	366	2.0	25	30.8	36
March	10	460	42	35	11		1966	1638	610	2.4	24	31	28	27	2		1830	1546	455	1.9	23	30.3	37
2	11	517	45	43	7	7.9	1856	1566	620				31	43	9	8	1778	1542	431				38
3	12	473	44	37									26	45	8								32
4	13																						
5	14	509	25	31	9	7.5	1738	1462	1169	2.4	27	30	[illegible]	35	5	8	1772	1524	771	1.9	25	26.6	28
6	15	533	48	31	8	7.5	1960	1684	816	2.2	27	28	33	39	6	8	2012	1724	861	2.0	27	27.6	33
7	16	517	48	44	8	7.6	1982	1662	1093	2.3	27	29	30	40	5	8	2000	1696	1000	1.9	27	27.9	36
8	17	549	43	40	8	7.6	1842	1522	561	2.2	26	28	30	32	6	8	1934	1634	1017	2.1	26	28.6	33
9	18	505	46	12	8	7.8	1872	1610	516	2.5	26	29	38	36	6	8	1978	1744	1104	2.0	27	28.3	33
10	19	416	49	36	8								34	44	6								41
11	20																						
12	21	481	46	36	6		1726	1446	637	2.3	24	29	36	40	6		1824	1504	694	2.0	27	28.8	39
13	22	545	40	36	7	7.5	1614	1372	578				41	48	5	8	1824	1532	621				45
14	23	567	68	44	11		1844	1442	479	2.4	26	29	36	44	8		2092	1662	518	2.0	26	27.1	38
15	24	568	64	44	18	7.7	1880	1604	390	2.4	26	31	35	44	18	8	2138	1820	429	2.1	25	29.8	39
16	25																						
17	26	454	667	39	18	7.5	1794	1428	399				41	39	21	8	1924	1734	476				27
18	27																						
19	28	524	69	41	21	7.7	1772	1518	423	2.4	26	30	38	47	22	8	2054	1766	454	2.1	24	29.7	29
20	29	522	68	25	23	7.7	1852	1490	378	2.3	23	36	35	49	24	8	2138	1730	382	2.0	22	32.2	30
21	30	522	68	41	23	7.8	1796	1510	418	2.3	22	34	42	41	22	8	2022	1732	420	2.1	21	34.2	41
22	31	516	67	47	23	7.8	1804	1516	360	2.3	20	35	34	56	16	8	2050	1744	415	2.3	23	34.8	34
23	32	528	67	60	24	7.9	1780	1512	337	2.3	21	34	[illegible]	56	23	8	2118	1810	393	2.0	24	33.2	31
24	33	448	69	53	25								23	24	21								26
25	34	493	70	37	26	7.9	1758	1446	341	2.3	20	39	39	45	23	8	2016	1712	380	2.1	19	36.5	46
26	35																						
27	36	481	66	41	27	7.8	1766	1500	330	2.3	22	35	23	41	24	8	2084	1764	376	2.0	24	32.2	24
28	37	473	64	49	25	7.8	1610	1412	352	2.4	19	39	39	49	24	8	1992	1714	335	2.1	22	35.5	40
29	38	489	64	29	23	7.7	1626	1354	349	2.4	21	38	45	25	24	8	1996	1686	334	2.1	20	34.2	49
30	39	522	68	37	27	7.7	1746		305	2.2	21	34	46	49	21	8	1976		321	2.2	22	32.8	50
31	40	551	49	62	20	7.8							40	41	16	8							47
April	41																						
2	42	461	46	37	11	7.8	1644		294				41	33	8	8	1984		302				42
3	43	617	51	41	10	7.8	1508		309	2.3	20	36	46	58	10	8	1852		333	2.1	24	29.7	45
4	44	539	53	37	12	7.9	1368		292	2.1	24	29	34	49	7	8	1928		328	2.1	27	25.1	35
5	45	543	50	58	13	7.7	1344		273	2.3	16	41	32	58	11	8	1800		352	2.2	28	32.7	31
6	46																						
7	47																						
8	48																						
9	49	572	50	49	13	7.9	1174		241	2.0	19	32	37	54	11	8	1892		299	2.0	27	27.8	34
10	50	444	47	54	14	7.9	1146		233	1.8	15	36	35	47	12	8	1768		302	1.7	21	28.3	31
11	51	477	50	41	15	7.6	1144		233	2.0	12	50	44	28.8	11	8	1810		295	1.8	17	35.5	41
12	52	452	48	41	12	7.7	1088	954	230	2.0	18	36	51	66	13	8	1716	1482	291	1.9	23	28.9	49
13	53	534	52	58	15	7.7	1044	910	223				47	49	14	8	1798	1506	269				46
14	54					7.7	1112	996	225	2.1	20	31				8	1726	1518	290	1.7	27	22.7	
15	55	500	50	45	17	7.7	1306	1104	230	2.1	20	34	47	41	12	8	1924	1636	312	1.8	23	27.4	44
16	56	512	60	45	18	7.8	1344	932	223	2.0	16	38	39	41	14	8	1980	1506	278	1.8	22	27.4	43

Date	Day	Influent COD mgCOD/l	Influent TKN mgN/l	CFR 1 EFFLUENT AND MIXED LIQUOR COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%aer	Nne mgN/l	CFR2 EFFLUENT AND MIXED LIQUOR. COD mgCOD/l	TKN mgN/l	pH	MLSS mgSS/l	MLVSS mgVSS/l	DSVI ml/g	DO mgO/l	OUR mgO/l/h	%aer	Nne mgN/l
17	57																						
18	58																						
19	59																						
20	60	490	46	55	18	7.4	1328	1172	213	1.9	17	33	34	53	15	8	2002	1744	275	1.8	21	26.4	35
21	61	484	52	45	20								38	45	17								36
22	62																						
23	63	512	54	49	23	7.8	1398	1136	238	2.0	16	37	37	41	16	8	2032	1682	279	1.8	22	25.4	29
24	64	526	52	55	20	7.9	1366	1124	232	2.1	17	35	40	58.9	16	8	2056	1718	268	1.9	25	25.9	36
25	65	518	46	43	18	7.9	1156	1110	288				37	26	16	8	1828	1676	283				35
26	66	506	49	55		7.9	1212	1012	248	2.0	15	40	27	67	22	8	1808	1540	286	1.7	21	27.4	35
27	67	477	52	47	27	7.9	1272	1048	236	2.0	15	39	38	47	21	8	1870	1568	267	1.8	22	28.4	30
28	68	487	50	61	25	7.9	1264	1080	264				40	57	23	8	1768	1550	302				34
29	69																						
30	70	432	51	55	26	7.7	1124	940	237	2.0	14	40	43	47	23	8	1760	1488	275	1.8	20	32.5	38
May 1	71																						
2	72	446	45	53	25	8.1	1138	996	249	2.1	14	44	43	49	23	8	1738	1516	269	1.7	18	30.7	37
3	73	325	56	61	25	7.9	1558	1308	225				46	53	20	8	1378	1160	339				41
4	74	471	57	41	25	7.6	1558	1252	257	2.0	15	42	47	45	18	8	1298	1040	231	1.7	13	41.1	40
5	75	450	58	45	29		1706	1450	244				50	37	23		1296	1112	206				54
6	76																						
7	77	349	58	49	30	7.7	1462	1284	342	2.1	14	43	43	61	20	8	1010	894	247	1.7	12	51.3	59
8	78	471	57	45	29	7.8	1382	1214	337	1.8	16	35	46	45	23	8	1022	908	228	1.6	14	37.6	62
9	79	523	65	45	31	7.8	1460	1272	354	1.9	23	33	43	49	22	8	1038	954	241	1.6	16	37.6	63
10	80	610	50	51	27	7.7	1520	1288	362	2.2	17	35	24	63	22	8	1078	932	216	1.9	14	40.6	33
11	81	570	53	47	23	7.6	1602	1376	374				60	55	16	8	1132	998	236				39
12	82	570	54	63	21								86	63	155								42
13	83																						
14	84	424	50	63	24	7.8	1534	1348	435	2.1	15	37	70	67	15	8	1062	962	282	1.6	12	46.7	37
15	85	531	50	49	21	7.7	1548	1340	431	2.3	16	36	75	61	18	8	1036	908	290	1.9	13	39.6	45
16	86	551	55	45	21	7.7	1676	1434	477	2.2	16	33	75	57	17	8	1098	940	304	1.8	15	38.6	40
17	87	524	56	47	25	7.8	1614	1396	454	2.5	20	30	60	71	20	8	1026	878	309	1.9	15	35	39
18	88	492	56	63	25	7.9	1534	1370	489	2.2	17	31	68	76	23	8	1060	954	315	1.9	16	35.5	26
19	89	624	58	40.8	26								54										
20	90	494	53	29	26	7.9	1578	1328	486	2.2	16	37	28	41	23	8	996	830	318	1.9	13	43.1	48
21	91																						
22	92	500	49	51	23	7.8	1550	1294	602	2.4	16	38	33	55	19	8	1034	866	355	2.0	13	44.2	55
23	93																						
24	94					7.7	1670	1438	639							8	904	812	479				
25	95	443	50	35	13	7.7	1500	1342	511	2.1	19	34	51	55	7	8	948	820	422	1.9	13	47.2	68
26	96	426	52	35	17								51	51	13								65
27	97																						
28	98	455	49	31	17	7.7	1506	1336	454	2.3	18	35	49	51	18	8	834	752	420	1.9	12	51.3	70
29	99	573	56	51	20	7.7	1462	1218	433	2.0	20	33	53	51	19	8	772	638	389	1.8	12	47.2	70
30	100	597	71	59	24	7.9	1528	1286	393	2.0	22	24	44	55	20	8	1100	930	303	1.8	15	39.6	68
31	101																						
June	102	561	42	75	17	7.9	1662	1464	381	2.0	18	29	13	63	12	8	1038	938	257	1.8	12	47.7	62
2	103	498	36	53	16								15	44	12								60
3	104																						
4	105	569	40	47	18	7.8	1766	1552	340	2.2	18	31	17	55	13	8	942	844	230	1.7	13	41.1	50
5	106	510	47	53	20	7.8	1618	1406	391	2.4	17	34	23	57	15	8	1122	994	208	1.8	12	51.3	56
6	107	514	54	60	24	7.8	1676	1478	318	2.2	15	42	28	64	24	8	1120	1004	208	1.9	13	46.2	60
7	108	559	59	39	27	8	1506	1300	310	2.2	16	39	28	39	27	8	1070	936	234	1.8	14	41.6	38
8	109	506	64	56	28		1480	1294	225	2.2	16	38	22	60	28		1138	1024	190	1.8	14	42.1	41
9	110																						
10	111																						

		Influent		CFR 1 EFFLUENT AND MIXED LIQUOR										CFR2 EFFLUENT AND MIXED LIQUOR.									
Date	Day	COD mgCOD /l	TKN mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	DO mgO /l	OUR mgO /l/h	%aer	Nne mgN /l	COD mgCOD /l	TKN mgN /l	pH	MLSS mgSS /l	MLVSS mgVSS /l	DSVI ml/g	DO mgO /l	OUR mgO /l/h	%aer	Nne mgN /l
11	112	473	59	39	23	7.7	1004	930	216				32	68	25	8	980	920	255				11
12	113	555	61	56	23	7.7	924	822	198	2.6	16	53	39	64	25	8	966	862	276	2.1	17	44.1	10
13	114	564	69	68	26	7.7	1078	936	139	2.5	17	47	41	72	27	8	1006	890	232	1.7	16	34	9
14	115	552	48	58	23	7.7	1108	964	135	1.7	13	37	38	54	32	8	1146	996	218	2.2	19	40.6	9
15	116	511	53	25	22	7.7	998	860	134	2.1	13	40	32	54	21	8	1114	958	210	1.9	17	36	9
16	117																						
17	118																						
18	119	505	66	64	29	7.8	826	704	81	2.9	19	46	23	72	28	8	1192	1056	196	2.2	21	37.6	9
19	120	505	60	60	29	7.8							20	56	28	8							9

APPENDIX D

Steady state data, COD balances and COD utilization rates calculations for phase I of the investigation

APPENDIX D

PHASE I COD BALANCE
AND
PBCOD utilization rates and anoxic/aerobic ratio.

CARBONATION INPUT PARAMETERS. NITRIFICATION INPUT PARAMETERS. PLANT OPERATING CONDITIONS

Yh mgVSS/ mgCOD	fcv mgCOD/ mgVSS	fus mgCOD/ mgCOD	bh /d	fbs mgCOD/ mgCOD	f mgVSS/ mgVSS	Yn mgVSS/ mgN	bn /d	Kn mgN/l	Unm /d	Kr l/ mgVSS/ d	fn mgN/ mgVSS	fna mgN/ mgN	fnu mgN/ mgN	Vp l	Q l/d	T degC	q d	Rhn d
0.450	1.480	0.050	0.240	0.24	0.200	0.100	0.040	1.000	0.330	0.015	0.100	0.750	0.030	7.5	10	20	0.375	0.75

MEASURED INPUT DATA.

	fup mgCOD/ mgCOD	fi mgVSS/ mgTSS	Rs d	Sti mgCOD/l	Ste mgCOD/l	Nti mgN/l	Nte mgN/l	Nne mgN/l	NO3add mgN/d	Xv mgVSS/l	Xt mgSS/l	OUR mgO/l/h	%Aerobic. %	DSVI ml/g	Dpred. mgN/l	Kav mgNO3-N /mgAVSS/d
CFR1																
1	0.152	0.827	20	523	77	91	29.0	3.3	0	3123	3778	45.48	44.19	173	43.02	0.112
2	0.111	0.827	20	518	63	79	23.0	19.1	600	2797	3384	33.27	34.42	219	52.63	0.177
3	0.158	0.826	10	523	69	82	19.0	7.6	600	1827	2213	40.36	31.58	214	45.78	0.250
4	0.034	0.837	10	523	68	80	18.0	20.3	270	1410	1685	37.95	39.44	214	46.90	0.130
5	0.001	0.866	10	536	67	81	38.0	34.2	540	1333	1539	26.15	35.71	257	52.85	0.101
6	0.090	0.865	10	525	72	47	45.0	6.2	540	1604	1854	27.16	31.88	389	49.71	0.096
7	0.182	0.843	10	503	67	57	36.0	10.9	540	1833	2175	22.65	36.45	354	39.68	0.134
8	0.099	0.848	10	523	63	59	19.0	39.6	540	1628	1919	28.07	31.53	262	[illegible]	0.083
9	0.045	0.833	10	530	52	55	15.0	30.7	540	1468	1762	21.00	35.00	181	50.37	0.106
10	0.112	0.836	10	508	48	52	11.0	29.2	540	1624	1942	26.35	33.89	415	45.48	0.123
11	0.079	0.864	10	511	47	48	9.0	4.6	0	1525	1766	22.03	37.66	397	44.85	0.041
12	0.013	0.843	10	514	58	50	9.0	38.8	540	1317	1563	22.76	39.19	412	47.34	0.098
13	0.153	0.848	10	518	72	48	8.0	5.4	0	1791	2113	24.01	34.22	359	43.90	0.038
14	0.105	0.836	10	518	43	51	11.0	38.9	540	1633	1954	23.61	39.04	340	43.12	0.100
CFR2																
1	0.139	0.824	20	522	57	94	17.0	9.6	0	3029	3674	76.33	30.32	270	54.46	0.105
2	0.224	0.835	15	524	56	86	11.0	6.6	0	2864	3429	68.41	32.03	237	45.55	0.123
3	0.171	0.830	15	518	49	79	25.0	25.6	600	2551	3072	37.38	32.07	245	48.28	0.168
4	0.126	0.830	15	523	51	82	23.0	16.3	600	2339	2819	41.78	30.44	221	52.82	0.188
5	0.107	0.851	15	523	43	80	18.0	30.0	270	2242	2636	48.57	37.53	328	48.48	0.099
6	0.095	0.842	15	535	46	84	18.0	29.9	540	2227	2646	55.16	37.88	523	50.03	0.170
7	0.185	0.857	10	526	51	49	6.0	85.1	540	1929	2251	29.83	100.00	739	0.00	0.000
8	0.223	0.841	10	503	64	57	44.0	8.7	540	1964	2334	22.73	35.45	346	38.17	0.124
9	0.173	0.851	10	523	45	59	23.0	25.4	540	1875	2202	26.57	30.69	294	45.54	0.114
10	0.137	0.866	10	530	32	55	22.0	27.2	540	1781	2056	21.69	33.11	219	46.55	0.101
11	0.208	0.875	10	506	34	52	11.0	5.1	0	1928	2203	28.12	32.50	302	40.96	0.043
12	0.120	0.837	10	511	34	48	3.0	31.5	540	1659	1983	22.61	38.80	724	41.96	0.139
13	0.188	0.840	10	514	53	50	8.0	6.7	0	1892	2253	28.43	31.84	394	43.16	0.039
14	0.130	0.838	10	518	71	48	7.0	40.6	540	1717	2048	26.39	34.71	491	44.80	0.092
15	0.206	0.833	10	518	67	51	15.0	5.8	0	1969	2363	28.43	32.92	325	41.75	0.024

CARBONATION RESULTS

	Sti mgCOD/l	Sbi mgCOD/l	Xa mgVSS/l	Xe mgVSS/l	Xi mgVSS/l	Xv mgVSS/l	Xt mgSS/l	M(Sti) mgCOD/d	M(Sbi) mgCOD/d	M(Xa) mgVSS/d	M(Xe) mgVSS/d	M(Xi) mgVSS/d	M(Xv) mgVSS/d	M(Xt) mgSS/d
CFR1														
1	523	417	864	829	1430	3123	3778	5230	4175	6478	6219	10725	23422	28335
2	518	435	899	863	1034	2797	3384	5180	4347	6745	6476	7757	20978	25380
3	523	414	731	351	745	1827	2213	5230	4141	5481	2631	5591	13703	16598
4	523	479	846	406	158	1410	1685	5230	4793	6344	3045	1187	10575	12638
5	536	509	898	431	4	1333	1539	5360	5087	6733	3232	33	9998	11543
6	525	452	797	383	424	1604	1854	5250	4516	5978	2869	3183	12030	13905
7	503	386	682	327	824	1833	2175	5030	3864	5114	2455	6178	13747	16312
8	523	445	786	377	465	1628	1919	5230	4452	5893	2828	3489	12210	14393
9	530	480	846	406	215	1468	1762	5300	4796	6347	3047	1616	11010	13215
10	508	426	751	361	512	1624	1942	5080	4258	5635	2705	3840	12180	14565
11	511	445	786	377	362	1525	1766	5110	4453	5893	2829	2716	11438	13245
12	514	482	850	408	59	1317	1563	5140	4818	6377	3061	440	9877	11722
13	518	413	729	350	712	1791	2113	5180	4130	5467	2624	5342	13433	15848
14	518	438	772	371	490	1633	1954	5180	4377	5794	2781	3673	12248	14655
CFR2														
1	522	423	876	841	1312	3029	3674	5223	4233	6569	6306	9842	22718	27555
2	524	381	745	536	1583	2864	3429	5239	3805	5584	4021	11875	21480	25718
3	518	404	790	568	1193	2551	3072	5177	4036	5922	4264	8947	19133	23040
4	523	431	844	607	888	2339	2819	5231	4312	6327	4556	6659	17543	21143
5	523	441	862	621	759	2242	2636	5230	4407	6467	4656	5693	16815	19770
6	535	457	895	644	688	2227	2646	5350	4573	6711	4832	5160	16703	19845
7	526	402	710	341	879	1929	2251	5260	4022	5323	2555	6590	14468	16883
8	503	366	646	310	1008	1964	2334	5030	3659	4843	2325	7562	14730	17505
9	523	407	718	344	813	1875	2202	5230	4066	5381	2583	6098	14062	16515
10	530	431	760	365	656	1781	2056	5300	4307	5700	2736	4922	13358	15420
11	506	376	663	318	947	1928	2203	5060	3756	4971	2386	7103	14460	16523
12	511	424	749	359	551	1659	1983	5110	4243	5616	2696	4131	12443	14873
13	514	392	692	332	868	1892	2253	5140	3919	5187	2490	6513	14190	16898
14	518	425	749	360	608	1717	2048	5180	4246	5620	2698	4560	12878	15360
15	518	385	680	326	963	1969	2363	5180	3852	5098	2447	7222	14768	17723

Nitrification calculation for complete nitrification

	Ns	Nae	Nue	Noi	Noe	Nte	Nne	M(Nne)	Xn	M(Xn)	M(On)	M(Ot)	Xn/Xv	Rsm
	mgN/l	mgN/l	mgN/l	mgN/l	mgN/l	mgN/l	mgN/l	mgN/d	mgVSS/l	mgVSS/d	mgO/d	mgO/d	mgVSS/mgV	d
CFR1														
1	11.71	0.37	2.73	14.66	1.37	4.47	74.82	748	111	831	3419	6654	0.04	3.45
2	10.49	0.37	2.37	13.50	1.21	3.96	64.55	646	96	717	2950	6319	0.03	3.45
3	13.70	0.74	2.46	12.45	1.35	4.55	63.75	638	61	455	2913	5854	0.03	3.45
4	10.57	0.74	2.40	16.41	1.56	4.70	64.73	647	62	462	2958	6361	0.04	3.45
5	10.00	0.74	2.43	17.79	1.60	4.77	66.23	662	63	473	3027	6639	0.05	3.45
6	12.03	0.74	1.41	7.16	0.72	2.86	32.11	321	31	229	1467	4674	0.02	3.45
7	13.75	0.74	1.71	6.36	0.73	3.18	40.07	401	38	286	1831	4575	0.02	3.45
8	12.21	0.74	1.77	9.49	0.96	3.47	43.32	433	41	309	1980	5141	0.03	3.45
9	11.01	0.74	1.65	10.48	1.00	3.38	40.61	406	39	290	1856	5261	0.03	3.45
10	12.18	0.74	1.56	7.60	0.80	3.10	36.72	367	35	262	1678	4701	0.02	3.45
11	11.44	0.74	1.44	7.84	0.80	2.97	33.59	336	32	240	1535	4697	0.02	3.45
12	9.88	0.74	1.50	10.56	1.00	3.24	36.89	369	35	263	1686	5107	0.03	3.45
13	13.43	0.74	1.44	5.22	0.57	2.74	31.82	318	30	227	1454	4387	0.02	3.45
14	12.25	0.74	1.53	7.55	0.78	3.05	35.71	357	34	255	1632	4740	0.02	3.45
CFR2														
1	11.36	0.37	2.83	15.80	1.46	4.66	78.16	782	116	868	3572	6852	0.04	3.45
2	14.32	0.48	2.58	10.98	1.17	4.23	67.36	674	84	632	3079	5936	0.03	3.45
3	12.76	0.48	2.36	11.34	1.15	3.98	61.90	619	77	580	2829	5859	0.03	3.45
4	11.70	0.48	2.46	13.60	1.30	4.23	66.07	661	83	619	3019	6258	0.04	3.45
5	11.21	0.48	2.40	13.80	1.29	4.17	64.62	646	81	606	2953	6263	0.04	3.45
6	11.13	0.48	2.52	15.04	1.36	4.36	68.51	685	86	642	3131	6565	0.04	3.45
7	14.47	0.74	1.47	4.19	0.47	2.67	31.86	319	30	228	1456	4312	0.02	3.45
8	14.73	0.74	1.71	4.98	0.60	3.05	39.22	392	37	280	1792	4391	0.02	3.45
9	14.06	0.74	1.77	6.88	0.76	3.27	41.67	417	40	298	1904	4792	0.02	3.45
10	13.36	0.74	1.65	7.18	0.75	3.14	38.50	385	37	275	1760	4818	0.02	3.45
11	14.46	0.74	1.56	4.34	0.51	2.81	34.73	347	33	248	1587	4254	0.02	3.45
12	12.44	0.74	1.44	6.43	0.68	2.86	32.70	327	31	234	1494	4507	0.02	3.45
13	14.19	0.74	1.50	4.49	0.51	2.75	33.06	331	31	236	1511	4294	0.02	3.45
14	12.88	0.74	1.44	6.00	0.64	2.81	32.31	323	31	231	1477	4492	0.02	3.45
15	14.77	0.74	1.53	4.00	0.46	2.73	33.50	335	32	239	1531	4267	0.02	3.45

COD Balance and COD Utilization rate Calculations.

	NO3gen mgN/l	NO3den mgN/d	M(Oc) mgO/d	M(On) mgO/d	M(Od) mgO/d	M(Oad) mgO/d	Mwaste mgCOD/d	Total COD mgCOD/d	MSti mgCOD/d	COD Balance %	RBCOD UTIL.RATE mgCOD/gVASS.h	PBCOD Utilization rates and ratio: Anoxic mgCOD/gVASS.h	Aerobic mgCOD/gVASS.h	anoxic/aerobic
CFR1														
1	50.3	470	2663	2298	1344	3618	1733	5167	5230	98.79	6.444	40.127	109.846	0.365
2	45.5	864	2453	2080	2471	2061	1552	4635	5180	89.48	6.444	63.553	125.609	0.506
3	49.3	1017	2950	2253	2909	2294	2028	5668	5230	108.37	7.556	89.623	205.483	0.436
4	51.4	581	2006	2350	1662	2694	1565	4251	5230	81.29	7.556	46.661	92.689	0.503
5	33.0	528	1683	1508	1510	1681	1480	3832	5360	71.50	7.556	36.155	79.932	0.452
6	0.0	478	2926	0	1367	1559	1780	5426	5250	103.35	7.556	34.509	184.349	0.187
7	7.3	504	2595	331	1440	1486	2035	5299	5030	105.35	7.556	47.960	166.433	0.288
8	27.8	422	1530	1270	1207	1593	1807	3967	5230	75.85	7.556	29.916	95.364	0.314
9	29.0	523	1494	1325	1495	1323	1629	3643	5300	68.74	7.556	37.859	76.485	0.495
10	28.8	536	1824	1317	1534	1607	1803	4107	5080	80.84	7.556	44.019	111.822	0.394
11	27.6	230	890	1260	657	1493	1693	3053	5110	59.75	7.556	14.842	42.599	0.348
12	31.1	463	1508	1422	1325	1606	1462	3550	5140	69.06	7.556	35.252	67.878	0.519
13	26.6	212	870	1214	605	1479	1988	3578	5180	69.08	7.556	13.537	50.589	0.268
14	27.8	429	1616	1268	1226	1659	1813	3859	5180	74.50	7.556	35.922	81.775	0.439
CFR2														
1	65.8	563	2767	3008	1609	4166	1681	5021	5223	96.13	6.444	37.591	167.208	0.225
2	60.6	540	2720	2769	1545	3944	2119	5399	5239	103.06	6.815	44.186	183.289	0.241
3	40.9	752	2441	1868	2152	2158	1888	4819	5177	93.08	6.815	60.204	153.858	0.391
4	47.3	910	2730	2162	2603	2289	1731	4971	5231	95.04	6.815	67.276	170.367	0.395
5	50.8	478	2327	2321	1367	3281	1659	4416	5230	84.43	6.815	35.577	113.029	0.315
6	54.9	790	3512	2507	2258	3761	1648	5620	5350	105.05	6.815	61.059	165.880	0.368
7	28.5	0	4065	1304	0	5369	2141	6717	5260	127.69	7.556	0.000	87.916	0.000
8	0.0	453	2746	[illegible]	1296	1450	2180	5566	5030	110.66	7.556	44.367	192.365	0.231
9	21.9	505	1911	1003	1445	1468	2081	4442	5230	84.93	7.556	40.996	137.049	0.299
10	19.6	464	1723	898	1328	1293	1977	4020	5300	75.85	7.556	36.093	106.584	0.339
11	26.5	214	1045	1213	613	1645	2140	3525	5060	69.67	7.556	15.342	73.326	0.209
12	32.6	551	1666	1488	1575	1579	1841	3847	5110	75.29	7.556	49.847	88.009	0.566
13	27.8	211	962	1271	604	1629	2100	3592	5140	69.89	7.556	13.840	65.272	0.212
14	28.1	415	1551	1285	1188	1649	1906	4167	5180	80.44	7.556	32.995	91.844	0.359
15	21.2	154	1156	970	441	1685	2186	4011	5180	77.44	7.556	8.614	78.515	0.110

APPENDIX E

Steady state data, COD balances and COD utilization rates calculations for phase II of the investigation

APPENDIX E

PHASE II COD BALANCE
AND
PBCOD utilization rates and anoxic/aerobic ratio.

CARBONATION INPUT PARAMETERS.						NITRIFICATION INPUT PARAMETERS.								PLANT OPERATING CONDITIONS				
Yh	fcv	fus	bh	f	fbs	Yn	bn	Kn	Unm	Kr	fn	fna	fnu	Vp	Q	T	q	Rhn
mgVSS/mgCOD	mgCOD/mgVSS	mgCOD/mgCOD	/d	mgVSS/mgVSS	mgCOD/mgCOD	mgVSS/mgN	/d	mgN/l	/d	l/mgVASS/d	mgN/mgVSS	mgN/mgN	mgN/mgN	l	l/d	degC	d	d
0.450	1.480	0.050	0.240	0.200	0.24	0.100	0.040	1.000	0.330	0.015	0.100	0.750	0.030	7.5	9.5	20	0.75	0.79

MEASURED INPUT DATA.

	fup	fi	Rs	Sti	Ste	Nti	Nte	Nne	NO3ad	Xv	Xt	OUR	%Aerobic	DSVI	Dpred	K2
CFR1	mgCOD/mgCOD	mgVSS/mgTSS	d	mgCOD/l	mgCOD/l	mgN/l	mgN/l	mgN/l	mgN/l	mgVSS/l	mgTSS/l	mgO/l/h	%	ml/g	mgN/l	mgNO3-N/mgAVSS/d
1	0.069	0.846	10	525	50	51	10.4	19.7	600	1457	1723	26.40	35.00	393	48.51	0.162
2	0.103	0.856	10	521	52	55	19.2	25.6	600	1554	1815	24.60	45.00	433	39.22	0.170
3	0.066	0.861	10	537	52	41	12.2	14.3	600	1480	1719	24.70	33.10	412	51.30	0.136
4	0.144	0.847	10	496	45	53	8.0	57.9	600	1606	1897	26.00	59.40	458	26.23	0.155
5	0.176	0.857	10	522	42	61	3.8	92.0	750	1791	2091	24.20	61.00	837	25.47	0.125
6	0.156	0.841	10	506	44	58	3.9	65.2	500	1672	1987	24.10	56.30	193	28.39	0.101
7	0.133	0.840	10	519	44	58	5.1	68.4	500	1643	1955	23.20	62.50	225	25.68	0.094
8	0.152	0.850	10	515	47	58	3.4	79.9	500	1689	1988	28.20	70.70	210	19.43	0.068
9	0.170	0.858	10	482	43	51	4.0	74.0	500	1633	1904	26.20	67.30	182	19.85	0.054
10	0.079	0.834	10	503	45	54	16.9	37.4	500	1426	1710	25.50	33.60	301	47.00	0.086
11	0.094	0.848	7.5	498	40	47	13.5	29.4	500	1184	1396	20.00	37.40	219	39.92	0.113
12	0.057	0.851	7.5	505	52	56	26.5	28.1	500	1122	1318	16.20	36.00	148	43.18	0.097
CFR2																
1	0.127	0.838	10	513	47	45	7.3	25.0	600	1607	1919	26.20	32.40	342	46.14	0.145
2	0.135	0.842	10	535	58	48	7.8	31.8	600	1700	2019	27.70	37.60	376	43.95	0.140
3	0.169	0.872	10	524	47	61	16.4	22.9	600	1773	2034	32.40	32.10	467	44.93	0.171
4	0.222	0.854	10	521	43	54	11.1	31.8	600	1929	2258	32.30	30.60	381	42.55	0.148
5	0.157	0.863	10	537	53	41	9.1	17.2	600	1776	2058	34.40	26.80	294	50.36	0.134
6	0.212	0.852	10	510	45	56	14.4	43.3	750	1856	2179	27.20	32.30	303	41.16	0.165
7	0.340	0.846	10	495	63	61	19.0	59.9	750	2189	2588	13.80	51.70	719	23.53	0.206
8	0.117	0.860	10	512	63	59	13.5	29.4	500	1572	1829	16.40	34.10	441	45.45	0.129
9	0.071	0.845	10	523	55	52	13.2	24.5	500	1460	1728	22.70	30.30	492	51.79	0.110
10	0.082	0.815	10	465	49	58	12.0	30.4	500	1327	1628	18.50	39.90	484	39.20	0.158
11	0.158	0.843	10	512	50	57	15.2	27.3	500	1696	2012	25.50	31.40	381	44.95	0.124
12	0.122	0.841	10	512	45	61	4.7	69.6	500	1586	1886	21.50	77.60	388	15.34	0.189
13	0.209	0.825	7.5	486	49	49	3.9	69.4	500	1402	1698	23.60	61.70	162	20.65	0.057
14	0.171	0.858	7.5	500	42	51	5.3	69.7	500	1359	1584	22.80	63.90	151	21.04	0.059

CARBONATION RESULTS

	Sti mgCOD /l	Sbi mgCOD /l	Xa mgVSS /l	Xe mgVSS /l	Xi mgVSS /l	Xv mgVSS /l	Xt mgSS /l	M(Sti) mgCOD /d	M(Sbi) mgCOD /d	M(Xa) mgVSS /d	M(Xe) mgVSS /d	M(Xi) mgVSS /d	M(Xv) mgVSS /d	M(Xt) mgSS /d	M(Oc) mgO /d
CFR1															
1	525	462	774	372	311	1457	1723	4983	4388	5808	2788	2335	10931	12919	3116
2	521	441	740	355	459	1554	1815	4950	4193	5549	2663	3443	11655	13612	2977
3	537	475	796	382	302	1480	1719	5099	4509	5967	2864	2265	11096	12891	3201
4	496	400	670	322	614	1606	1897	4716	3799	5028	2413	4602	12044	14227	2698
5	522	404	678	325	788	1791	2091	4963	3840	5082	2440	5910	13432	15680	2727
6	506	402	674	324	674	1672	1987	4809	3820	5056	2427	5056	12539	14905	2713
7	519	424	710	341	591	1643	1955	4929	4026	5328	2558	4435	12321	14662	2859
8	515	410	688	330	671	1689	1988	4888	3899	5160	2477	5032	12669	14908.	2768
9	482	376	630	302	701	1633	1904	4576	3569	4724	2267	5259	12250	14282	2534
10	503	438	734	353	339	1426	1710	4777	4162	5508	2644	2541	10693	12828	2955
11	498	426	651	234	299	1184	1396	4727	4048	4880	1757	2242	8879	10467	2739
12	505	451	688	248	185	1122	1318	4798	4283	5163	1859	1391	8412	9885	2898
CFR2															
1	513	422	708	340	559	1607	1919	4877	4013	5311	2549	4192	12053	14391	2850
2	535	436	731	351	618	1700	2019	5082	4141	5481	2631	4639	12750	15146	2940
3	524	410	687	330	757	1773	2034	4980	3890	5149	2472	5679	13300	15258	2763
4	521	379	636	305	988	1929	2258	4949	3605	4771	2290	7407	14468	16934	2560
5	537	426	714	343	720	1776	2058	5099	4045	5353	2570	5399	13322	15434	2872
6	510	376	631	303	922	1856	2179	4840	3574	4731	2271	6919	13920	16342	2538
7	495	302	506	243	1441	2189	2588	4699	2865	3791	1820	10805	16416	19407	2034
8	512	427	716	343	513	1572	1829	4868	4055	5366	2576	3850	11792	13720	2879
9	523	460	771	370	319	1460	1727	4971	4369	5782	2775	2393	10950	12956	3102
10	465	404	677	325	325	1327	1628	4417	3835	5076	2436	2436	9949	12212	2723
11	512	406	680	326	690	1696	2012	4861	3852	5099	2447	5174	12720	15089	2736
12	512	424	711	341	534	1586	1886	4863	4027	5330	2559	4003	11892	14145	2860
13	486	360	550	198	654	1402	1698	4621	3423	4125	1485	4901	10512	12735	2315
14	500	389	595	214	550	1359	1584	4751	3699	4459	1605	4126	10190	11880	2503

Nitrification calculation for complete nitrification

	Ns mgN/l	Nae mgN/l	Nue mgN/l	Noi mgN/l	Noe mgN/l	Nte mgN/l	Nne mgN/l	M(Nne) mgN/d	Xn mgVSS /l	M(Xn) mgVSS /d	M(On) mgO/d	M(Ot) mgO/d	Xn/Xv mgVSS/ mgVSS	Rsm d
CFR1														
1	11.5	0.74	1.54	8.81	0.87	3.14	36.56	347	33	248	1587	4703	0.02	3.45
2	12.3	0.74	1.66	8.54	0.88	3.27	39.76	378	36	270	1726	4703	0.02	3.45
3	11.7	0.74	1.23	6.64	0.64	2.60	26.72	254	24	181	1160	4361	0.02	3.45
4	12.7	0.74	1.60	6.86	0.77	3.10	37.42	356	34	254	1625	4322	0.02	3.45
5	14.1	0.74	1.84	7.29	0.81	3.39	43.88	417	40	298	1905	4632	0.02	3.45
6	13.2	0.74	1.74	7.46	0.83	3.31	41.59	395	38	282	1806	4518	0.02	3.45
7	13.0	0.74	1.74	8.11	0.86	3.34	41.79	397	38	284	1814	4673	0.02	3.45
8	13.3	0.74	1.75	7.51	0.82	3.30	41.56	395	38	282	1804	4573	0.02	3.45
9	12.9	0.74	1.51	5.57	0.66	2.91	34.69	330	31	235	1506	4041	0.02	3.45
10	11.3	0.74	1.63	9.27	0.96	3.32	39.72	377	36	270	1725	4680	0.03	3.45
11	12.5	1.11	1.40	7.11	0.82	3.32	30.82	293	23	169	1338	4077	0.02	3.45
12	11.8	1.11	1.67	10.30	1.13	3.90	39.99	380	29	219	1736	4634	0.03	3.45
CFR2														
1	12.7	0.74	1.33	5.38	0.57	2.64	29.17	277	26	198	1266	4116	0.02	3.45
2	13.4	0.74	1.44	5.66	0.59	2.76	31.72	301	29	215	1377	4318	0.02	3.45
3	14.0	0.74	1.82	7.38	0.81	3.37	43.33	412	39	294	1881	4644	0.02	3.45
4	15.2	0.74	1.61	4.04	0.47	2.82	35.75	340	32	243	1552	4112	0.02	3.45
5	14.0	0.74	1.23	3.34	0.35	2.32	24.66	234	22	167	1071	3943	0.01	3.45
6	14.7	0.74	1.68	5.06	0.60	3.02	38.43	365	35	261	1668	4207	0.02	3.45
7	17.3	0.74	1.83	2.05	0.29	2.86	40.86	388	37	277	1774	3808	0.02	3.45
8	12.4	0.74	1.76	8.84	0.93	3.43	42.76	406	39	290	1856	4736	0.02	3.45
9	11.5	0.74	1.57	9.01	0.89	3.20	37.68	358	34	256	1636	4738	0.02	3.45
10	10.5	0.74	1.73	10.15	1.13	3.60	43.73	415	40	297	1899	4622	0.03	3.45
11	13.4	0.74	1.70	7.03	0.78	3.21	40.10	381	36	272	1741	4476	0.02	3.45
12	12.5	0.74	1.82	9.12	0.97	3.52	44.56	423	40	302	1935	4794	0.03	3.45
13	14.8	1.11	1.46	3.86	0.51	3.08	30.96	294	23	170	1344	3660	0.02	3.45
14	14.3	1.11	1.52	5.34	0.66	3.29	33.01	314	24	181	1433	3936	0.02	3.45

COD Balance and COD Utilization rate Calculations.

	NO3gen mgN/l	NO3den mgN/d	M(Oc) mgO/d	M(On) mgO/d	M(Od) mgO/d	M(Oad) mgO/d	Mwaste mgCOD/d	Total COD mgCOD/d	MSti mgCOD/d	COD Balance %	RBCOD UTIL.RATE mgCOD/ gVASS.h	PBCOD Utilization rates Anoxic mgCOD gVASS.h	Aerobic mgCOD gVASS.h	anoxic/ aerobic ratio
CFR1														
1	29.3	691	2368	1272	1977	1663	1618	4462	4983	89.54	7.56	58.1	138.1	0.420
2	23.8	583	2626	1035	1668	1993	1725	4844	4950	97.87	7.56	60.9	123.9	0.492
3	17.1	627	2521	743	1793	1472	1642	4659	5099	91.38	7.56	48.7	152.0	0.320
4	32.5	359	2394	1412	1026	2780	1782	4602	4716	97.60	7.56	55.4	92.7	0.598
5	43.5	289	1596	1887	826	2657	1988	3987	4963	80.34	7.56	44.7	56.8	0.786
6	41.0	270	1435	1780	773	2442	1856	3712	4809	77.20	7.56	36.3	55.4	0.654
7	40.0	230	1531	1738	659	2610	1824	3769	4929	76.47	7.56	33.8	49.9	0.677
8	41.5	135	2174	1800	386	3589	1875	4493	4888	91.92	7.56	24.4	66.9	0.365
9	33.6	116	2047	1459	332	3174	1813	4265	4576	93.20	7.56	19.4	72.9	0.266
10	26.1	393	1531	1135	1124	1542	1583	3538	4777	74.06	7.56	31.0	95.9	0.323
11	20.6	417	1642	896	1192	1346	1752	3775	4727	79.86	8.30	40.6	104.2	0.390
12	17.4	398	1434	755	1139	1050	1660	3591	4798	74.84	8.30	34.9	88.1	0.396
CFR2														
1	24.5	595	2167	1064	1703	1528	1784	4396	4877	90.13	7.56	51.9	149.8	0.346
2	26.7	551	2293	1158	1577	1875	1887	4732	5082	93.13	7.56	50.2	131.6	0.382
3	30.3	670	2474	1315	1917	1872	1968	4890	4980	98.20	7.56	61.1	179.5	0.341
4	27.5	559	2185	1193	1598	1779	2141	4733	4949	95.64	7.56	52.9	179.5	0.295
5	17.9	606	2618	776	1734	1659	1972	5095	5099	99.92	7.56	47.9	220.5	0.217
6	27.0	596	2111	1174	1703	1581	2060	4602	4840	95.08	7.56	59.1	165.1	0.358
7	24.7	416	1400	1073	1189	1284	2430	4425	4699	94.18	7.56	73.8	81.7	0.903
8	32.7	531	1107	1419	1519	1007	1745	3451	4868	70.89	7.56	46.3	68.1	0.680
9	27.7	530	1553	1201	1516	1238	1621	3691	4971	74.25	7.56	39.6	103.2	0.383
10	35.3	547	1359	1534	1564	1329	1472	3301	4417	74.73	7.56	56.7	76.3	0.743
11	28.1	508	1673	1220	1452	1441	1883	4033	4861	82.97	7.56	44.5	123.1	0.361
12	43.4	251	1837	1883	718	3003	1760	4022	4863	82.71	7.56	67.7	48.0	1.412
13	30.1	127	[illegible]	1309	363	2621	2074	4212	4621	91.15	8.30	20.5	74.0	0.277
14	31.0	132	1655	1346	378	2622	2011	4061	4751	85.48	8.30	21.2	64.3	0.329

APPENDIX F

Steady state data, COD balances and COD utilization rates calculations for phase III of the investigation

APPENDIX F

PHASE III COD BALANCE
AND
PBCOD utilization rates and anoxic/aerobic ratio.

CARBONATION INPUT PARAMETERS.						NITRIFICATION INPUT PARAMETERS.								PLANT OPERATING CONDITIONS				
Yh mgVSS/ mgCOD	fcv mgCOD/ mgVSS	fus mgCOD/ mgCOD	bh /d	fbs mgCOD/ mgCOD	f mgVSS/ mgVSS	Yn mgVSS/ mgN	bn /d	Kn mgN/l	Unm /d	Kr l/ mgVSS/ d	fn mgN/ mgVSS	fna mgN/ mgN	fnu mgN/ mgN	Vp l	Q l/d	T deg C	q d	Rhn d
0.450	1.480	0.050	0.240	0.24	0.200	0.100	0.040	1.000	0.330	0.015	0.100	0.750	0.030	7.5	9.5	20	0.75	0.79

MEASURED INPUT DATA.

	fup mgCOD/ mgCOD	fi mgVSS/ mgTSS	Rs d	Sti mgCOD/l	Ste mgCOD/l	Nti mgN/l	Nte mgN/l	Nne mgN/l	NO3add mgN/d	Xv mgVSS/l	Xt mgSS/l	OUR mgO/l/h	%Aerobic. %	DSVI ml/g	Dpred mgN/l	K2 mgNO3-N/ mgAVSS/d
CFR1																
1	0.198	0.837	10	469	32	45	12.6	30.0	500	1671	1996	24.00	29.20	450	40.326	0.090
2	0.180	0.846	8	511	40	60	17.7	36.9	500	1480	1749	22.60	33.40	408	39.948	0.090
3	0.118	0.855	6	492	50	50	19.1	39.8	500	1037	1213	16.30	37.30	238	35.850	0.066
4	0.043	0.865	10	522	49	52	21.0	50.3	500	1368	1582	17.80	32.80	460	51.389	0.036
5	0.046	0.878	5	527	52	59	24.4	34.1	500	869	990	15.80	44.30	151	34.816	0.081
CFR2																
1	0.148	0.853	10	501	43	52	14.1	36.9	500	1632	1914	23.50	29.80	415	45.568	0.077
2	0.019	0.876	6	517	59	55	30.2	45.1	500	919	1049	13.80	40.90	278	39.741	0.038
3	0.065	0.882	5	518	54	52	17.2	59.0	500	881	999	12.90	45.50	304	32.767	0.031
4	0.101	0.888	5	527	64	59	26.2	9.5	0	947	1067	18.00	38.50	231	36.087	0.018

CARBONATION RESULTS

	Sti mgCOD/l	Sbi mgCOD/l	Xa mgVSS/l	Xe mgVSS/l	Xi mgVSS/l	Xv mgVSS/l	Xt mgSS/l	M(Sti) mgCOD/d	M(Sbi) mgCOD/d	M(Xa) mgVSS/d	M(Xe) mgVSS/d	M(Xi) mgVSS/d	M(Xv) mgVSS/d	M(Xt) mgSS/d	M(Oc) mgO/d
CFR1															
1	469	352	591	284	796	1671	1996	4456	3349	4432	2127	5973	12533	14970	2378
2	511	394	615	236	630	1480	1749	4855	3738	4609	1770	4721	11100	13118	2558
3	492	409	574	165	298	1037	1213	4674	3889	4304	1239	2235	7778	9098	2522
4	522	473	793	381	194	1368	1582	4959	4496	5951	2856	1453	10260	11865	3193
5	527	476	617	148	104	869	990	5007	4526	4629	1111	778	6518	7425	2827
CFR2															
1	501	402	673	323	635	1632	1914	4760	3816	5051	2425	4764	12240	14355	2710
2	517	481	675	194	50	919	1049	4912	4574	5061	1458	374	6892	7867	2966
3	518	458	594	142	145	881	999	4921	4353	4452	1069	1087	6607	7492	2719
4	527	447	579	139	229	947	1067	5007	4249	4345	1043	1714	7103	8003	2654

Nitrification calculation for complete nitrification

	Ns mgN/l	Nae mgN/l	Nue mgN/l	Noi mgN/l	Noe mgN/l	Nte mgN/l	Nne mgN/l	M(Nne) mgN/d	Xn mgVSS/l	M(Xn) mgVSS/d	M(On) mgO/d	M(Ot) mgO/d	Xn/Xv mgVSS/mgV	Rsm d
CFR1														
1	13.19	0.74	1.35	3.61	0.45	2.54	29.27	278	26	199	1271	3649	0.02	3.45
2	14.61	1.00	1.80	6.99	0.84	3.64	41.75	397	32	240	1813	4371	0.02	3.45
3	13.64	1.68	1.50	7.08	0.91	4.08	32.27	307	20	148	1401	3923	0.02	3.45
4	10.80	0.74	1.56	9.91	0.95	3.25	37.95	361	34	258	1648	4840	0.03	3.45
5	13.72	2.67	1.77	11.34	1.37	5.80	39.48	375	21	156	1714	4541	0.02	3.45
CFR2														
1	12.88	0.74	1.56	6.42	0.72	3.01	36.10	343	33	245	1567	4277	0.02	3.45
2	12.09	1.68	1.65	11.44	1.27	4.60	38.31	364	23	176	1663	4629	0.03	3.45
3	13.91	2.67	1.56	9.15	1.14	5.37	32.72	311	17	130	1421	4140	0.02	3.45
4	14.95	2.67	1.77	9.37	1.19	5.63	38.42	365	20	152	1668	4322	0.02	3.45

COD Balance and COD Utilization rate Calculations.

	NO3gen mgN/l	NO3den mgN/d	M(Oc) mgO/d	M(On) mgO/d	M(Od) mgO/d	M(Oad) mgO/d	Mwaste mgCOD/d	Total COD mgCOD/d	MSti mgCOD/d	COD Balance %	RBCOD UTIL.RATE mgCOD/gVASS.h	PBCOD Utilization rates and ratio Anoxic mgCOD/gVASS.h	Aerobic mgCOD/gVASS.h	anoxic/aerobic
CFR1														
1	19.2	397	1564	834	1137	1261	1855	3723	4456	83.56	7.556	37.833	143.534	0.264
2	27.7	413	1336	1202	1180	1359	2054	3770	4855	77.65	8.111	40.049	100.394	0.399
3	17.3	286	1163	749	817	1094	1918	3556	4674	76.08	9.037	28.920	81.504	0.355
4	20.2	214	786	877	612	1051	1518	2770	4959	55.86	7.556	11.626	42.790	0.272
5	20.9	374	1424	906	1071	1260	1929	3847	5007	76.85	9.778	42.257	77.041	0.549
CFR2														
1	25.0	387	1282	1086	1107	1261	1812	3502	4760	73.57	7.556	31.563	98.872	0.319
2	12.7	192	1014	552	550	1016	1700	3275	4912	66.68	9.037	13.998	52.204	0.268
3	20.9	138	544	907	395	1057	1956	3013	4921	61.23	9.778	10.594	23.798	0.445
4	17.8	79	699	775	227	1247	2102	3410	5007	68.11	9.778	0.855	42.477	0.020