UNIVERSITY OF CAPE TOWN
Department of Civil Engineering

FINAL REPORT TO THE WATER RESEARCH COMMISSION ON A THREE YEAR CONTRACT ON DEVELOPMENT AND FULL SCALE EVALUATION OF PREVENTATIVE AND REMEDIAL METHODS FOR CONTROL OF ACTIVATED SLUDGE BULKING

(June 1985 to May 1988)

by

D M D Gabb, D A Still, G A Ekama, D Jenkins, M C Wentzel and G v R Marais

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SYNOPSIS

This report outlines the research undertaken into evaluation of bulking control in long sludge age systems, in particular in nitrogen (N) and nutrient (N and P) removal ones. The objectives of the research were to:

(i) identify the filamentous organisms causing bulking in nutrient removal systems in south Africa,

(ii) evaluate non-specific bulking control with chlorination on biological N and P removal, and

(iii) evaluate specific bulking control procedures for long sludge age systems, in particular the role of aerobic, anoxic or anaerobic selectors for bulking control in nitrogen (N) and nutrient (N and P) removal systems.

In the survey, which covered 33 out of about 45 nutrient (N and P) removal plants in South Africa, the six most frequently dominant filamentous organisms were found to be 0092, dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *Microthrix parvicella* in 33%, 0914 in 33% and 1851 in 21%. In a different order these 6 filaments are also the six most frequently dominant ones in all (96) activated sludge plants most of which are nitrogen (N) or nutrient (N and P) removal plants. Four of the 6 filaments sort into the low F/M[1] (low Food/Micro-organism ratio or equivalently long sludge age) group of filaments.

Chlorination bulking control was investigated on a Modified UCT (University of Cape Town) system with a bulking sludge caused by 0092, *M.parvicella* and 0914. Following the procedure set out in the Manual on Causes and Control of Filamentous Bulking and Foaming by Jenkins, Richard and Daigger (1984), it was concluded that chlorination is a viable method without significant reduction in biological N and P removal.

With regard to specific bulking control of low F/M filaments, the promoted method is system configuration modification so as to incorporate alternating feed-starve conditions such as intermittent (batch) feeding, multi-reactor or plug flow systems or

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[1]All abbreviations and acronyms are defined in the glossary at the back of the report.

completely mixed systems incorporating selector reactors. The mechanism whereby these systems apparently effect control of the low F/M filaments is hypothesized to be by the preferential removal of the readily biodegradable COD (RBCOD) at a high concentration and rate by the floc-formers at the time of feeding in intermittently fed systems, at the influent end of plug flow or multi-reactor systems or in the selectors.

The above mechanism and systems for controlling low F/M filaments were investigated and the following conclusions emerge from this work:

1 The alternating feed-starve conditions imposed by

(i) intermittent feeding to completely mixed reactor systems,
(ii) selector reactors (aerobic) incorporated in continuously fed completely mixed systems

under aerobic or anoxic conditions stimulate in the mixed liquor a high readily biodegradable (or dissolved, 0,45 μm filtered) COD (RBCOD) uptake rate. The RBCOD uptake rate is 2 to 3 times higher than in systems which do not have alternating feed-starve conditions, such as continuously fed completely mixed systems. If the conditions are aerobic the high RBCOD uptake rate gives rise to an associated high initial oxygen uptake rate under batch conditions; if the conditions are anoxic, it gives rise to an associated high (initial) nitrate uptake rate under batch conditions. For convenience, a sludge in which a high RBCOD uptake rate has been stimulated, is said to have acquired a "selector effect". The selector effect can be stimulated or lost in a period of less than a sludge age in long sludge age systems by introducing or eliminating alternating feed-starve conditions. The acquisition of a selector effect by a sludge under alternating feed-starve conditions is in agreement with the literature.

2 Low F/M bulking sludges (Diluted Sludge Volume Index, DSVI > 250 mℓ/g and containing usually in varying proportions, 0092, *M.parvicella*, 0914, 0675, 1851 and 0041 filaments) from long sludge age full scale nitrogen removal plants, when used to start up laboratory scale long sludge age activated sludge systems under *fully aerobic conditions* invariably ceased bulking (DSVI < 80 mℓ/g) within a month irrespective of whether or not the system stimulated a selector effect. Evidently, in long sludge age fully aerobic systems, the selector effect was irrelevant because the low F/M filament growth was suppressed both when the selector effect was present or absent.

3 In long sludge age (low F/M) systems in which there was no selector effect, when bulking was observed, it was *not* due to proliferation of low F/M filaments but due to the low dissolved oxygen (DO) filament *Sphaerotilus natans* and/or septic sewage filament *Thiothrix*. Curiously, *S.natans* has not yet been observed to cause bulking in South African full scale long sludge age plants and *Thiothrix* only rarely.

4 It was established that *S.natans* proliferation in laboratory units can be caused by seeding from *S.natans* attached growth on the feed line walls. This artefact seems to have been present in many laboratory scale studies throughout the world because numerous investigators have reported the proliferation of *S.natans* in their laboratory units under a wide range of operating conditions.

5 The selector effect (i.e. aerobic selectors and intermittent feeding conditions) controlled the proliferation of *S.natans* and *Thiothrix*. This observation is in conformity with results reported in the literature. The success of the selector effect in controlling bulking by *S.natans* and *Thiothrix* in laboratory scale systems possibly contributed to the notion that the selector effect also controls low F/M filament proliferation.

6 The research programme was continued by investigating the earlier observation that purely aerobic conditions ameliorated bulking by low F/M filaments irrespective of the presence of a selector effect. Three single reactor systems were set up all at the same sludge age (20 days), received the same sewage, and started up with a low F/M bulking sludge from a laboratory scale nutrient removal (Modified UCT) system; two were *purely aerobic*, one intermittently fed, the other continuously fed and one was anoxic ($\frac{1}{2}$ hour) — anaerobic ($5\frac{1}{2}$ h) — aerobic (16 h) and intermittently fed. The DSVI in the two purely aerobic systems declined and bulking by the low F/M filaments was ameliorated while over the same period, the DSVI remained high and the low F/M filaments continued to proliferate in the parent Modified UCT system and in the anaerobic-aerobic intermittently fed system. This indicated that (i) continuous aeration inhibits the growth of most of the low F/M filaments, (in particular *M.parvicella*, 0092 and 0914) irrespective of whether the conditions are alternating feed-starve (intermittently fed) or completely mixed (continuously fed), and (ii) in systems with alternating unaerated:aerated conditions the low F/M filaments continue to proliferate.

7 To grow low F/M filaments in laboratory systems other than nutrient 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 2,0 mg/ℓ) were set up. It was found that in these systems most (but not necessarily all together) of the low F/M filaments proliferated (DSVI > 300 mℓ/g), in particular *M.parvicella* and 0092, but also 0914, 0041, 0675 and 1851. Switching from intermittent aeration to continuous aeration caused a shardecline in bulking (DSVI < 80 mℓ/g in under one sludge age) 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 (DSVI > 300 mℓ/g).

8 Installing an aerobic selector (which stimulated a selector effect) on a single reactor intermittent aeration system did not control most of the low F/M filaments; the DSVI remained above 280 mℓ/g for over 5 sludge ages.

9 Aerobic selectors and anaerobic reactors stimulate removal of RBCOD by floc-formers. Because these do not control low F/M filament proliferation, it would appear that the influent readily biodegradable COD does not play an important role in low F/M bulking.

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PAPERS, REPORTS AND OTHER CONTRIBUTIONS

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I PAPERS PUBLISHED

1. Blackbeard J R and G A Ekama (1984) Survey of activated sludge bulking and foaming in Southern Africa, IMIESA, 9, 3, 20-25.

2. Ekama G A and G v R Marais (1986). Implications of the IAWPRC hydrolysis hypothesis on low F/M bulking. Presented at IAWPRC specialized seminar on mathematical modelling, Copenhagen, Aug. 1985. Wat.Sci.Tech., 18, 11-19.

3. Blackbeard J R, G A Ekama and G v R Marais (1986). A survey of filamentous bulking and foaming in activated sludge plants in South Africa. Presented at IWPC biennial conference, Durban, May 1985. Wat.Pollut. Control, 1, 90-99.

4. Ekama G A and G v R Marais (1986). Sludge settleability and secondary settling tank design procedures. Presented at IWPC biennial conference, Durban, May 1985. Wat.Pollut. Control, 1, 101-113.

5. Blackbeard J R, D M D Gabb, G A Ekama and G v R Marais (1988). A survey of filamentous organisms in nutrient removal activated sludge processes. Presentation at IWPC conference, Port Elizabeth, May 1987. Water SA, 14, 1, 29-33.

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7. Gabb D M D, G A Ekama, D Jenkins and G v R Marais (1989). Incidence of *Sphaerotilus natans* in laboratory activated sludge systems. Presented at 14th IAWPRC biennial conference, Brighton, July 1988. Wat.Sci.Tech., 21, Brighton, 29-41.

8. Ekama G A (1988). Evaluation of bulking control methods for long sludge age activated sludge systems. Presented at Technology Transfer Seminar arranged jointly by the Johannesburg City Council, Water Research Commission and University of Cape Town, 27 October 1988.

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2. W 54 Ekama G A, G v R Marais and J R Blackbeard (1985). Final report to the Water Research Commission on a two-year exploratory study on activated sludge bulking and foaming (1983-1984). (1) Survey of extent and severity of bulking and foaming (2) Identification of filamentous micro-organisms (3) sludge settleability and secondary settling tank behaviour. WRC Report No. 114/1/85.

3. W 55 Still D A, J R Blackbeard, G A Ekama and G v R Marais (1986). The effect of feeding patterns on sludge growth rate and sludge settleability.

4. W 61 Gabb D M D, G A Ekama, D Jenkins and G v R Marais (1987). Specific control measures for filamentous bulking in long sludge age activated sludge systems.

5. W 62 Gabb D M D, D A Still, G A Ekama, D Jenkins, M C Wentzel and G v R Marais (1988). Final report to the Water Research Commission on a three year contract on development and full scale evaluation of preventative and remedial methods for control of activated sludge bulking. WRC Report No. 165/1/88.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

During 1984 and 1985, an exploratory study into solid liquid-separation problems in activated sludge plants was conducted by the University of Cape Town under contract with the Water Research Commission.[1] This study encompassed (1) evaluation of the extent and severity of bulking and foaming problems in activated sludge plants in South Africa; (2) identification of filamentous organisms associated with bulking and foaming; (3) evaluation of secondary clarifier design criteria; (4) review of information on bulking and foaming control. From the information collected in the study the following recommendations were made:

(1) Compile a manual setting out current practice of filamentous bulking and foaming control,

(2) Undertake research into preventative and remedial measures for filamentous bulking and foaming,

(3) Compile a manual setting out secondary settling tank design procedures.

In pursuance of the recommendations above the Water Research Commission concluded four contracts, with:

(1) Dr David Jenkins at the University of California, to compile a manual on bulking and foaming control.

(2) University of Pretoria, to investigate causes of foaming and measures for its control.

(3) University of Cape Town, to compile a manual on secondary clarifier design.

(4) University of Cape Town, to investigate causes of bulking in nutrient (N and P) removal plants and measures for its control.

Of these contracts, (1) and (2) have been completed (Jenkins *et al.*, 1984, Laubscher and Pretorius, 1987); (3) is in the process of completion; this report reviews the work conducted under (4).

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[1]The final report of this study is given by Ekama *et al.* (1985).

1.2 RESEARCH OBJECTIVES

The specific objectives set for contract number (4) were as follows:

(1) Investigate the prevalence and severity of filamentous bulking in nutrient (N and P) removal activated sludge systems in South Africa.

(2) Investigate the effect of the non-specific chlorination filamentous bulking control on nutrient N and P removal activated sludges.

(3) Investigate the causes of filamentous bulking in activated sludge systems in South Africa, in particular, in biological nitrogen (N) and nutrient (N and P) removal systems.

(4) Develop specific methods of control of filamentous bulking in nitrogen and nutrient removal systems.

1.3 LAYOUT OF REPORT

The investigation into the prevalence and severity of filamentous bulking in nutrient removal activated sludge systems (objective 1) is reported on in Chapter 2 and that into non-specific filamentous bulking control with chlorination in nutrient removal activated sludges in Chapter 3. In Chapters 4 to 8 the results of the investigations in pursuance of objectives 3 and 4 are presented, commencing with a review of literature on specific bulking control procedures in aerobic and anoxic-aerobic systems (Chapter 4) and continuing with a description of the experimental investigation into specific bulking control of low F/M filaments in *aerobic* (Chapter 5) and *anoxic-aerobic* (Chapter 6) long sludge age systems, the establishment of the conditions for developing low F/M filament bulking sludges (Chapter 7) and evaluation of aerobic selectors for controlling low F/M filaments in long sludge age systems (Chapter 8). A glossary defining the terms, acronyms and abbreviations used in this report is given at the back of this report.

CHAPTER 2

BULKING IN NUTRIENT REMOVAL PLANTS IN SOUTH AFRICA

2.1 SURVEY OF FILAMENTOUS ORGANISMS

Over the past ten years biological nutrient (N and P) removal activated sludge plants[1] have become the preferred method for removing nitrogen (N) and phosphorus (P) from municipal waste waters in South Africa. Today there are about 45 nutrient removal plants in operation, of varying size, ranging from 2 to 150 Mℓ/d, with a total design capacity of about 1 200 Mℓ/d. Information on nutrient removal plants, from the data supplied in the survey on bulking and foaming of activated sludge plants in South Africa (Blackbeard *et al.*, 1986) indicate that nutrient removal plants are prone to producing bulking sludges.

Information was abstracted on the 26 nutrient removal plants listed in the survey by Blackbeard *et al.* (1986). Requests for samples were sent to 15 other nutrient removal plants not included in the survey; response from 7 plants were received. Hence information was available on 33 nutrient removal plants representing about three quarters of the nutrient removal plants in operation in South Africa.

From the filament abundance in the samples, 27 out of the 33 nutrient removal plants appeared to have bulking sludges.

Taking all 33 samples together the dominant[2] filaments in decreasing order of frequency of dominance were 0092, dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *M.parvicella* in 33%, 0914 in 33% and 1851 in 21% (Fig 2.1). These six filamentous organisms are also the six most frequently dominant filaments in all activated sludge plants surveyed in South Africa, but in different order: In the first survey of 96 plants (see Blackbeard *et al.*, 1986, see also Ekama *et al.*, 1985), the majority of which were nitrogen or nutrient removal plants, the six filaments in descending order of frequency of dominance are: 0092 dominant in 34% of plants, 0914 in 24%, *M.parvicella* in 20%, 1851 in 17%, 0675 in 16% and 0041 in 14% (see top of Fig 2.1).

From the two surveys, it is clear that activated sludge plants in South Africa, including nutrient removal ones, have sludges that are dominated by a limited number

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[1]N and P removal plants commonly are called nutrient removal plants; nitrification/denitrification plants are called nitrogen (N) removal plants. This nomenclature is retained in this report.

[2]Dominant 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; non-bulking sludge usually has only one filament that is dominant. Filaments in the mixed liquor that are not dominant are termed secondary.

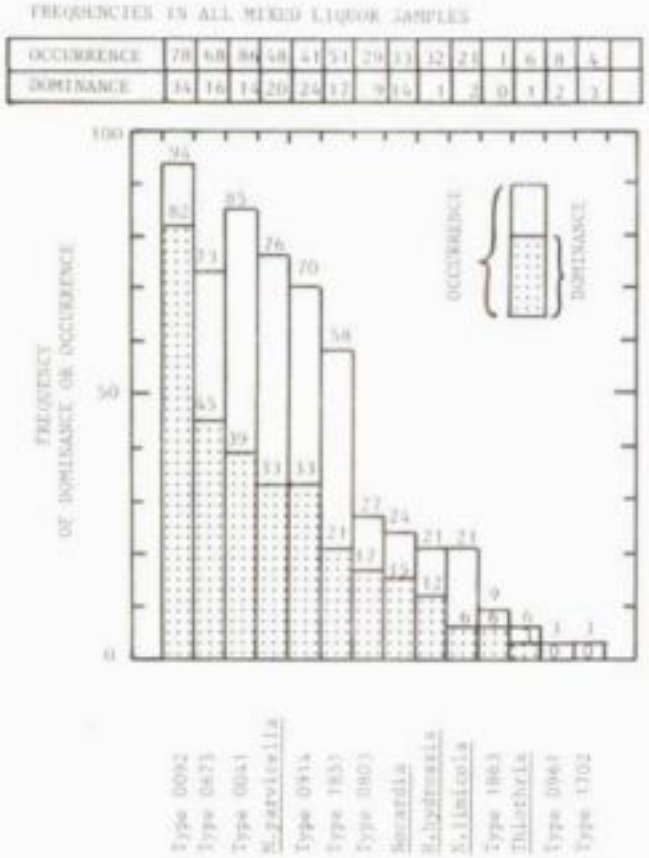

Fig 2.1: *Frequency of dominance and frequency of occurrence of different filamentous organism types in the mixed liquor of 55 biological nutrient removal plants in South Africa ranked in descending order of frequency of dominance. For comparison, the frequencies of dominance and of occurrence of the filamentous organism types in the mixed liquor of all activated sludge plants in South Africa found by Blackbeard et al. (1986) are given at the top of the figure (see also Table 1.1) (from Blackbeard et al., 1988).*

TABLE 2.1

FREQUENCY OF DOMINANCE AND FREQUENCY OF OCCURRENCE OF FILAMENTOUS ORGANISM TYPES IN MIXED LIQUOR SAMPLES FROM NUTRIENT REMOVAL PLANTS (LEFT) AND ALL ACTIVATED SLUDGE PLANTS (RIGHT) IN SOUTH AFRICA*

Filamentous organism type	South Africa			
	Nutrient removal plants		**All activated sludge plants	
	+Dominance	++Occurrence	+Dominance	++Occurrence
Type 0092	82 (1)	94 (1)	54 (1)	78 (2)
Type 0675	45 (2)	73 (4)	16 (5)	68 (5)
Type 0041	39 (3)	85 (2)	14 (6)	86 (1)
M. parvicella	33 (4)	76 (3)	20 (3)	68 (5)
Type 0914	33 (5)	70 (5)	24 (2)	61 (6)
Type 1851	21 (6)	58 (6)	17 (4)	51 (4)
Type 0803	17	27	9	29
Nocardia	15	24	14	55
H. hydrossis[1]	12	21	1	52
N. limicola[2]	6	21	2	23
Type 1863	6	9	0	1
Thiothrix	3	6	1	6
Type 0961	0	3	2	8
Type 1702	0	3	3	4
Number of samples	55		96	
Number of plants	55		99	

* For a comparison with the frequencies of dominance of filamentous organisms in USA, European and West German Plants, see Blackbeard *et al.*, 1986.

** Data from Blackbeard *et al.*, 1986 for bulking and non bulking sludges.

\+ Percentage of plants in which particular filamentous organisms were dominant.

++ Percentage of plants in which particular filamentous organisms were present.

( ) Denotes rank in descending order.

[1] *Haliscomenobacter hydrossis*

[2] *Nostocoida limicola*

of filamentous organism types. Of the six, four i.e. 0092, *M.parvicella*, 0675 and 0041 are classified by Jenkins *et al.* (1984) into a group designated low F/M (low Food/Micro-organism ratio or long sludge age). Types 0675 and 0041 also sort into a nutrient deficiency group. Types 0914 and 1851 have not yet been grouped but their frequency of appearance with low F/M types suggests that possibly these two filaments should also be classified low F/M types.

In the survey above it should be noted that *Sphaerotilus natans* was not, and *Thiothrix* only rarely, identified as a dominant filamentous organism in South African plants. This observation is significant and will be addressed again later in this report.

From the two surveys it was concluded that application of activated sludge technology in general and that of nutrient removal in particular, will be greatly facilitated with substantial savings, if bulking can be ameliorated by controlling the growth of filamentous organisms.

2.2 EFFECT OF FILAMENTOUS ORGANISMS ON SLUDGE SETTLEABILITY

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 $\approx$ 30 km/g the DSVI $\approx$ 150 mℓ/g (Fig 2.2). At this TEFL the filamentous organisms commence to dominate the behaviour of the settling sludge. As a rough guide therefore, a bulking sludge can be accepted as one having a DSVI > 150 mℓ/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 (see Fig 2.2) (Lee *et al.*, 1983). However taking note of reported data, one can accept, roughly, that an SVI between 100 and 200 mℓ/g possibly is a bulking sludge, and an SVI > 200 mℓ/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 overflow rate (m/h) in the secondary settling tank, and the daily mass of COD treated sets the sludge concentration in the biological reactor. Ekama and Marais (1986) showed that a sludge with a DSVI of 150 mℓ/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, or, the same overflow rate can be maintained (at 1 m/h) provided the reactor MLSS concentration is reduced to 2,4 g/ℓ. In this instance a DSVI increase from 150 to 200 mℓ/g causes that about 33% less flow and load can be treated in the plant. In contrast, if the DSVI is reduced from 150 to 100 mℓ/g the overflow rate can be increased to 1,8 m/h at 3,5 g/ℓ, or, the reactor concentration can be increased to 5,4 g/ℓ at an overflow rate of 1 m/h, i.e. both the flow and load can be increased by about 67% (Fig 2.3).

Clearly the settling tank can be the bottle-neck in plant performance. Should a plant

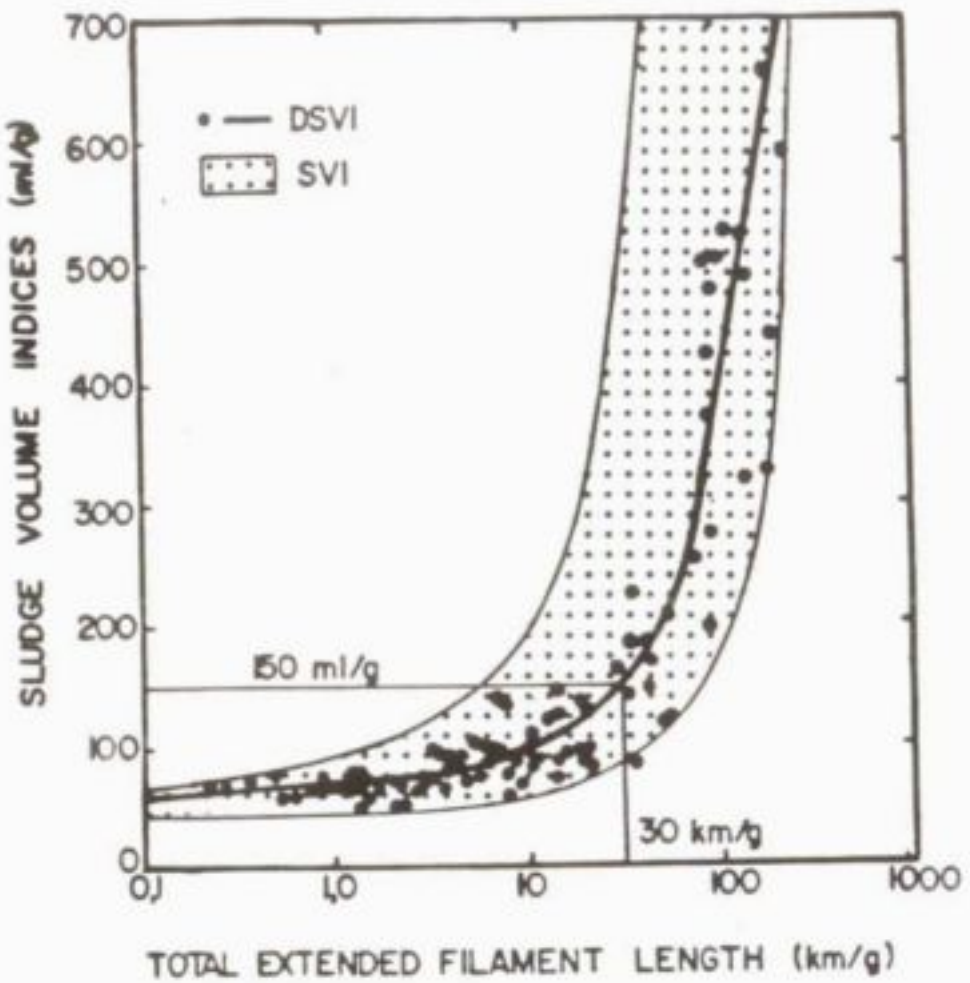

Fig. 2.2: *Sludge settleability in terms of the conventional (SVI) and diluted (DSVI) sludge volume indices as a function of total extended filament length (TEFL). For TEFL > 30 km/g, the filamentous organisms appear to attain an abundance level where they begin to dominate the settling behaviour of the sludge, as reflected in the sharp increase in DSVI. (adapted from Lee et al., 1983).*

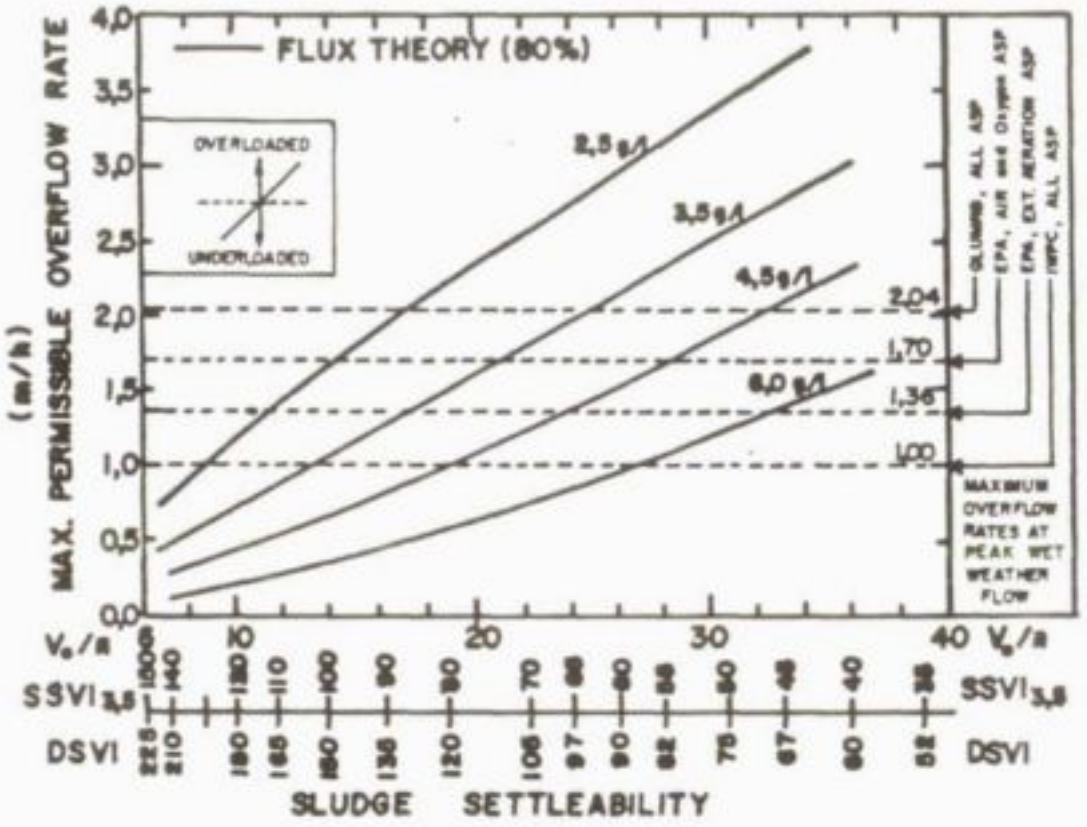

Fig 2.3: *Maximum permissible overflow rate (reduced to 80%) versus sludge settleability in terms of DSVI, $SSVI_{3,5}$ and V_o/n for the flux theory at 80% optimum overflow rate for 2,5; 3,5; 4,5 and 6,0 g/ℓ reactor concentration. Also shown are the hydraulic overflow rate criteria of the EPA, GLUMRB and IWPC: Criteria give safe designs for settleabilities better than that given by the intersection point of the flux predictions and criteria lines (i.e. left of intersection point) e.g. 1 m/h IWPC criterion is safe for DSVI < 150 mℓ/g at 3,5 g/ℓ. (from Ekama and Marais, 1986) (see glossary for explanation of acronyms.*

be designed for a specific load and DSVI, if the DSVI in fact is found to be higher, the settling tank will limit the attainable load to less than the design load. To achieve the expected treatment load in the operating plant, will require augmentation of the settling tank capacity; this may have major financial implications. Controlling, or preferably eliminating bulking, therefore, holds promise of major financial savings.

CHAPTER 3

NON-SPECIFIC BULKING CONTROL BY CHLORINATION

3.1 INTRODUCTION

The principal non-specific control procedure is by chlorination. Chlorination has the potential to reduce all the filamentous organism types irrespective of the specific causes that give rise to their growth such as low DO, nutrient deficiency, long sludge age, system configuration or system operation; hence the designation non-specific.

Non-specific bulking control by chlorination is well documented in the literature, e.g. the bulking control manual of Jenkins *et al.* (1984). However, no investigations have been reported on control of bulking by chlorination on nutrient removal systems. Because so many nutrient removal plants experience bulking, non-specific bulking control with chlorination was investigated in a laboratory scale nutrient removal system. The results of this investigation are summarized below; details have been published by Lakay *et al.* (1988).

3.2 EXPERIMENTAL STUDY

The laboratory scale system selected for study was a long sludge age (20 days) modified UCT system receiving unsettled municipal sewage from Mitchell's Plain at 1000 mgCOD/ℓ strength. System details are shown in Table 3.1 and Fig 3.1.

Past history of this system is that it was prone to producing a bulking sludge, Fig 3.2. In the period prior to commencing the chlorination study the sludge settleability progressively deteriorated from a DSVI of 150 mℓ/g up to 230 mℓ/g at which point it was no longer possible to contain the sludge in the system (see Fig 3.2). Microscopic examination of the sludge indicated

(1) the overall filament abundance was abundant (5) to excessive (6) (after Jenkins *et al.*, 1984);

(2) a large number of polyphosphate accumulating organisms were present; and

(3) the dominant filamentous organisms were Types 0092 (ranked 1st), Type 0914 (2nd) and *M.parvicella* (3rd).

These 3 filaments are amongst the 6 most frequently dominant filaments in nutrient removal plants (Chapter 2). The presence of large numbers of polyP accumulating organisms in the mixed liquor and the high biological P removal obtained (about 20 mgP/ℓ[1] for an influent readily biodegradable COD, RBCOD, concentration (S_{bsi}) of

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[1]Phosphorus *removal* is reported as mgP/ℓ which is obtained from the difference between the influent and effluent P concentrations. Provided the effluent P concentration is greater than about 1 mgP/ℓ (which was the case in our experiments),

around 200 mg/ℓ yielding a $\Delta P/S_{bsi}$ of 20/200 = 0,10 mgP/mgRBCOD), indicated that biological P removal was fully active[2] in the system. These conditions presented a worthwhile opportunity to investigate chlorination bulking control in a biological excess P removal system.

Chlorine (appropriately diluted sodium hypochlorite) was dosed into the inter-reactor flow between the 2nd anoxic and aerobic reactors (Fig 3.1). This point was chosen in preference to the underflow because it best satisfied the recommended chlorination parameters proposed by Jenkins *et al.* (1984), i.e. (1) frequency of exposure F = 4,6/d (recommended F > 2,5/d), (2) local dose concentration C = 7,6 mg$C\ell_2/\ell$ at an overall mass dose rate of 8 mg$C\ell_2$/(gMLSS.d) (recommended C < 35 mg/ℓ), and (3) absence of nitrite (because nitrite reduces chlorine to chloride). Dosing into the underflow would have yielded a frequency of exposure of only 1,6/d which is below the recommended value — in South African activated sludge plants because of their long sludge ages (≈ 20d) and retention times (≈ 24h) it is not possible usually to attain the required frequency of exposure by dosing into the underflow.

3.2.1 Diluted Sludge Volume Index (DSVI) reduction

Following a lead-in period at overall mass dose rates of 2 and 4 mg$C\ell_2$/(gMLSS.d), the maximum dosing rate at 8 mg$C\ell_2$/(gMLSS.d) was continued for 19 d, during which time the DSVI decreased from 230 to 48 mℓ/g. Dosing was terminated when the system manifested overdosing symptoms, e.g. high effluent turbidity.

3.2.2 COD, P and N removal

Even at the maximum dosing rate of 8 mg$C\ell_2$/(gMLSS.d), the COD removal remained essentially unchanged except when overdosing became apparent towards end of the dosing period. Nitrification also was unaffected in that the effluent TKN concentration remained unchanged (Fig 3.2); to evaluate the effect of chlorination on nitrification, it would have been better to have measured the free and saline ammonia concentration. However, only the TKN concentration was measured, which is the sum of organic nitrogen and free and saline ammonia. From experience, when the effluent TKN concentration is less than about 7% of the influent value which was the case before, during and after the chlorination period, the ammonia concentration usually is less than 1 mgN/ℓ and the major fraction of the effluent TKN concentration is unbiodegradable and unbiodegraded soluble organic N. Denitrification was only marginally affected in that the effluent nitrate concentration increased slightly towards

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the P removal in mgP/ℓ gives the system P removal capability. This method of reporting biological P removal performance is, in the opinion of the authors, superior to the percentage P removal method because it gives an indication of the actual mass concentration of P removed.

[2]The *maximum* biological P removal that can be attained is directly proportional to the influent RBCOD concentration; a $\Delta P/RBCOD$ = 0,10 mgP per mg influent RBCOD reflects virtually complete utilization of the influent RBCOD for P removal for a 20 day sludge system. The lower the ratio $\Delta P/RBCOD$ is below 0,10, the poorer the biological P removal below that attainable.

TABLE 3.1

DESIGN AND OPERATING PARAMETERS OF MODIFIED UCT SYSTEM IN CHLORINATION BULKING CONTROL (SEE FIG. 1 FOR SYSTEM CONFIGURATION).

Parameter	Value
Sludge age	21 d
Temperature	20°C
Influent : Mitchell's Plain raw sewage	
Flow	15 ℓ/d
COD concentration	1 000 mg/ℓ
Readily biodegradable COD concentration	210 mg/ℓ
TKN concentration	70-100 mgN/ℓ*
Total P concentration	30 mgP/ℓ**
Reactor volumes; mass fractions	
Anaerobic	6ℓ ; 0,16
1st Anoxic	2ℓ ; 0,10
2nd Anoxic	4ℓ ; 0,21
Aerobic	10ℓ ; 0,53
Unaerated mass fraction	0,47
Recycles	
Underflow 1 : 1	15 ℓ/d
Mixed liquor – Aerobic to 2nd Anoxic 4 : 1	60 ℓ/d
Mixed liquor – 1st Anoxic to Anaerobic 1 : 1	15 ℓ/d
VSS concentration in aerobic reactor	3 400 mg/ℓ
MLSS concentration in aerobic reactor	4 500 mg/ℓ
Mass MLSS in system	86 g

* *TKN/COD ratio differed between individual sewage batches.*

** *The influent was supplemented with 15 mgP/ℓ orthophosphate to raise the concentration to around 30 mgP/ℓ. This was necessary to ensure that the effluent P concentration always was high (>5 mgP/ℓ) so that the difference between influent and effluent P gives the system P removal capability in mgP/ℓ influent.*

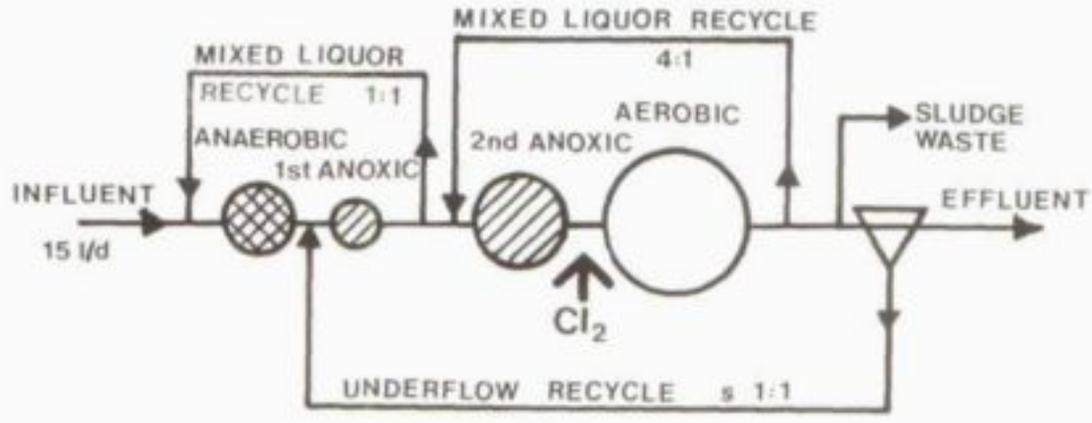


Fig 3.1: *Diagrammatic representation of the Modified UCT system showing the point of application of the chlorine for bulking control.*

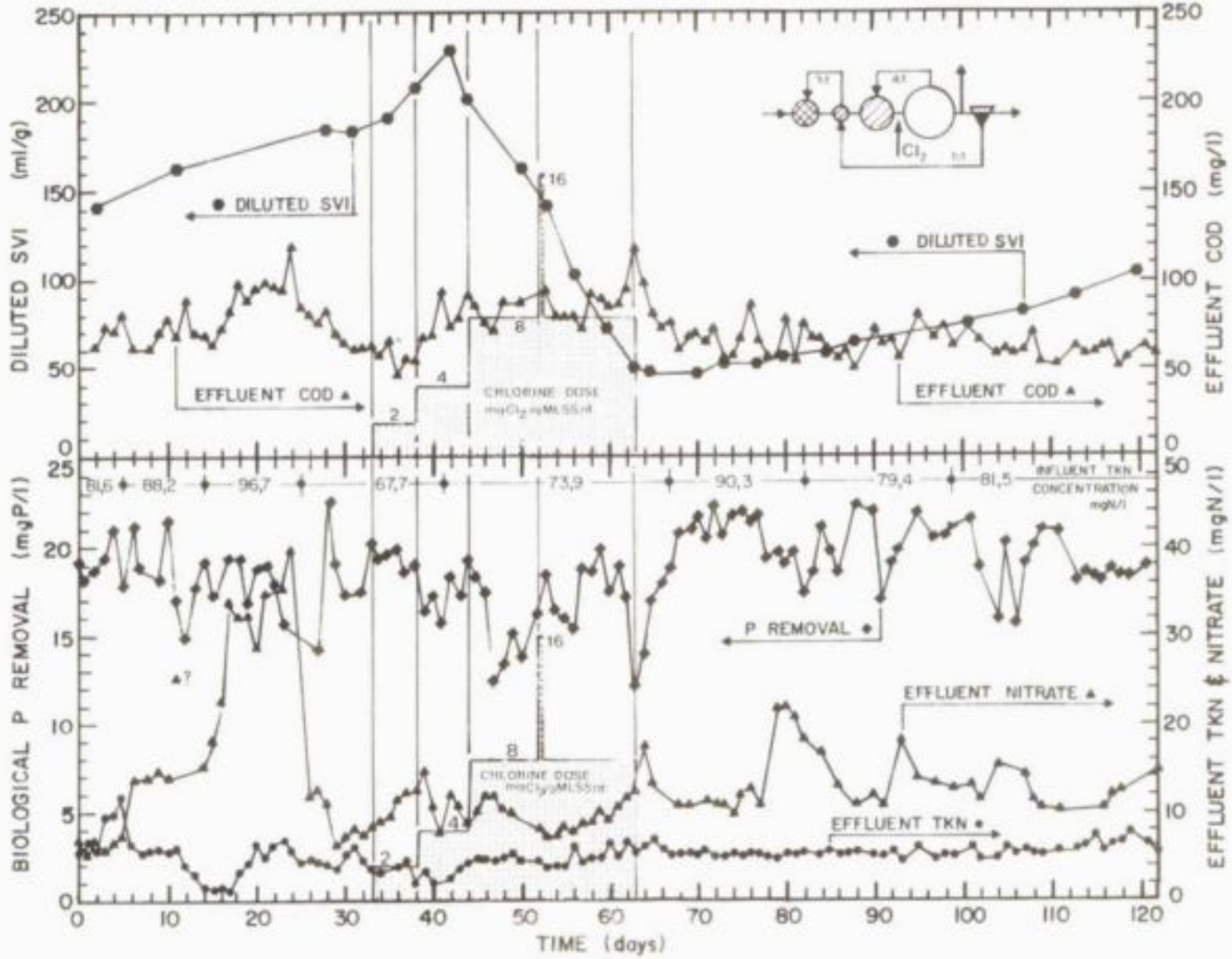


Fig 3.2: *Diluted SVI and unfiltered effluent COD concentration (top) and biological P removal and effluent TKN (unfiltered) and nitrate concentrations (bottom) versus time in a modified UCT nutrient removal system at 20° C and 21d sludge age before, during and after a chlorination episode for filamentous bulking control. Chlorination period and dose rates are also shown.*

CHAPTER 4

SPECIFIC BULKING CONTROL
REVIEW OF LITERATURE

In contrast to non-specific bulking control, which focuses on eliminating the *symptoms* of bulking i.e. filament proliferation, specific control of bulking focuses on identifying and eliminating the *causes* of filament proliferation. Once the causes are identified 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 specific bulking situation.

Five conditions have been identified that lead to filamentous organism proliferation (Jenkins *et al.*, 1984), viz. low DO, low F/M, nutrient deficiency, septic influent and low pH; each condition favours the growth of certain filamentous organisms. From the surveys on bulking mentioned earlier, the most frequently dominant filamentous organisms in South African activated sludge plants belong to the low F/M group.

In 1973, Chudoba *et al.* proposed an organism selection criterion as an explanation for the occurrence or non-occurrence of bulking. This criterion is based on competition between floc-formers and filaments for a mutually limiting soluble substrate concentration, 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 ($\hat{\mu}_H$) and the half saturation coefficient (K_s) than the floc-formers. Consequently at low substrate concentrations the filamentous organisms have a higher specific growth rate than the floc-formers and at high substrate concentrations, a lower specific growth rate (Fig 4.1).

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), van Veen *et al.* (1982), Richard *et al.* (1981) and Chudoba *et al.* (1985) showed that in general, $\hat{\mu}_H$ and K_s are both considerably smaller for the filaments than for the floc-formers; Chudoba *et al.* (1973) and Cech *et al* (1984) found that organisms with high $\hat{\mu}_H$ rates have high K_s values and ones with low $\hat{\mu}_H$ rates have low K_s values. Slijkhuis (1983) measured the $\hat{\mu}_H$ of *Microthrix parvicella* (one of the principal filaments causing low F/M bulking) to be 1,66/d; this is considerably lower than a $\hat{\mu}_H$ 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

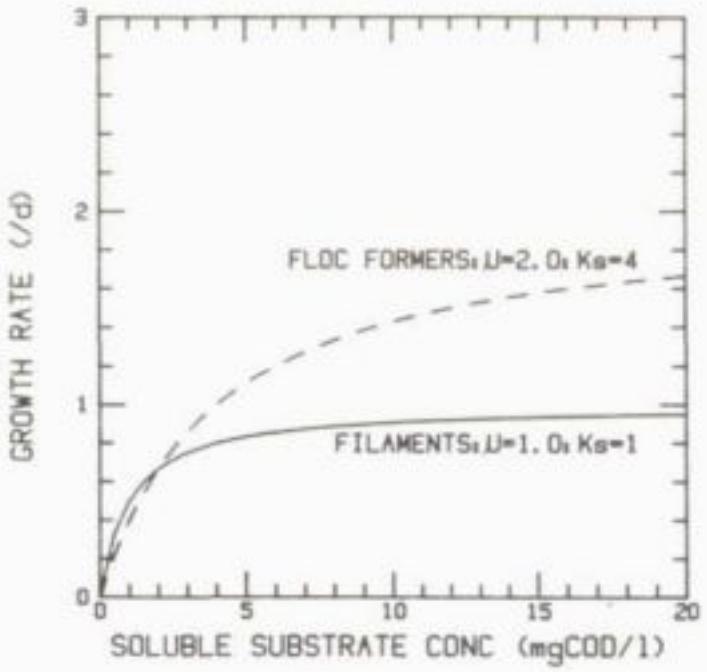


Fig 4.1: *Monod specific growth rate functions for filament and floc forming organisms in accordance with the selection criterion of Chudoba et al. (1973).*

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 of the main aeration reactor and receives the influent flow and underflow recycle. In the selector reactor, the substrate concentration is high

the end of the chlorination period (see Fig 3.2). Biological P removal also was affected: On increasing the chlorine dose, initially there was a reduction in P removal but there was recovery in the following 4 to 5 d, except when chlorinating at the high rate of 8 mg$C\ell_2$/gMLSS.d, when after 19 days, P removal began to decline continuously, from 20 to 12 mgP/ℓ when dosing terminated. However, on cessation of chlorination, P removal recovered rapidly, to its normal 21 mgP/ℓ within 5 d (see Fig 3.2).

3.2.3 Filament susceptibility

Of the 3 filamentous organisms in the system, Type 0914 was the least and *M.parvicella* the most resistant to chlorination. The former completely disappeared from the system while the latter and Type 0092 were considerably reduced. Regrowth of Type 0092 and *M.parvicella* commenced and Type 0914 reappeared about a week after termination of chlorination.

3.3. DISCUSSION

Provided the chlorination guidelines set down by Jenkins *et al.* (1984) are followed, filamentous bulking in biological nutrient removal plants can be controlled by chlorination, with only minor temporary loss of denitrification and biological P removal. In practical situations, the setting of a target DSVI at which chlorination must cease is mandatory, so that overdosing, as observed in the experiment, is unlikely to arise — in the experiment, dosing was continued to obtain very low DSVI values, to observe the effects of chlorination under extreme conditions, conditions that should not be allowed to develop in full-scale application.

Chlorination has the drawback that undesirable compounds, such as trihalomethanes and chlorinated hydrocarbons, tend to form, which pose a potential health risk. To eliminate the health risk, van Leeuwen (1988) and van Leeuwen and Pretorius (1988) investigated the use of ozone for bulking control in a nutrient removal pilot plant. They concluded that ozonation successfully controls filamentous bulking and imparts a number of additional advantages viz (1) improves the removal of organic substances, (2) aids nitrification and to some extent excess P removal, and (3) produces an effluent that is more suitable for reuse than activated sludge treatment without ozonation (van Leeuwen, 1988).

3.4. CONCLUSIONS

Bulking in biological N and P removal plants can be controlled by chlorination. The guidelines for chlorination put forward by Jenkins *et al.* (1984) appear to be satisfactory, and are recommended. If these guidelines are followed, nitrification, denitrification and biological excess P removal will be affected only temporarily.

and, in terms of the selection criterion, the floc-formers should grow faster than the filaments, and, usually will utilize the major fraction of the soluble substrate. A low concentration of substrate still will pass through the selector reactor to the main aeration reactor because the floc-formers, with the higher half saturation coefficient (K_s), cannot reduce the concentration to very low values within the short retention time in the selector. In the main reactor this concentration presumably will be more accessible to the filaments, with the lower K_s value than to the floc-formers; however, the mass of soluble substrate will be a small fraction of that available to the floc-formers in the selector so that filament growth will be restricted and insufficient to cause bulking.

It should be noted that even though the systems operated by Chudoba *et al.* (1973) were long sludge age — low F/M — ones, the filaments causing bulking were not low F/M filaments. This situation was present in many laboratory scale investigations cited below where bulking in long sludge age systems was caused by *non-low F/M filaments*, in particular *S.natans* (see Chapter 5 or Gabb *et al.*, 1989). To avoid confusion, the term low F/M bulking will not be used in this report; rather, bulking by low F/M filaments or *S.natans* etc. if the causative filaments have been identified; where the causative filaments have not been identified, the general term bulking will be used.

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

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

(2) batch or intermittent feeding to completely mixed aeration basins (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982; Eikelboom, 1982; Rensink *et al.*, 1982; Goronszy, 1979; Goronszy and Barnes, 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).

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; indeed in most of the laboratory investigations, bulking was caused by *S.natans* which is a low DO filament, not a low F/M filament (see Chapter 5 or Gabb *et al.*, 1989).

A common characteristic of the three types of systems outlined above is that a soluble COD ($< 0{,}45\mu m$) concentration gradient is induced either in time (i.e. in batch or

intermittently fed systems, type 2), or in space (i.e. in compartmentalised or selector reactor systems, types 1 and 3).

Some of the investigators above concluded that Chudoba's selection criterion does not account completely for the suppression of filamentous organism growth and that other factors also play an important part:

(1) Many investigators (*inter alia* Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982; Grau *et al.*, 1982; Eikelboom, 1982; Jenkins *et al.*, 1983; Daigger *et al.*, 1985; Ekama and Marais, 1986; Still *et al.*, 1986 and 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 and oxygen uptake rates that are much higher than in sludge grown in single reactor completely mixed systems with a constant flow and load. They speculated that the soluble COD concentration gradient induced by the three modifications stimulates the growth of floc-forming organisms with high substrate uptake (and storage?) rates which finds no counterpart in the growth of filamentous organisms with the result that filamentous organisms are unable to compete successfully for substrate, and.

(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 importance of these factors in bulking control in long sludge age systems is not yet clear.

The system modification approach for bulking control in low F/M (long sludge age) systems also was applied by incorporating initial *anoxic* mixing zones/selectors into aerobic activated sludge systems. In laboratory, pilot and full scale work, Heide and Paaveer (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 and had a beneficial influence on sludge settleability. In evaluating anoxic selectors for bulking control in low F.M (long sludge age) activated sludge systems receiving real sewage (with or without acetate or glucose supplementation), Shao (1986) concluded that (1) anoxic selectors controlled bulking in low F/M systems provided they removed practically all the RBCOD, (2) RBCOD and nitrate uptake rates were significantly higher in the system incorporating anoxic selectors than systems without anoxic selectors. In contrast 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 was taken up in the selectors. The leakage of soluble biodegradable COD into the aerobic zone was suggested as the cause for the ineffectiveness of the anoxic selectors. Shao (1986) concluded that the uptake rate of RBCOD is slower under anoxic conditions than under aerobic conditions so that anoxic selectors should be sized larger than aerobic selectors. At the opposite end of the spectrum, 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 volumes could hardly be considered as selectors in that they probably did not stimulate a rapid soluble biodegradable COD uptake rate but they probably did remove virtually all the soluble biodegradable COD. Instead of a single large completely mixed primary anoxic reactor, Cooper and Boon (1983) installed a channel type anoxic zone by replacing the surface aerators with stirrers in 25% of the aeration basin (normal anoxic hydraulic retention time 2,5h) and a good settling sludge (SVI < 100 m*l*/g) was maintained.

As in the aerobic systems work, so also in anoxic-aerobic work above, either the filamentous organisms were not identified in which case the filaments that were being controlled cannot be specified or where the filaments were identified, in certain investigations, e.g. Lee *et al.* (1982), Shao (1986) and Still *et al.* (1986), these were not low F/M filaments. Consequently there are very few investigations where it was established that the particular system modification controlled bulking by low F/M filaments. Even in these few investigations, it cannot be stated unequivocally that it was the system modification *per se* that led to the amelioration of bulking or some other effect that formed part of the modification. For example, Wheeler *et al.* (1983) report the successful control of low F/M filament 0041 with aerobic selectors in a full scale system. The aeration in the aerobic selector was provided by *additional* aeration so it could be argued that the increased aeration may have led to the reduction in 0041 and improvement in settleability. In this report experimental evidence is presented (Chapters 5, 6, 7 and 8) that indicates that increasing aeration by switching from the intermittent-aeration to continuous-aeration ameliorates bulking by low F/M filaments. Switching from intermittent to continuous aeration clearly is a significant increase in aeration and probably constitutes a considerably larger increase in aeration than the installation of the aerobic selector in the full scale system of Wheeler *et al.* (1983). Nevertheless, the increase in aeration may have contributed to the effectiveness of the selector effect in ameliorating the 0041 bulking.

The research reviewed above indicates that (1) anoxic selectors, like aerobic selectors, appear to have the ability to control bulking by certain filaments in long sludge age (low F/M) systems provided they remove virtually all the soluble biodegradable COD; (2) anoxic selectors, like aerobic selectors, stimulate in the sludge a high soluble COD uptake and concomitantly, a high nitrate utilization rate; (3) the soluble COD uptake rate apparently is slower under anoxic than under aerobic conditions, implying that anoxic selectors need to be sized larger than aerobic ones; (4) large primary anoxic volume fractions, which (i) lead to long actual anoxic retention times, (ii) probably do not stimulate a rapid soluble COD uptake rate but (iii) probably do remove all the soluble biodegradable COD, tend to promote bulking in long sludge age systems.

From the evidence in this brief literature review, it appears that a conclusion widely held is that the selection criterion, in its many interpretations, provides a basis for devising system modifications that control bulking in long sludge age (low F/M) systems. The control stems apparently from providing conditions in which the substrate uptake and utilization rate of the floc formers is increased by natural selection or adaptation of species with high substrate uptake and utilization rates from the large species diversity of the floc former population; the filamentous organisms apparently

cannot do likewise due to their inability for adaptation or restricted species diversity. This enables the floc formers to become dominant over the filamentous organisms and consequent amelioration of bulking.

In applying the results and observations of the experimental work reviewed above, to amelioration of bulking by low F/M filaments in long sludge age systems, a number of problems arise: (1) In a considerable proportion of the experimental work, in particular that on full scale plants, the filamentous organisms causing bulking were not identified. (2) Where the filamentous organisms causing bulking were identified, usually in the laboratory scale investigations, often the filaments were not low F/M types. This brings a measure of uncertainty in the applicability of the three modifications cited above to control of bulking by the low F/M filaments. Consequently it was decided to repeat some of the experimental work reviewed above in order to obtain greater clarity on the effectiveness of the proposed system modifications for bulking control by low F/M filaments. The results of these repeated experiments, and the experiments that were conducted subsequently that flowed from them, are discussed in this report.

CHAPTER 5

EVALUATION OF SPECIFIC BULKING CONTROL PROCEDURES IN AEROBIC LONG SLUDGE AGE SYSTEMS

5.1 INTRODUCTION

From the literature survey in Chapter 4, the general proposal for specific control of filamentous bulking in long sludge age systems is to provide conditions under which the soluble biodegradable (readily biodegradable, RBCOD) uptake and/or utilization rates of the floc formers exceeds that of the filamentous organisms, thereby enabling the floc formers to outcompete the filamentous organisms — the so-called "selection criterion". The literature records a number of methods to achieve this:

Imposing a gradient in the RBCOD concentration through the system; this increases the RBCOD uptake and utilization rates of the floc formers but not that of the filaments. Plug flow conditions, incorporation of a selector reactor upstream of the main aeration reactor and intermittently fed fill-and-draw (batch) operation are examples of achieving this. Activated sludge under these conditions i.e. alternating feed-starve, acquires rapid RBCOD uptake and utilization rates; activated sludge that has been stimulated by alternating feed starve conditions to have rapid RBCOD uptake and utilization rates is said to have acquired a "selector effect".

Laboratory scale experiments have demonstrated that the "selector effect" controls certain filaments, e.g. *Sphaerotilus natans* and *Thiothrix*, but there is very little evidence that it also controls the low F/M filaments; it appears that it has been tacitly accepted that the "selector effect" also controls low F/M filament proliferation. Consequently experiments were initiated, the objectives of which were to verify that the selector effect induced under aerobic conditions controls also the low F/M filaments.

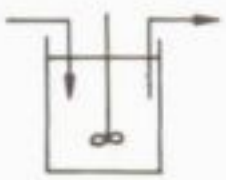
There are basically two systems wherein the selector effect can be readily induced, (1) in intermittently fed fill-and-draw systems or (2) in continuously fed systems incorporating a selector reactor. In this chapter a study of the effect of these two systems on low F/M filaments under completely aerobic conditions is briefly reported.

5.2 INTERMITTENTLY FED FILL AND DRAW CONDITIONS

5.2.1 System set-up

Two laboratory-scale activated sludge systems were operated, *one continuously fed completely mixed* (CFCM) (Table 5.1) (denoted CFCM 1), the other *intermittently fed fill-and-draw* (IFFD), (denoted IFFD 1) fed once daily. The former system (i.e. CFCM1) served as a control system against which the results observed in the experimental system (i.e. IFFD1) could be compared. All process parameters such as sludge age (30 days), temperature (20°C), mass of COD feed daily, system volume and reactor MLSS concentration were identical (see Table 5.1). Both systems were started with mixed liquor from the Mitchell's Plain activated sludge plant, (a N removal system), which had a DSVI of about 250 mℓ/g, caused by the low F/M filaments 0092,

Table 5.1: Operating parameters and conditions of Intermittently Fed Fill-and-Draw and (IFFD) Continuously Fed Completely Mixed (CFCM) systems.

System	IFFD1	CFCM1
Operating Conditions	IFFD	CFCM
Graphical representation		
Aeration	fully aerobic	fully aerobic
DO concentration (mg/ℓ)	2–4	2–4
Feed	intermittent (once daily)	continuous (24h)
Sewage source	Mitchell's Plain settled	
Mass of COD fed/d	3500	3500
Volume of feed (ℓ)	5,4	10
Concentration (mg/ℓ)	650	350
Mass of TKN fed/d (mgN/d)	500	500
Sludge age (d)	30	30
Temperature (°C)	20	20
Volume of reactor (ℓ)	10	10
MLVSS concentration (mg/ℓ)	1250	1250
MLSS concentration (mg/ℓ)	1500	1500
pH	7–8	7–8
Nominal hydraulic retention time (h)	44	24
Load factor (mgCOD/gVSS/d)	280	280

0675, 0041 and *Nocardia*. The laboratory-scale systems were fed Mitchell's Plain settled wastewater throughout the experiment.

5.2.2 Results

Selector effect

Because of the time and labour associated with measuring the uptake rate of soluble substrate, the oxygen utilization rate (OUR) was accepted as a substitute parameter. Research reported in the literature (van den Eynde *et al.*, 1982, Jenkins *et al.*, 1983 and van Niekerk, 1985) and our own measurements indicate that this is permissible. Accepting this approach, the system response was monitored as follows:

> Sludge was harvested from the CFCM or IFFD systems, a batch of sewage (also Mitchell's Plain settled) was added and the OUR was monitored for 24h. An example of the responses is shown in Fig 5.1, one on each of the CFCM and IFFD systems. Batch test conditions were identical in that in both tests the same mass of COD was added per mass MLVSS i.e. the Load Factor was the same. For comparison purposes, the OUR is normalised by dividing by the MLVSS concentration in the batch reactor i.e. mgO/(gVSS.h) (this is permissible because both systems received the same wastewater and were operated at the same sludge age so that the active fraction of the MLVSS would be the same). The batch test data in Fig 5.1 were measured after the sludges had adapted to their respective system conditions and show that the initial OUR in the IFFD sludge is nearly 2,5 times that in the CFCM sludge. This indicates that the selector effect had been stimulated in the IFFD sludge.

In the experiment, the information of interest was the initial OUR in the aerobic batch tests. Accordingly this rate was regularly monitored in both systems (but not so regularly on the CFCM sludge as to induce a selector effect in it!), as follows:

For the IFFD system, the OUR was measured daily in the system reactor itself, for about 45 minutes after feeding. The first 3 to 4 readings, representing the initial rapid OUR, were averaged and plotted in Fig 5.2 as mgO/(gVSS.h) (marked max OUR, IFFD). For the CFCM system, sludge was harvested regularly and a batch test conducted to measure the initial rapid OUR; the batch test was conducted at the same COD loading rate (i.e. mgCOD applied per mgVSS) as the IFFD system. For these tests the OUR values of the first 2 to 3 hours were averaged (because the initial rapid OUR continues for a longer time - see Fig 5.1) and the averages are shown plotted in Fig 5.2 (marked max OUR, CFCM). Also shown in Fig 5.2 are the OUR in the IFFD system just prior to feeding (marked IFFD before feed) and the OUR in the CFCM system under its normal steady state operating conditions (marked CFCM steady state). From Fig 5.2, it can be seen the IFFD system had a consistently higher initial OUR (per gVSS) than the CFCM system.

After operating the systems for about 2 months (only the latter part of the 2 month period is shown in Fig 5.2), the sludges in the two units were interchanged, i.e. the IFFD sludge was placed in the CFCM system and the CFCM sludge was placed in the IFFD system. The changes in the initial OUR in the two systems versus time from the sludge interchange also are shown in Fig 5.2 and gives an impression of the rate at which the selector effect is stimulated and lost in the sludge. The initial OUR of the sludge in the IFFD system increased from the low value associated with the CFCM

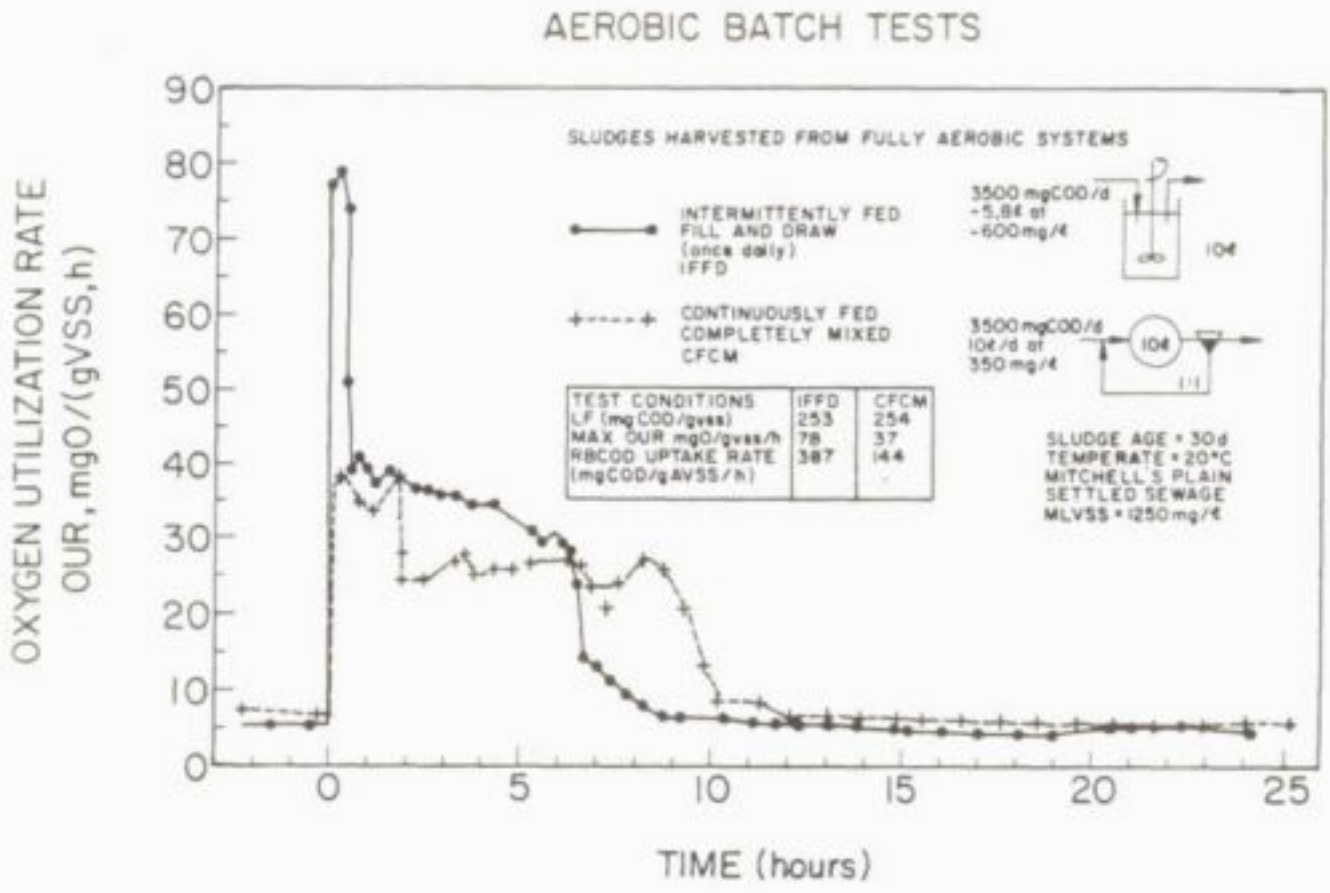


Fig 5.1: *Oxygen Utilization Rate (OUR) response in mgO/(gVSS.h) observed under aerobic batch test conditions at the same COD load per gVSS on sludges harvested from aerobic single reactor systems fed (1) intermittently (batch) once daily (•——•) and (2) continuously (+·····+), both receiving the same sewage feed (Mitchell's Plain settled) and operated at the same sludge age (30d) and temperature (20° C). Note that the initial OUR is more than twice as high in the sludge from intermittently fed system compared with that in the sludge from the continuously fed system.*

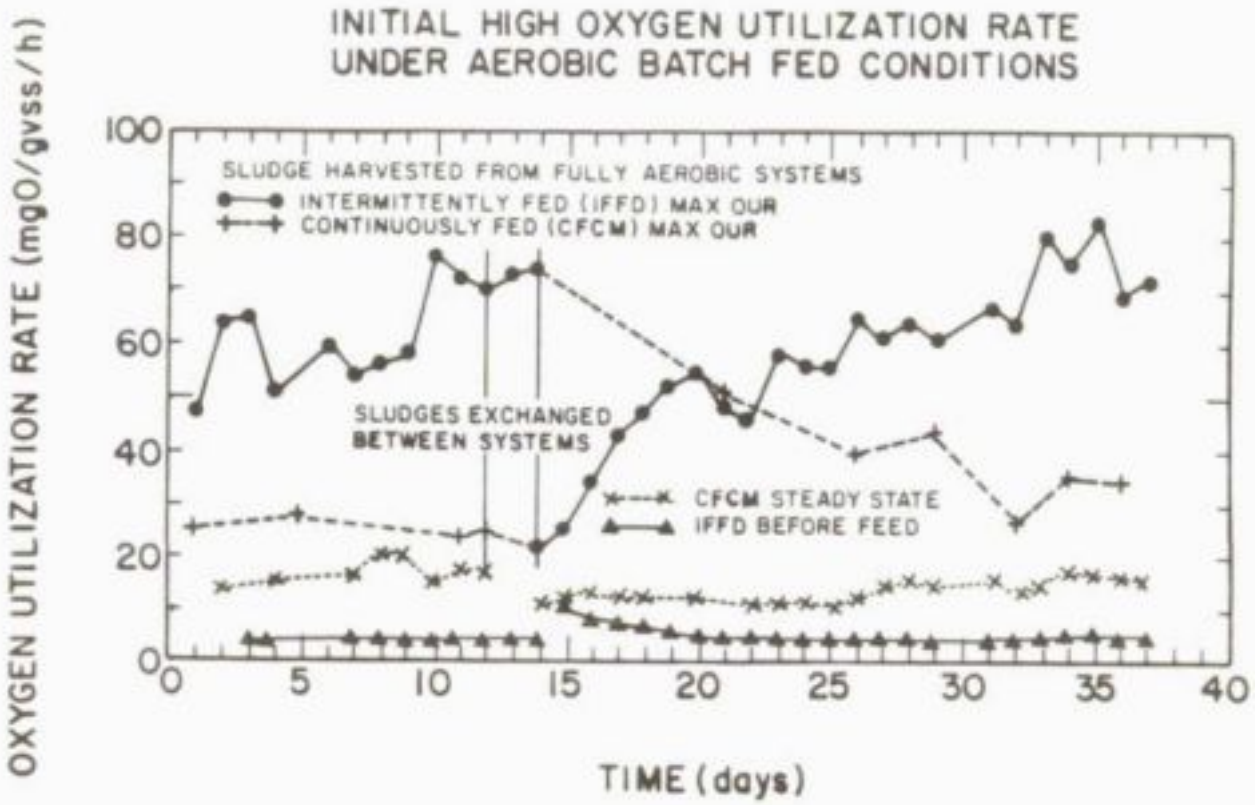


Fig 5.2: *Initial high ozygen utilization rate [OUR, in mgO/(gVSS.h)] with time observed in aerobic batch tests under identical COD loading per gVSS on sludges harvested from aerobic single reactor systems fed (1) intermittently (batch) once daily (•———•) and (2) continuously (+·····+) both receiving the same sewage (Mitchell's Plain) and operated at the same sludge age (30d) and temperature (20° C). Note the higher initial OUR in the intermittently fed system than in the continuously fed system like in Fig 5.1. After exchanging the sludges between the two systems, a high initial OUR develops gradually under intermittently fed conditions in the previously continuously fed sludge while the high initial OUR of the previously intermittently fed sludge declines gradually under continuously fed conditions.*

system to the same high value associated with the IFFD system; in contrast the initial OUR of the sludge in the CFCM system declined from the high value associated with the IFFD system to the low value associated with the CFCM system. In the IFFD system the stimulation of the selector effect took only about 15 days, and in the CFCM system the change to the loss of the selector effect took somewhat longer, about 20 days. Since the units were operated at 30 days sludge age, the stimulation and loss of the selector effect took place in less than one sludge age.

Sludge settleability

With regard to sludge settleability, (Fig 5.3) in *both* the CFCM and IFFD systems, the DSVI declined from the starting value of 250 mℓ/g to about 100 mℓ/g over the first 3 weeks, and thereafter declined to below 90 mℓ/g, with an average of around 50 mℓ/g. After 3 weeks both systems had the same low DSVI. Neither system contained many filamentous organisms. The few present in the IFFD system were of the low F/M group i.e. 0675, 0041, *Haliscomenobacter hydrossis*, and 0092; the few present in the CFCM system were *H.hydrossis*, and *S.natans*. Both sludges had rather poor clarification characteristics due to the pin-point floc typical of sludges with very low DSVI values.

Despite the relatively low initial OUR under batch conditions for the CFCM sludge, indicating an absence of a selector effect, the CFCM system failed to bulk. *Indeed it seemed that the CFCM system cured the bulking by low F/M filaments in the starter sludge equally as effectively as the IFFD system.* These results cast doubt on the *relevance* of the selection effect for controlling the proliferation of low F/M filaments.

5.2.3 Conclusions

From this study the following conclusions can be made:

(1) Intermittently fed fill-and-draw operation of a single completely mixed reactor induced high initial oxygen uptake rates under batch conditions in sludges in aerobic long sludge age (low F/M) systems; continuous constant feeding to a single completely mixed reactor induced a low initial oxygen uptake rate under batch conditions.

(2) Low F/M filament proliferation did not take place in the aerobic long sludge age single reactor system under constant flow; indeed, bulking by low F/M filaments in the starter sludge was ameliorated in this system over the first 3 weeks as effectively as in the intermittently fed system.

(3) From (2) above it appears that the selector effect did not play a role in ameliorating bulking by the low F/M filaments in the starter sludge.

5.3 AEROBIC SELECTOR REACTORS

Having verified that alternating feed-starve conditions imposed by intermittently fed fill-and-draw operation induce a high initial OUR under batch conditions, an investigation was undertaken to check if this also is so if aerobic selectors are incorporated in long sludge age continuously fed completely mixed aerobic systems. Specifically the objectives were to:

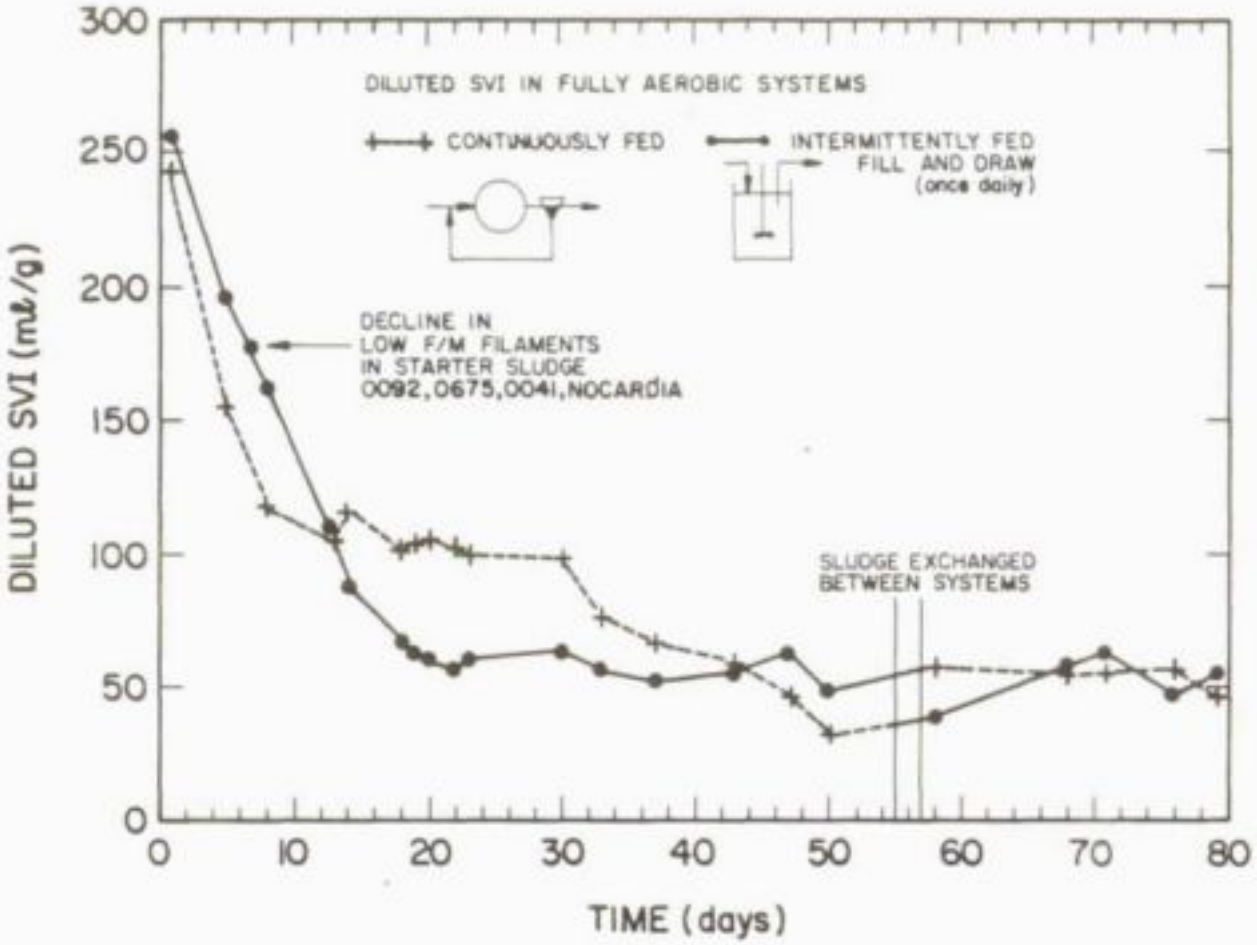


Fig 5.3: *Sludge settleability in Diluted SVI (DSVI) of sludges in two fully aerobic single reactor systems fed (1) intermittently (batch) once daily (•——•) and (2) continuously (+----+) receiving the same sewage feed (Mitchell's Plain settled) and operated at the same sludge age (30d) and temperature (20° C). Note that in the first 20 days the DSVI in the starting sludge (Mitchell's Plain) dropped sharply from 250 to 100 ml/g with a concomitant reduction in low F/M filaments 0092, 0675, 0041 and* Nocardia. *Thereafter neither system developed a bulking sludge (DSVI < 80 ml/g) and on average the sludge in one system did not settle better than that in the other.*

(1) investigate the effect of aerobic selectors on the initial OUR under batch conditions, and

(2) evaluate the effect of aerobic selectors on the low F/M filaments.

5.3.1 System set-up

Two systems were set up, one Control and one Experimental: The first system, designated CFCM2 or the Control system, comprised a single 15ℓ completely mixed aerated reactor and served as the control (see Table 5.2); it was identical to the CFCM system operated in the experiment discussed above. The second system, designated CFCM/SEL or the Selector system, comprised a single 300 mℓ aerobic selector (i.e. 1/50th of the total system volume) followed by a 14,7ℓ completely mixed aerated reactor and served as the experimental system (see Table 5.2). Both systems were fed at a constant flow rate of 15ℓ/d settled sewage from the Mitchell's Plain plant, and the influent COD concentration was maintained constant at 350 mg/ℓ by dilution with tap water. A 20 day sludge age was maintained in both systems and the DO concentration in the Control system and in the selector and main aeration reactors of the Selector system was kept between 2 to 3 mg/ℓ (see Table 5.2).

The selector reactor was sized on the basis that it must remove more than 95% of the influent readily biodegradable COD (RBCOD). No information on substrate utilisation rates was available, but this could be approximated sufficiently accurately for our purpose from the RBCOD utilisation rate (K_{ms}) calculated from the high initial OUR measured under IFFD conditions in the experiment described in Section 2 above (Fig 5.2). Other information required to size the selector is the influent RBCOD fraction, (f_{ts}) and the active fraction of the VSS (f_{av}) for the particular wastewater characteristics and system parameters. With this information the fraction of the total process volume required to remove more than 95% of the RBCOD can be calculated (see Still *et al.*, 1986). This fraction is set equal to the selector fractional volume (f_{xs}). For the particular conditions of the experiment, the selector fractional volume (f_{xs}) was calculated to be 0,015 i.e. 1/68th of the total system volume. This approach to selector sizing seemed reasonable when comparing the calculated value with the 1/50th to 1/74th fraction volumes found by Lee *et al.* (1982) for Richmond, California settled sewage. To take account of a lower RBCOD utilisation (K_{ms}) rate and variations in the influent RBCOD fraction, the size was increased to 0,020 i.e. 1/50th of the total system volume (0,30ℓ in 15ℓ).

As in the previous IFFD and CFCM experiments, the two systems were started up with mixed liquor from the Mitchell's Plain activated sludge plant. The starter sludge had a DSVI of about 250 mℓ/g and the dominant filamentous organisms were (in descending order of dominance) type 0581, 0092, 0675, *Nocardia* and 0041. All of these filaments have been classified by Jenkins *et al.* (1984) as low F/M types. It was noted that *S.natans* was not observed in the mixed liquor, nor had it ever been observed previously in the Mitchell's Plain plant.

5.3.2 Results

Selector effect

The two systems were operated for 180 days after start up. During this period, batch

Table 5.2: Operating parameters and conditions of fully aerobic Continuously Fed Completely Mixed (CFCM) systems, one with an aerobic selector (CFCM/SEL) and one without an aerobic selector (CFCM2).

System	Selector	Control
Operating conditions	CFCM/SEL with selector	CFCM without selector
Graphical representation		
Aeration	fully aerobic	fully aerobic
DO concentration; selector	2–3	–
main reactor	2–3	2–3
Feed	continuous	continuous
Sewage feed source	Mitchell's Plain settled	
Influent flow (ℓ/d)	15	15
COD concentration (mg/ℓ)	350	350
TKN concentration (mgN/ℓ)	50–70	50–70
Sludge age (d)	20	20
Temperature (°C)	20	20
Volume of reactor (ℓ)		
selector	0,30	–
main reactor	14,7	15,0
MLVSS concentration (mgVSS/ℓ)	1150	1150
MLSS concentration (mgSS/ℓ)	1400	1400
pH	7–8	7–8
Nominal hydraulic retention time (h)	24	24
Load factor (mgCOD/gVSS/d)	280	280

tests were conducted on sludge harvested from both systems to measure the initial OUR from which a RBCOD utilization rate (K_{ms}) was calculated. In the starter sludge the K_{ms} was 142 mgCOD/(gAVSS.h). By day 54 the K_{ms} in the Control system was 92 and in Selector system was 271 mgCOD/(gAVSS.h); by day 68 these were 67 and 233 mgCOD/(gAVSS.h) respectively. Comparing these K_{ms} values with those in the previous experiments on IFFD and CFCM systems;

(1) in the Selector system, the K_{ms} attained a value of similar magnitude to that in the IFFD system, and

(2) in the Control system, the K_{ms} had a value equal to that in the CFCM system.

On day 89, the sludges on the two systems were interchanged. Batch tests were conducted on the sludge in both systems on days 141 and 153 which yielded for the Selector system K_{ms} rates of 146 and 138 mgCOD/(gAVSS.h) respectively, and forthe Control system, 67 and 68 mgCOD/(gAVSS.h) respectively. These results confirmed that the Selector system stimulates a high K_{ms} and the Control system a low K_{ms} value. For further details see Still *et al.* (1986).

In the Selector (CFCM/SEL) system, amorphous *Zoogloeal* colonies developed. These colonies were absent in the Control (CFCM2) system. These observations are in conformity with those of Van Niekerk (1985) who observed many large amorphous *Zoogloeal* colonies in their Selector and IFFD systems but not in their CFCM system. They identified the *Zoogloeal* colonies as strains of the floc former *Z.ramigera*. The *Zoogloeal* colonies appear to be a characteristic feature of activated sludge exposed to alternating feed-starve conditions of soluble (RBCOD) COD, i.e. in which a high RBCOD uptake rate or high initial OUR, has been induced. According to Jenkins *et al.* (1984) the attainment of these high rates and the presence of *Zoogloeal* colonies are indicators that a selector effect has been induced in the sludge.

Sludge settleability

With regard to the sludge settleability in the Selector and Control systems, after 17 days operation (with DO in both units 2-3 mg/ℓ), the DSVI's in both the Selector and Control systems had declined from the start up value of 250 mℓ/g to 120 mℓ/g (Fig 5.4). Microscopic evaluation of the sludges a week after start up indicated that in both units the dominant filamentous organism was *S.natans* at "common" level (see Table 5.3). From day 17 the DSVI in the Control system increased to around 200 mℓ/g while that in the Selector system continued to decline, to about 90 mℓ/g by day 47. Microscopic examination on day 45 indicated that filament abundance reflected the difference in DSVI's: In the Control system, *S.natans* and *Thiothrix* were dominant at "abundant" level whereas in the Selector system the filamentous organisms were *H.hydrossis* and 0041 at "common" level (Table 5.3).

In the Control (CFCM) system, from day 47, the DSVI increased sharply from about 200 mℓ/g to about 800 mℓ/g by day 55; in the Selector system the DSVI remained below 100 mℓ/g (Fig 5.4). No filamentous organism identification was done in this

Table 5.3: Filamentous organism identification and microscopic analysis of sludge, University of Cape Town study

Day	System	Filament Abundance*	Floc Structure	Dominant Filaments	Remarks	DSVI
0	Starter sludge	Abundant (5) to Excessive (6)	Open 75%<150µm 25%>150µm	1. Type 0581 2. Type 0092 3. Type 0675 4. *Nocardia* 5. Type 0041	Filaments mainly of low F/M types	250
7	CS	Common (3)	Open	1. Mainly *S.natans*	This is a low DO type	170
	SS	Very common (4)	Open	1. *S.natans*	*S.natans* developing	230
45	CS	Abundant (5)	Bridging mainly 150 to 500 µm	1. *S.natans* 2. *Thiothrix* II		165
	SS	Common (3)	Mainly <150µm	1. *N.hydrossis* 2. Type 0041		90
63	CS	Excessive (6)	Mainly <500µm	1. *Thiothrix* I 2. *Thiothrix* II 3. *S.natans* 4. Type 0041		670
	SS	Common (3)	Small 30 to 50µm	1. Type 1701 2. *Thiothrix* I		130
89	SLUDGE INTERCHANGED BETWEEN UNITS - SLUDGE SWITCH					
96	CS (new)	Abundant (5)	Bridging	1. *S.natans*		190
	SS (new)	Very common (4) to Abundant (5)	Bridging	1. *Thiothrix* 2. *S.natans* 3. Type 0041	*Zoogloea* present	210
158	SLUDGE INTERCHANGED BETWEEN UNITS AGAIN - SLUDGE SWITCH					
175	CS (new)	Very common (4)	Compact and firm 150 to 500µm filaments little effect	1. *S.natans* 2. Type 0041 3. Type 0675		125
	SS (new)	Some (2)	Small	1. *N.hydrossis* 2. *S.natans* 3. *N.limicola* III 4. Type 0041		100

CS = Control system CFCM; SS = Selector system CFCM/SEL.
* Filament abundance levels in accordance with Jenkins *et al.*, 1984.

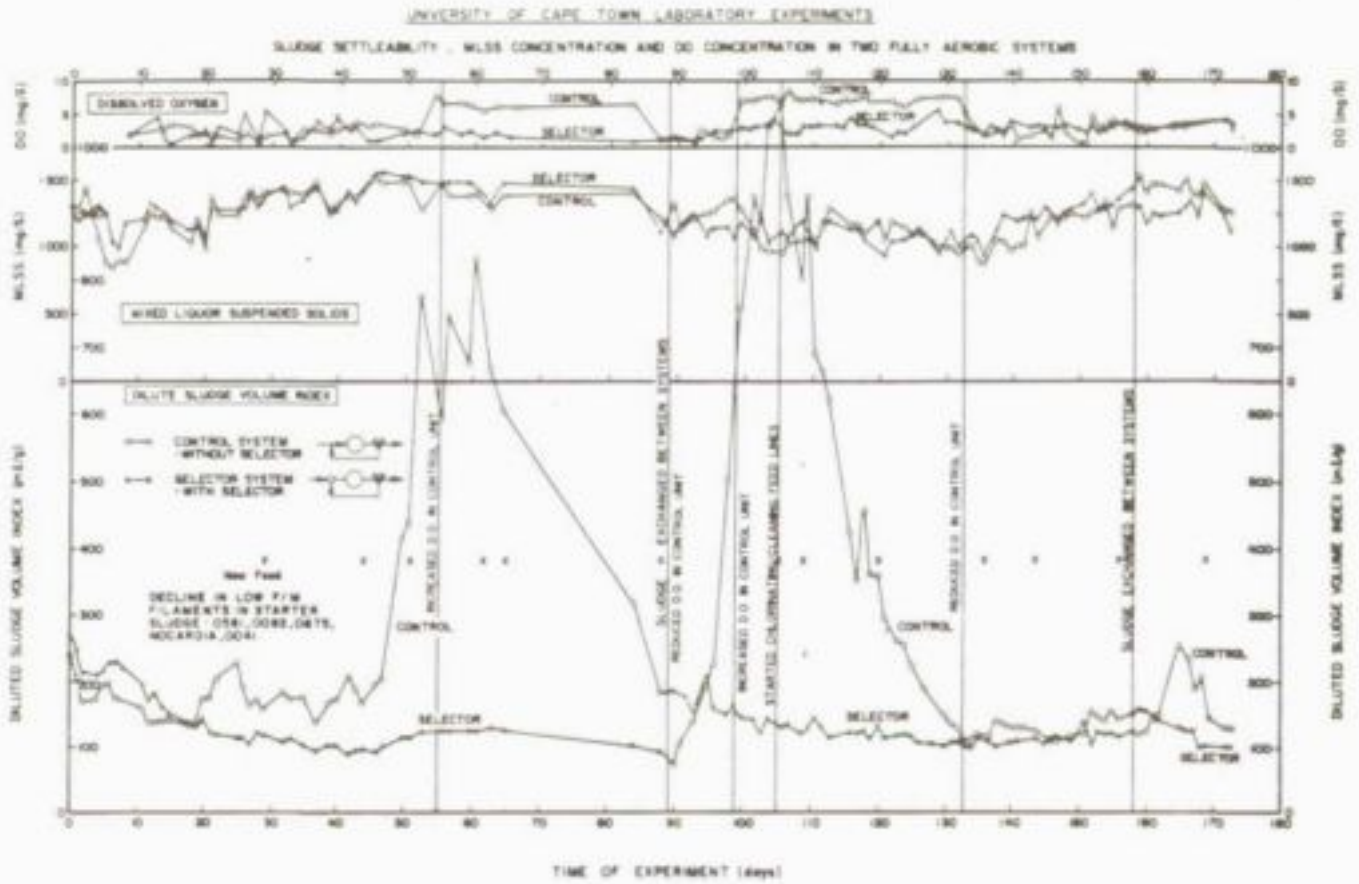


Fig 5.4: *Sludge settleability in DSVI and reactor MLSS and DO concentrations with time in two continuously fed fully aerobic single reactor systems (1) with an aerobic selector (+-----+) and (2) without an aerobic selector (●———●), both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20 days) and temperature (20° C). Note that in the first 20 days, the DSVI in the starter sludge (Mitchell's Plain) decreased from a starting value of 250 ml/g to 130 ml/g with a concomitant decline in low F/M filaments. Thereafter the Selector system DSVI remained relatively low (< 125 ml/g) but that in the Control system (without the selector) increased dramatically (> 700 ml/g) from day 45 due to an explosive proliferation of* S.natans and Thiothrix. *Increasing the reactor DO (on day 55) ameliorated the bulking. On day 90 the sludges were exchanged between the two systems. Thereafter, the DSVI in the selector system remained relatively low (< 125 ml/g) but in the system without the selector the DSVI again increased dramatically (> 1000 ml/g) (from day 90) due to an explosive proliferation of* S.natans. *Increasing the reactor DO (day 98) did not ameliorate the bulking but cleaning the influent feed lines (day 105) did. Because reducing the reactor DO (day 132) did not cause regrowth of* S.natans, *the cause for their proliferation appeared to be seeding from attached wall growths on the feed lines.*

period, but later, on day 63, (when the DSVI in the Control and Selector systems unit had not changed significantly from 800 and 100 mℓ/g respectively), microscopic examination indicated *Thiothrix* (types I and II) and *S.natans* were dominant at "excessive" level in the Control system whereas in the Selector system, type 1701 and *Thiothrix* I were present at "common" level (Table 5.3). None of these filaments were identified in the starter sludge nor have these filaments been known to cause bulking at the Mitchell's Plain plant.

The proliferation of *S.natans* and *Thiothrix* in the Control system was unexpected: Should the Control system have bulked, it was expected that this would have been due to low F/M filamentous organisms, not *S.natans* and *Thiothrix* — *S.natans* is a low DO filamentous organism and *Thiothrix* a septic/high sulphide sewage or nutrient deficiency one (Jenkins *et al.*, 1984), and these have not been observed to cause bulking in the Mitchell's Plain plant.

In an attempt to bring down the DSVI in the Control system, the DO was increased from 2-3 to 7-8 mg/ℓ (on day 57) because past research (Sezgin *et al.*, 1978; Palm *et al.*, 1980 and Jenkins *et al.*, 1984) had shown that high DO concentrations control *S.natans* bulking. Increasing the DO was successful; by day 89, the DSVI had decreased to 180 mℓ/g. Unfortunately no microscopic evaluation was done during this period but as *Thiothrix* (types I and II) had been the most dominant filamentous organism with *S.natans* secondary dominant, the reduction in DSVI must have been due to a decline in *Thiothrix* (types I and II) and very likely also in *S.natans*. However, what was established was that high DO concentration appeared to control the growth of the filamentous organisms. Throughout this period, the DSVI in the Selector system remained below 100 mℓ/g indicating no undue filamentous organism growth, even though the DO remained at 2-3 mg/ℓ.

On day 89 the sludges were interchanged. At the same time, the DO in the Control system was reset at the same value as that in Selector system reactors, i.e. at 2-3 mg/ℓ. The DSVI in the Control system immediately began to increase sharply, from 80 mℓ/g on day 90 to 650 mℓ/g on day 99, due to an explosive growth of *S.natans* — microscopic examination indicated that *S.natans* had grown to "abundant" level, (see Table 5.3). Note that on this occasion *Thiothrix* was absent. In contrast, in the Selector system, the DSVI declined from approx. 180 mℓ/g on day 90 to a stable minimum of about 100 mℓ/g by day 130 (Fig 5.4).

To control the growth of *S.natans* in the Control system, the same procedure that was successful previously, i.e. increasing the reactor DO from 2-3 to approx. 8 mg/ℓ, was put into operation. However, the DSVI now continued to increase, from 500 mℓ/g on day 98 to approx. 1100 mℓ/g on day 105. *Clearly some cause other than low DO concentration was stimulating the growth of S.natans.*

5.4 CAUSES FOR THE GROWTH OF *Sphaerotilus natans*

The proliferation of *S.natans* in laboratory systems has been cited frequently as the dominant organism causing bulking in laboratory-scale activated sludge systems viz. Hattingh (1963), Clesceri (1963), Genetelli and Heukelekian (1964), Genetelli (1967), Ford and Eckenfelder (1967), Chudoba *et al.* (1973a), Chudoba *et al.* (1973b), Sezgin *et al.* (1978), Houtmeyers (1978), Houtmeyers *et al.* (1980), Palm *et al.* (1980), Verachtert *et al.* (1980), Chiesa and Irvine (1982), Lee *et al.* (1982), Rensink *et al.*

(1982), van den Eynde *et al.* (1982), Wu *et al.* (1983), Gabb *et al.* (1985), van Niekerk (1985), Shao (1986), Burke *et al.* (1986), Wilderer and Dettmer (1987), Rensink and Donker (1987), Wanner *et al.* (1987a, 1987b, 1987c). In these investigations *S.natans* evidently grew well under a wide ranges of sludge age, hydraulic retention time (HRT), dissolved oxygen (DO) concentration and system configuration.

In contrast, surveys of filamentous organisms in full scale activated sludge plants in several countries have indicated that *S.natans* is not a common filamentous organism causing bulking — Eikelboom (1977) in Western Europe, Wagner (1982) in West Germany, Jenkins *et al.* (1984) in the USA and Blackbeard *et al.* (1986, 1988) in South Africa. Even in West Germany, where the highest incidence of *S.natans* has been reported, it is responsible for only 9 percent of bulking activated sludges; in South Africa, *S.natans* has not been observed as a dominant filamentous organism in any full-scale plant.

In seeking an explanation for the high incidence of bulking due to *S.natans* in laboratory-scale systems, as against the low incidence in full-scale systems, the findings of Gabb *et al.* (1985) appeared to be of significance:

> In operating small scale pilot plants (40ℓ) at the San José/Santa Clara treatment works, they experienced considerable trouble in the plants with bulking due to *S.natans*, a problem not encountered on the full-scale works. The feedline to the pilot plant, a 33mm hose, was 15 m long. Although regularly chlorinated, examination of the internal surfaces of the hose showed extensive attached growth of *S.natans*. They concluded that growth of *S.natans* in pilot plants was promoted by continuous seeding from the feed line. After replacing the feed line and instituting a program of keeping a "clean" feed line, bulking due to *S.natans* disappeared.

5.4.1 Experimental investigation

Taking note of the findings of Gabb *et al.* (1985), it was hypothesized that in our investigation the proliferation of *S.natans* observed in the Control system was due also to the attached growth of *S.natans* in the feed lines, seeding the system.

Accordingly, the feed lines (3m long, 5mm dia.) to the systems were replaced with clean ones, and thereafter, two sets of feed lines were used; after one week in use, the old set was soaked in strong chlorine solution and rinsed with near boiling water for 5 min. before reuse. Following implementation of this procedure, the DSVI (and correspondingly the *S.natans* population) in the Control system fell rapidly from 1100 mℓ/g on day 105 to 100 mℓ/g by day 133. Thus under *high* DO conditions and with "clean" feed lines, *S.natans* bulking was effectively eliminated in the Control system.

In order to check that the "clean" feed lines were the major influence controlling *S.natans* in the Control system, the DO was reduced to reinstate the same conditions in the Control system as those at the beginning of the experiment. Accordingly on day 132 the DO in the Control system was reduced from 7-8 to 2-3 mg/ℓ. Proliferation of *S.natans* did not recur over the following 42 days, see Fig 5.4, confirming that cleaning the feed lines had a positive effect on controlling the growth of *S.natans* in the Control system irrespective of the DO level. Microscopic evaluation on day 175 indicated that *S.natans* was still the main filamentous organism in the Control system, with types 0041 and 0675 also present, at "very common" level but

the DSVI remained low (Table 5.3). Further details on this aspect of the experiments are given by Gabb *et al.* (1989).

5.4.2 Discussion and Conclusions

The high incidence of *S.natans* bulking in laboratory-scale units, compared to that in full-scale plants, due to seeding, very likely arises from the high surface area/volume ratio of the former compared to that of the latter: This ratio is approx. 2-3 orders of magnitude greater in the laboratory units than in full-scale plants and one can expect therefore that the seeding intensity in laboratory scale systems will be correspondingly higher.

> Operating experience with laboratory-scale systems at the University of Cape Town over the past 15 years has established that attached growth readily develops on the wetted surfaces of reactors and interreactor connections; these also can seed the mixed liquor though not necessarily with *S.natans* It is most important to brush daily the reactor walls and stirrers, and squeese the interreactor plastic tubing to dislodge attached growth. But this is not sufficient: some of this attached growth becomes very firmly attached with time and cannot be dislodged completely by daily thorough brushing — it is necessary to dismantle the units every 3-4 weeks, scrub the surfaces and flush with water to destroy the strongly attached growth. If this is not done, the system tends to develop deviatory response in kinetic behaviour. It appears now that in low F/M bulking research a deviatory behaviour in settleability by *S.natans* proliferation also can readily occur if the feed lines are not regularly thoroughly cleaned.

In this study the aerobic selector controlled the growth of *Thiothrix* (types I and II) and that of *S.natans*. The control of *S.natans* was achieved even when seeding took place but presumably this will be so only if the seeding rate is not too high. The observation that the aerobic selectors, and equivalently, intermittent feeding conditions control *Thiothrix* and *S.natans* proliferation is in conformity with the findings *inter alia* of Chudoba *et al.* (1973); Houtmeyers (1978); Lee *et al.* (1982); Rensink *et al.* (1982); Van den Eynde *et al.* (1982); Chiesa and Irvine (1982); Wu *et al.* (1984) and van Niekerk (1985). This study shows further that such control is achievable at DO concentrations as low as 2 to 3 mg/ℓ in the selector reactor.

In the aerobic Selector system, control of *S.natans* and *Thiothrix* has been hypothesised to be effected by competitive removal of soluble biodegradable COD [or readily biodegradable COD (RBCOD) of Dold *et al.*, 1980, see also Ekama *et al.*, 1986] by floc formers (*inter alia* Van Niekerk *et al.*, 1985) in the selector reactor. A selector reactor causes the specific substrate uptake rate to increase to 2-3 times higher than the rate in systems without selectors. The increase most likely is due to selection of floc formers with high soluble COD uptake rates. The specific substrate uptake rate of *S.natans* and *Thiothrix* is unlikely to change appreciably as these do not possess the diversity of the floc former population. Consequently the selected floc formers out-compete the *S.natans* sp. and *Thiothrix*, which effectively limits substrate acquisition by these filaments, and thereby curtails their proliferation in the mixed liquor. High soluble COD (RBCOD) uptake rates also are achieved by batch feeding as indicated by this investigation and the work of *inter alia* Houtmeyers *et al.* (1980), Verachtert *et al.* (1980), van den Eynde *et al.* (1982), Rensink *et al.* (1982), Eikelboom (1982) and Jenkins *et al.* (1983), and this system also controls *S.natans* and *Thiothrix* proliferation.

Recent research has shown that anoxic selectors (Shao, 1986; Wanner *et al.*, 1987a) and/or anaerobic (Wanner *et al.*, 1987b) reactors receiving the influent feed ahead of the main aeration reactor also control the growth of *S.natans* and *Thiothrix*. Based on the hypothesized mechanism of control by aerobic selectors a possible explanation is as follows: In the anoxic reactor/selector, the RBCOD is utilised 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 (Wentzel *et al.*, 1985). Consequently with anaerobic reactors in systems exhibiting excess P removal, very little soluble substrate enters the anoxic or aerobic reactors. Because *S.natans* is an obligate aerobe (Mulder and Deinema, 1982), it is unable to obtain sufficient soluble biodegradable COD in the aerobic zone for growth. The same applies to *Thiothrix*; however *Thiothrix* is reported variously as obligate aerobic (Harold and Stanier, 1955 and Nielsen, 1984) or facultative (Richard *et al.*, 1983); in either case with little soluble biodegradable COD entering the anoxic or the aerobic zones, it is unable to grow. This explanation is supported by (i) survey of filamentous organisms in full-scale biological nutrient removal (anaerobic-anoxic- aerobic) plants by Blackbeard *et al.* (1988) and (ii) laboratory-scale experiments at the University of Cape Town on biological N and/or P removal systems in which the feed lines were not regularly cleaned (i.e. a high likelihood of *S.natans* seeding); in both the survey and laboratory experiments *S.natans* was not and *Thiothrix* only rarely identified as filamentous organisms responsible for bulking. In terms of this explanation, where the removal of soluble biodegradable COD in the anaerobic and/or anoxic reactors is incomplete, *S.natans* and *Thiothrix* bulking is possible.

With regard to *S.natans* bulking in laboratory and pilot scale systems, if the seeding rate is sufficiently high, the system still can experience *S.natans* bulking irrespective of the presence of (i) high DO, as found once in this study, or (ii) an aerobic selector, as indicated in the laboratory-scale investigation of Gabb *et al.* (1985), or (iii) an anaerobic and anoxic reactor (van Leeuwen and Pretorius, 1987).

A consequence of the seeding effect of *S.natans* is that in laboratory research into bulking, and its amelioration, it is vital to ensure that the filamentous organism population developed in the laboratory-scale system corresponds to that in the full scale system, otherwise procedures that ameliorate bulking in the laboratory-scale system may not be transferable to the full-scale system. Even if compatibility is achieved, invasions of "contaminating" filamentous organisms, e.g. *S.natans* in experiment described above, may so overwhelm the effects of the other filamentous organisms that ameliorating the *S.natans* bulking may lead to the erroneous conclusion that bulking due to the other filamentous organisms has also been controlled. This observation applies particularly to long sludge age (low F/M) systems where the low F/M filamentous organisms often develop to bulking levels only slowly, over a long period of time (2 to 3 sludge ages). It is vital therefore that in bulking research the mixed liquor, especially that of the control units, is regularly examined microscopically to identify the filamentous organisms that are principally responsible for bulking to ensure that filamentous organisms in the laboratory units correspond to those that require to be controlled in the full scale plant.

CHAPTER 6

EVALUATION OF SPECIFIC BULKING CONTROL PROCEDURES IN ANOXIC/AEROBIC LONG SLUDGE AGE SYSTEMS

6.1. INTRODUCTION

In Chapter 5 it was demonstrated that fully aerobic systems incorporating alternating feed-starve conditions e.g. single reactor intermittently fed fill and draw (IFFD) systems and continuously fed completely mixed systems including selectors (CFCM/SEL), induced in the sludge a high readily biodegradable COD (RBCOD) and initial oxygen utilization (OUR) rates under batch test conditions, i.e. stimulated a selector effect, whereas fully aerobic single reactor continuously fed completely mixed (CFCM) systems induced a low initial RBCOD and OUR rates, i.e. did not stimulate a selector effect. As regards the propensity of the two types of system (i.e. with and without a selector effect) to support low F/M filaments, starting the systems with sludges from full-scale (anoxic/aerobic) N removal plants bulking with low F/M filaments, in both types of system a decline in the low F/M filament abundance took place and low F/M filament bulking disappeared. It was concluded that, in *aerobic* long sludge age systems, irrespective of whether or not a selector effect was induced, the systems did not support low F/M filament growth.

In this chapter the aerobic IFFD and CFCM experiment described in Chapter 5, Section 2 was repeated except that in this experiment alternating aeration/non-aeration periods were imposed on the IFFD and CFCM systems. The objective of imposing alternating aeration/non-aeration was to:

(1) determine whether or not a high RBCOD uptake rate and a concomitantly high initial nitrate utilization rate (NUR) could be induced i.e. whether or not a selector effect could be induced under anoxic conditions leading to a high initial denitrification rate, and

(2) observe the effect of alternating anoxic/aerobic periods on low F/M filament growth.

The need for investigating whether or not a selector effect can be stimulated under anoxic conditions arises from the desirability of 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 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 by means of oxygen rather than by means of nitrate. However, if the selector can be anoxic rather than aerobic, the RBCOD will be utilized with nitrate and no loss of denitrification will occur.

6.2 EXPERIMENTAL INVESTIGATION

6.2.1 System set-up

Two single reactor systems were operated, one IFFD, denoted IFFD2, and one CFCM,

denoted CFCM3. In both systems all process parameters, such as sludge age (20 days), temperature (20°C), and mass of COD fed daily (5250 mgCOD/d), were the same (see Table 6.1). Both systems were fed Mitchell's Plain settled sewage and were started up with Mitchell's Plain activated sludge. This sludge was a bulking one with a DSVI of 230 mℓ/g caused by the low F/M filaments *M.parvicella*, 0092 and 0675.

Anoxic-aerobic conditions were imposed on the systems by alternating aeration with non-aeration on a 4 hourly cycle (3h aeration on and 1h aeration off). In the CFCM system the feed was continuous and with the aeration/non-aeration cycle the sludge in the system was exposed to influent RBCOD both under anoxic and aerobic conditions. The IFFD system was batch fed once a day and in order to expose the sludge to RBCOD under both aerobic and anoxic conditions, as in the CFCM system, the time of the daily feeding was alternated in accordance with the aeration/non-aeration cycle imposed on the system; on one day, the system was fed at the time it became aerobic and on the next day, the system was fed one hour earlier when it became anoxic. In both the IFFD and CFCM systems the DO concentration was maintained above 2 mg/ℓ during the aerobic periods.

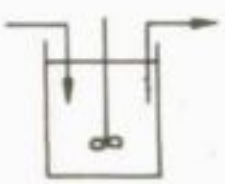
6.2.2 Results

Selector effect

The two systems were operated for approximately 70 days. During this time the DSVI was measured every second day in both systems (Fig 6.1). Also, in the IFFD system the OUR before feeding (on the days the system was aerobic just prior to feeding) and after feeding (on the days the system was aerobic after feeding) were measured and in the CFCM system the OUR during the aerobic period was measured (Fig 6.2). Between days 20 and 60, aerobic batch tests of 24 h duration were conducted on sludge harvested from the two systems to check whether OUR responses follow the same respective patterns as were induced in the sludges harvested from the fully aerobic IFFD and CFCM systems described in Chapter 5 (Section 2). Two such batch tests on the IFFD and one on the CFCM systems were performed and these confirmed that this was the case, see Fig 6.3, i.e. in particular in the CFCM system the initial OUR, and concomitantly RBCOD uptake rate, was low whereas in the IFFD system the initial OUR, and concomitant RBCOD uptake rate, was high.

Having established the similarity of response between the fully aerobic CFCM (CFCM1) and anoxic/aerobic CFCM (CFCM3) systems and between fully aerobic IFFD (IFFD1) and anoxic/aerobic IFFD (IFFD2) systems respectively insofar as aerobic batch response is concerned, two types of batch test were conducted on sludge harvested from the two anoxic/aerobic systems, (1) an aerobic test during which the OUR was measured for 2 to 3 hours and (2) an anoxic test over 2h during which the nitrate was measured (after 2h the batch was aerated and the OUR measured, but this is not of central importance in the experiment). Two sets of results on each of the IFFD (IFFD2) and CFCM (CFCM3) system sludges typical of five such aerobic batch tests on the IFFD system and three on the CFCM system are shown in Fig 6.4. One set of results on each of the IFFD and CFCM system sludge typical of three anoxic batch tests on each of the IFFD and CFCM systems are shown in Figs 6.5. From Figs 6.4 and 6.5 it can be seen that the anoxic/aerobic IFFD sludge had much higher *initial* OUR and NUR values than the anoxic/aerobic CFCM sludge. From these initial OUR and NUR of all the batch tests, the readily biodegradable COD (RBCOD)

Table 6.1: Operating parameters and conditions of Intermittently Fed Fill-and-Draw (IFFD) and Continuously Fed Completely Mixed (CFCM) systems.

System	IFFD2	CFCM3
Operating Conditions	IFFD	CFCM
Graphical representation		
Aeration	alternating aeration (3h)/non-aeration (1h)	
	0 during anoxic 0	
DO concentration	2–4 during aerobic 2–4	
Feed	intermittent (once daily)	continuous (24h)
Sewage source	Mitchell's Plain settled	
Mass of COD fed/d (mg/d)	5250	5250
Volume of feed (ℓ)	- 6	15
Concentration (mg/ℓ)	-875	350
Mass of TKN fed/d (mgN/d)	780	780
Sludge age (d)	20	20
Temperature (°C)	20	20
Volume of reactor (ℓ)	10	10
MLVSS concentration (mg/ℓ)	1700	1700
MLSS concentration (mg/ℓ)	2000	2000
pH	7–8	7–8
Nominal hydraulic retention time (h)	40	16

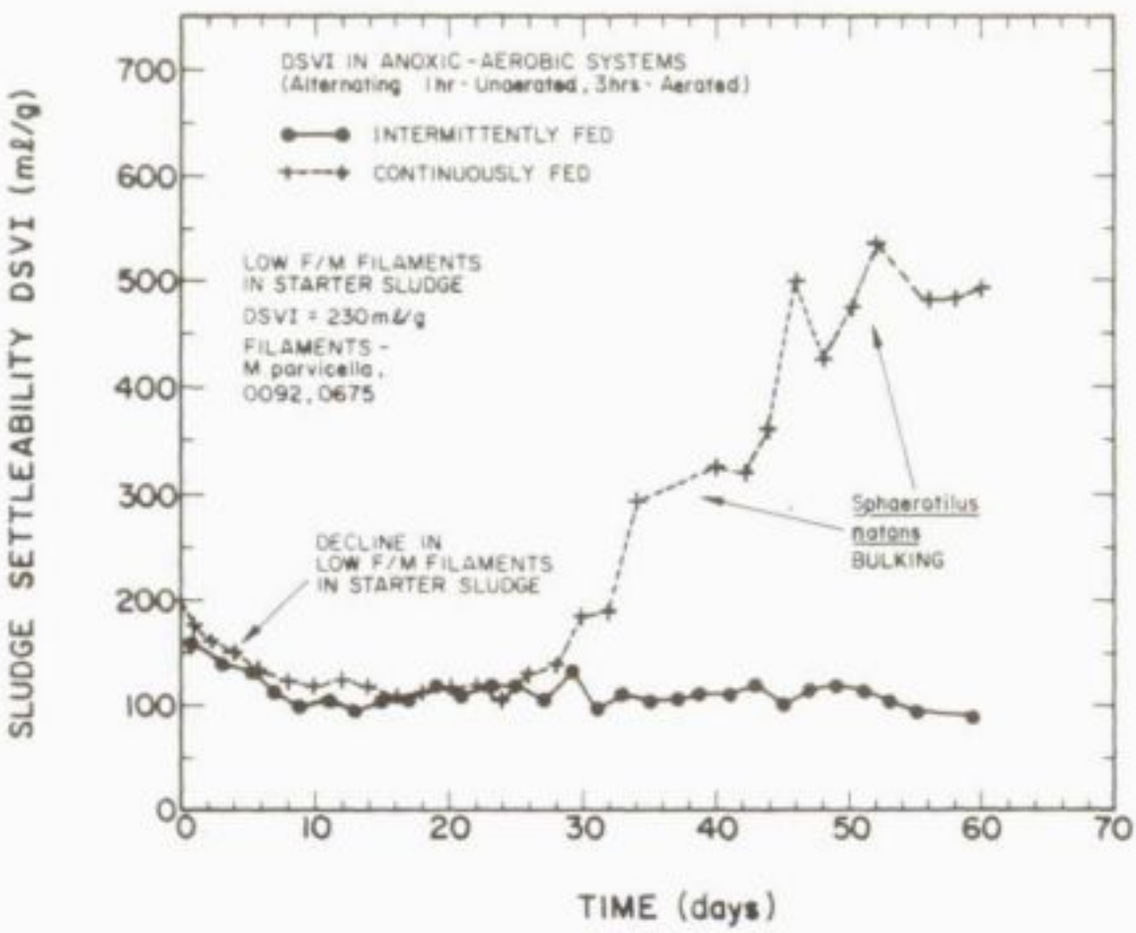


Fig 6.1: *Sludge settleability in Diluted SVI (DSVI) of sludges in two anoxic-aerobic (alternating 1 h anoxic, 3 h aerobic) single reactor systems fed (1) intermittently (batch) once daily (•——•) and (2) continuously (+----+) both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20d) and temperature (20° C). Note that in the first 20 days the DSVI of the starter sludge (Mitchell's Plain) dropped from a starting value of 230 ml/g to around 100 ml/g with a concomitant reduction in low F/M filaments* M.parvicella, *0092 and 0675. Thereafter the settleability in the intermittently fed system remained good (DSVI < 115 ml/g) but that in the continuously fed system deteriorated dramatically (DSVI - 500 ml/g) due to an explosive proliferation of Sphaerotilus natans.*

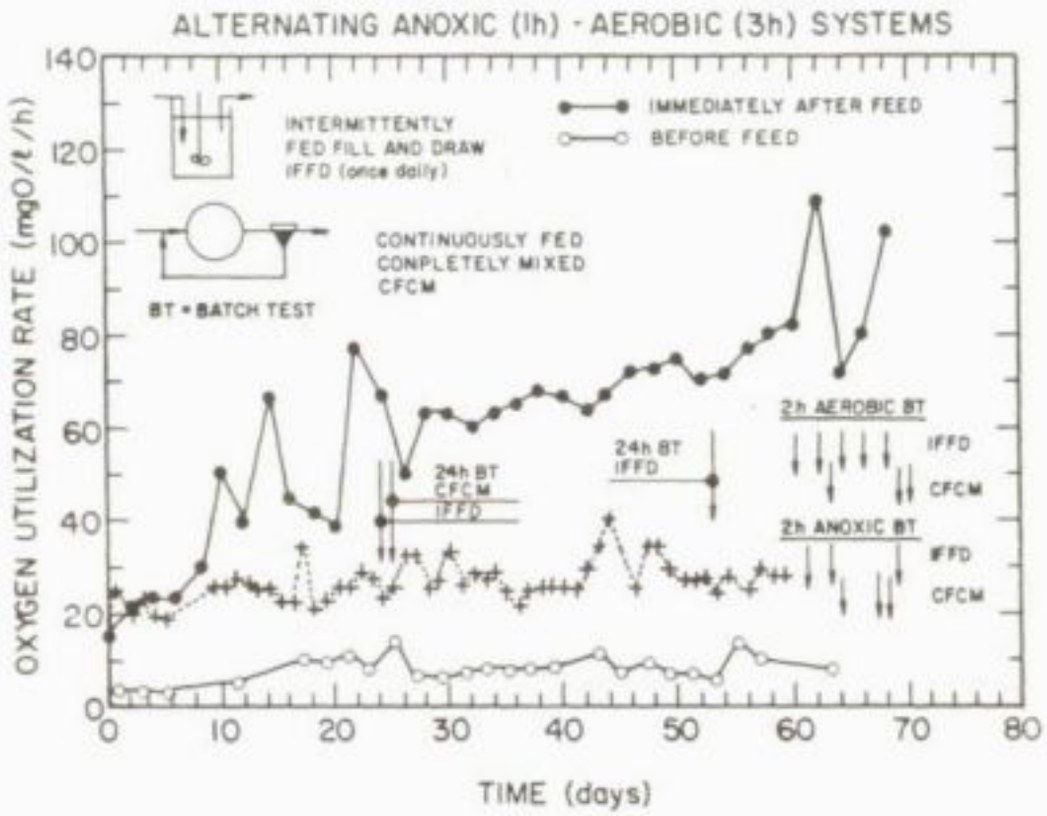


Fig 6.2: *Ozygen utilization rate (in mgO/ℓ/h — MLVSS concentration ~ 1800 mg/ℓ) in two alternating anoxic (1 h) — aerobic (3 h) single reactor systems, one fed continuously (CFCM) for which the OUR shown is the steady state value during the aerobic period (x———x), the other intermittently fed (IFFD) for which the OUR shown is that before (o———o) and after (•———•) feeding when the system is aerobic on these occasions. Also shown are the days on which the 24 h aerobic, 2 h aerobic and 2 h anoxic batch tests were conducted.*

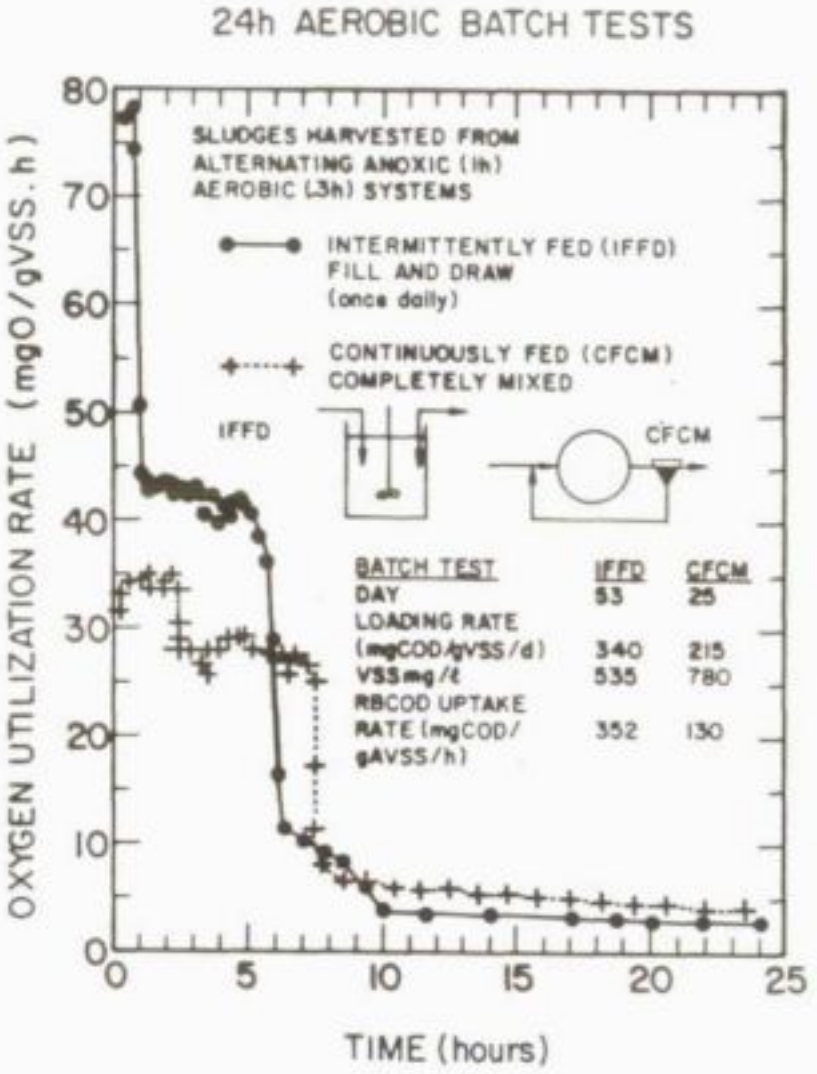


Fig 6.3: *Oxygen utilization rate [in mgO/(gVSS.h)] in 24 h aerobic batch tests (with nitrification) on sludges harvested from intermittently fed (•——•) and continuously fed (+----+) alternating anoxic (1 h) — aerobic (3 h) systems both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20d) and temperature (20° C). Note that the initial OUR in the intermittently fed system is much higher than that in the continuously fed system.*

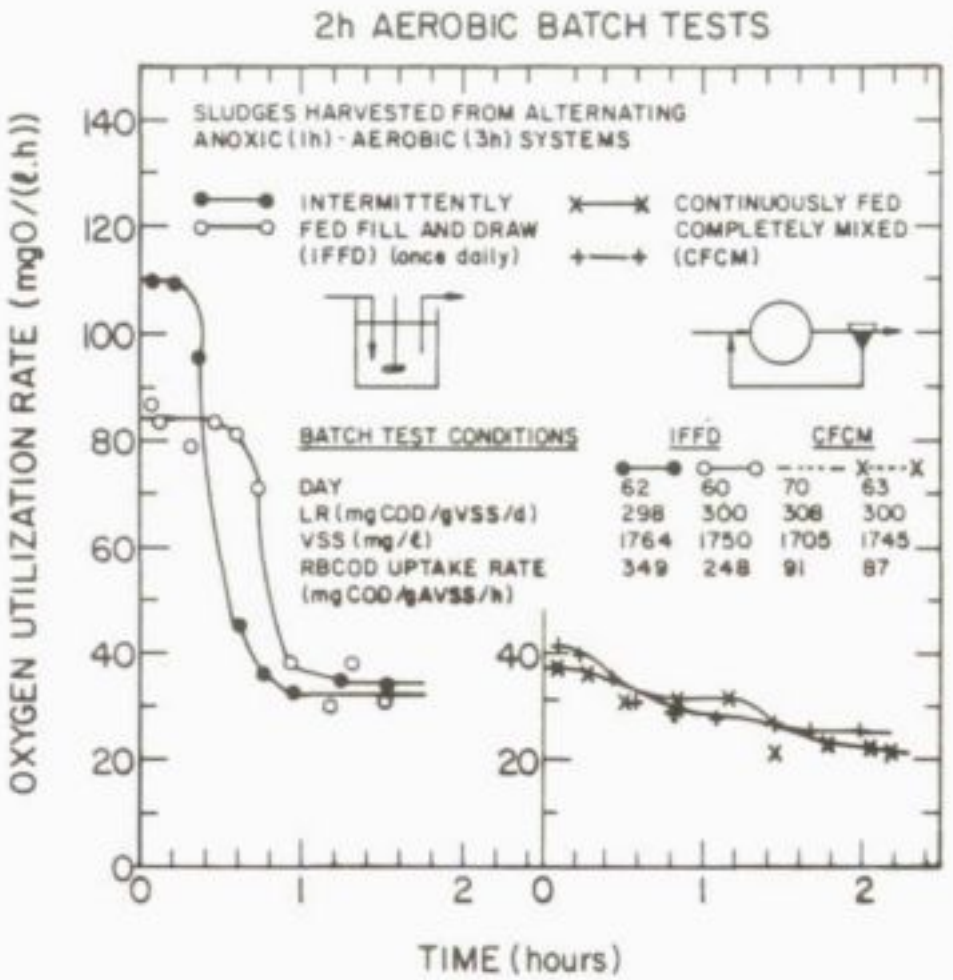


Fig 6.4: *Oxygen utilization rate [in mgO/(gVSS.h)] in 2 h aerobic batch tests (with nitrification) on sludges harvested from intermittently fed (•——•) and continuously fed (+——+) alternating anoxic (1 h) – aerobic (3 h) systems both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20d) and temperature (20° C). Note that the initial OUR in the intermittently fed system is much higher than that in the continuously fed system.*

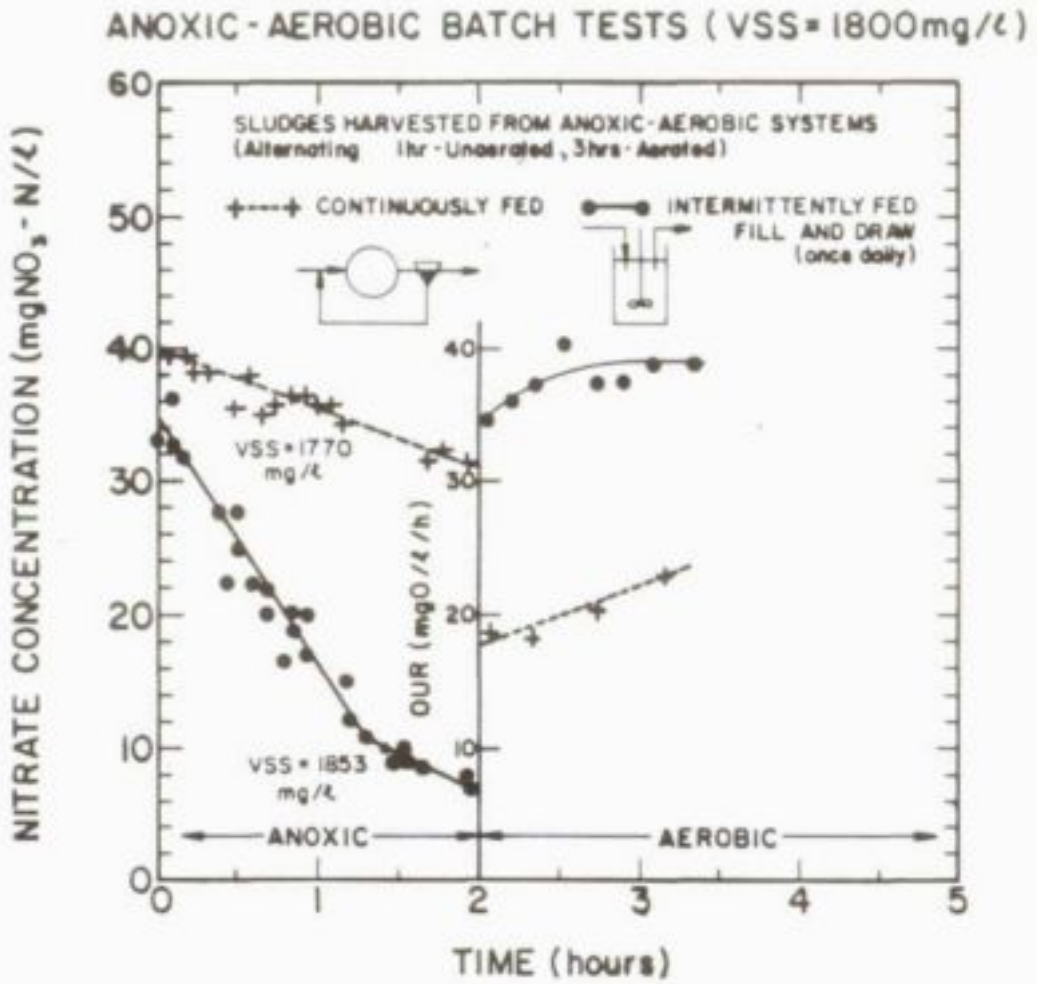


Fig 6.5: *Nitrate concentration versus time response observed in 2 h anoxic batch tests at the same COD load per gVSS and the same VSS concentration (1800 mgVSS/ℓ) for sludges harvested from alternating anoxic-aerobic (3 h) single reactor systems fed (1) intermittently (batch) once daily (●——●) and (2) continuously (+----+) both receiving the same sewage (Mitchell's Plain settled) and operated at the same sluthat the nitrate utilization rate (NUR) in the sludge from the intermittently fed system is more than 2 times higher than that in the sludge from the continuously fed system.*

utilization rate was calculated assuming no RBCOD storage takes place (see Ekama *et al.*, 1986); The average RBCOD utilisation rates for each of the 3 types of batch test conducted on the IFFD and CFCM systems are shown in Table 6.2, together with the average value for aerobic batch tests on the fully aerobic IFFD (IFFD1), CFCM/SEL and CFCM (CFCM1 and CFCM2) systems described in Chapter 5.

From Table 6.1, it can be seen that the RBCOD utilisation rate under both aerobic and anoxic batch conditions is much greater in the IFFD system than in the CFCM system. These results are in agreement with those of Shao (1986). Consequently, should the selector effect prove applicable for controlling bulking by low F/M

Table 6.2: Average maximum specific readily biodegradable COD utilisation rate mgRBCOD/(g Active VSS h) under anoxic and under aerobic conditions for sludges harvested from an alternating anoxic/aerobic intermittently fed fill and draw (IFFD) system and an alternating anoxic/aerobic continuously fed completely mixed (CFCM) system. Also listed are averages obtained from aerobic batch tests on sludges harvested from the same types of systems operated fully aerobically (Chapter 5).

Batch Test / Conditions		Parent System (anoxic/aerobic) IFFD	CFCM
		IFFD2	CFCM3
24h aerobic		310 (2)	130 (1)
2h aerobic		283** (5)*	83 (3)
2h anoxic-aerobic		258*** (3)	48 (3)
Averages from experiments on purely aerobic parent systems	(1)Fill and draw experiment	IFFD1 -320 (>20)	CFCM1 -100 (>20)
	(2)Selector experiment	CFCM/SEL 197 (4)	CFCM2 73 (4)

* Figure in brackets denotes number of tests.

** Calculated from OUR in mgO/(gAVSS.h) by multiplying by 3 mgCOD utilized per mgO utilized.

*** Calculated from NUR in $mgNO_3$-N/(mgAVSS.h) by multiplying by 8,6 mgCOD utilized per $mgNO_3$-N utilized.
Active fraction of sludge estimated at 0,45 mgAVSS/mgVSS for the sewage and system parameters (for details see glossary).

filaments, then one may expect that anoxic selectors will be as effective as aerobic selectors to control the bulking, for reason that similarly high RBCOD utilization rates are stimulated under anoxic conditions (when nitrate serves as the electron acceptor) as under aerobic conditions (when oxygen serves as the electron acceptor).

Sludge settleability

The sludge settleability measured on the anoxic-aerobic IFFD and CFCM systems is shown in Fig 6.1. The starter sludge for both systems had a DSVI of 230 mℓ/g. By the time routine analysis commenced a few days after the systems were started, the DSVI had already dropped to below 230 mℓ/g. By day 10 both systems had a DSVI around 110 mℓ/g. From day 25, the DSVI in the CFCM system suddenly commenced to increase rapidly, to 500 mℓ/g over about 20 days. The poor settleability was caused by a proliferation of the filament *Sphaerotilus natans* which is *not* a low F/M type, but a low DO type (Jenkins *et al.*, 1984) and consequently was of no particular relevance in this experiment. (The problems of *S.natans* bulking in laboratory systems are discussed in detail in Chapter 5, Section 4). No control strategy against *S.natans* was taken and the DSVI remained high (>500 mℓ/g) for the remainder of the experiment. In contrast, the DSVI in the IFFD system remained at around 100 mℓ/g; even though *S.natans* was identified in the sludge, it did not proliferate to cause poor settleability.

6.3. CONCLUSIONS

From operating intermittently fed fill-and-draw (IFFD) (fed once daily) and continuously fed completely mixed (CFCM) systems in which the unaerated:aerated time ratio was 1:3 over a 4h cycle, it was found that:

(1) The IFFD system stimulated in the sludge much higher oxygen (OUR) and nitrate (NUR) utilization rates compared to those in the sludge of the CFCM system. The RBCOD utilization rates in the IFFD system calculated from the OUR and NUR are approximately similar [i.e. 260 — 310 mgRBCOD/(gAVSS.h)], which in turn are similar to the RBCOD utilization rates stimulated under purely aerobic IFFD conditions.

(2) From (1) above provided the sludge is suitably acclimatized to anoxic conditions, a selector effect can be stimulated under anoxic conditions. Consequently, for controlling bulking by low F/M filaments, it is expected that anoxic selectors will be equally as effective as aerobic selectors.

(3) Both IFFD and CFCM systems appeared to ameliorate equally effectively, bulking due to the proliferation of low F/M filaments 0092, *M.parvicella* and 0675 in the starter sludge.

(4) Bulking by the filament *S.natans* took place in the CFCM system but not in the IFFD system.

The control of the proliferation of *S.natans* in the IFFD system compared to the CFCM system was unimportant insofar as the objective of development control strategies against low F/M filaments is concerned because *S.natans* is *not* a low F/M filament. The finding that *S.natans* is controlled by IFFD conditions and also aerobic

selectors, has been reported before (*inter alia*, Van den Eynde *et al.*, 1982) and is discussed in Chapter 5 of this report, but this finding is of little practical value for South African activated sludge plants because, in the surveys discussed in Chapter 2, *S.natans* has not been observed to cause bulking in any full-scale activated sludge plant in South Africa. In Chapter 5 (Section 4) *S.natans* proliferation in laboratory units (without a selector effect) appears to be an artefact of the laboratory set-up and can be controlled by regular cleaning of the influent feed lines.

CHAPTER 7

CONDITIONS FOR DEVELOPING LOW F/M FILAMENT BULKING SLUDGES

7.1 INTRODUCTION

Up to this stage, the main objective of the investigation has been to evaluate the stimulation of the "selector effect" in activated sludge and its role in control of bulking by low F/M filaments. With regard to the stimulation of the selector effect, it was found that the alternating feed-starve conditions imposed by (i) intermittent feeding to single reactor systems or (ii) selector reactors (aerobic) incorporated in continuously fed completely mixed systems, under aerobic or anoxic-aerobic conditions, stimulate in the sludge the selector effect, i.e. a high readily biodegradable (or dissolved) COD (RBCOD) uptake rate: This rate is 2 to 3 times higher than in systems which do not have alternating feed-starve conditions, such as continuously fed completely mixed systems. If the conditions are aerobic, the high RBCOD uptake rate gives rise to an associated high initial oxygen uptake rate (OUR) under batch conditions and if the conditions are anoxic, it gives rise to an associated high (initial) nitrate uptake rate (NUR) under batch conditions. It was found that the selector effect can be stimulated or lost in a sludge over a period of less than a sludge age in long sludge age systems by introducing or eliminating alternating feed-starve conditions respectively. The observations regarding the stimulation of a selector effect in a sludge under alternating feed-starve conditions was in agreement with research reported in the literature.

With regard to the role of the selector effect in controlling bulking by low F/M filaments, this could not be investigated because none of the laboratory systems bulked with low F/M filaments. Indeed, the laboratory scale systems, when started up with bulking sludges with low F/M filaments (DSVI > 250 mℓ/g and containing usually in varying proportions, 0092, *Microthrix parvicella*, 0914, 0675, 1851 and 0041 filaments) from long sludge age full scale nitrogen removal (anoxic-aerobic) plants (Bellville Orbal or Mitchell's Plain 4 stage Bardenpho), invariably *ceased* bulking (DSVI < 80 mℓ/g) within a month from start up irrespective of whether or not the system incorporated alternating feed-starve conditions. Apparently bulking by low F/M filaments was ameliorated under fully aerobic or alternating anoxic (1h) – aerobic (3h) conditions irrespective of the presence or not of a selector effect. It appears from this that the selector effect does not apply to the control of bulking by low F/M filaments and that instead the dissolved oxygen (DO) concentration plays an important role in ameliorating bulking by the low F/M filaments. In view of this, it was necessary therefore to evolve new hypotheses that may resolve partially, or completely, the causes for low F/M filament proliferation. In this chapter the various attempts towards evolving such hypotheses are reported.

7.2 PRELIMINARY CONSIDERATIONS

In examining the situations where low F/M filament proliferation and bulking have been reported (data collected in the surveys discussed in Chapter 2 was used for this also) it becomes clear that low F/M filament bulking difficulties are frequently

associated with nutrient (N and P) removal and nitrogen (N) removal systems operating at long sludge ages, (10 to 30 days). With regard to nutrient removal systems bulking by low F/M filaments frequently occurs in the modified Bardenpho, UCT and MUCT systems, both at full-scale (Blackbeard *et al.*, 1988) and laboratory-scale (Lakay *et al.*, 1988) (see Chapters 2 and 3). A characteristic feature of these systems is the serial separation of the anaerobic, anoxic and aerobic phases into specific reactors, generally, with the organism mass residing in these different phases for appreciably long periods. In nitrogen removal systems also, bulking by low F/M filaments frequently occurs in Carousel, Orbal and ditch type plants. These plants consist of an endless canal along which the mixed liquor is moved at a relatively high velocity, by aerators at one or more points in the line of flow. At the aerator the DO is raised to 1-2 mgO/ℓ but is reduced to zero at some point in the line of flow, thereafter denitrification takes place in the line of flow up to the next aerator. A slug of mixed liquor passes around the circuit once every 15-20 minutes so that the system essentially is completely mixed with the slug subjected to short alternating anoxic/aerobic periods.

From the prevalence of bulking by low F/M filaments in nutrient and nitrogen removal systems, one could form a working hypothesis that low F/M filament growth is promoted in long sludge age systems that operate with (1) a sequence of anaerobic/anoxic/aerobic conditions, or (2) alternating anoxic/aerobic conditions. To test this hypothesis two sets of experiments were devised; one for the anaerobic/anoxic/aerobic sequencing system and one for the alternating anoxic/aerobic system.

7.3 ANAEROBIC/ANOXIC/AEROBIC SYSTEMS

7.3.1 System set-up

Three single reactor systems were set up with a sludge age of 20 days, temperature 21°C and feed source Mitchell's Plain raw sewage. Two of the systems were operated as intermittently fed fill-and-draw (IFFD) systems (fed once daily); the third was operated as a continuously fed completely mixed (CFCM) system (Table 7.1). One of the IFFD systems (IFFD3) was not aerated for the first 6 h after feeding, to induce an anoxic/anaerobic state, followed by 16 h aerobic and 2 h settling. The other system (IFFD4) was operated fully aerobic from the time of feeding for 22 h followed by 2 h settling. In the anoxic/anaerobic/aerobic IFFD system (IFFD3) the first 10 to 20 minutes after feeding were anoxic while denitrification of the residual nitrate left in the mixed liquor after the supernatant was withdrawn took place; complete denitrification was obtained in a short period because the nitrate concentration was kept as low as possible by withdrawing as much supernatant as the sludge settleability allowed at the end of every 24 h cycle. This was done to minimize RBCOD utilization by denitrification and so allow maximum RBCOD availability for P release when the system became anaerobic. Operating in this fashion, P release in the anaerobic phase was obtained, that is, RBCOD was removed by the polyP organisms. During the aerobic period of 16h, the DO concentration was controlled to be around 6 mg/ℓ. These strategies were taken so that biological excess P removal would take place in the system in order to monitor the possible effect of P removal on bulking by low F/M filaments. In effect this operation procedure resulted in the system operating approximately as an anaerobic/aerobic long sludge age A/O or Phoredox system.

In the fully aerobic IFFD system (IFFD4) pure oxygen was used for aeration

immediately after feeding to ensure that during the high initial OUR period, the DO remained above 6 mg/ℓ. In the CFCM system (CFCM4) the mixed liquor was kept fully aerobic with the DO maintained at around 6 mg/ℓ.

The starter sludge for the 3 systems was taken from a laboratory scale modified UCT (MUCT) system (details of system given in Table 7.1). The sludge in this system typically had a DSVI > 150 mℓ/g with *M.parvicella*, 0092 and 0914 the dominant filamentous organisms. It treated Mitchell's Plain raw sewage (the same as that fed to the IFFD3, IFFD4 and CFCM4 systems) and was operated at 22 days sludge age and 21°C. The DO in the aeration reactor was kept between 2 and 4 mg/ℓ. The volumes of the four reactors of the system were; anaerobic 6ℓ, 1st anoxic 2,5ℓ, 2nd anoxic 4,5ℓ and aerobic 9ℓ. The nominal hydraulic retention of the system was 35 h and the nominal and actual retention times in the anaerobic reactor 9,6 h and 4,8 h respectively at 15ℓ/d influent flow; at 10ℓ/d influent flow these retention times are 53 h, 14,4 h and 7,2 h respectively (see Table 7.1).

The objectives of operating the 3 single reactor systems were to;

(1) confirm (for a fourth time) that fully aerobic IFFD and CFCM conditions ameliorate bulking by low F/M filaments, but on this occasion, to monitor the Modified UCT system as a control,

(2) investigate the effect of anaerobic-aerobic sequencing under IFFD conditions on the growth of low F/M filaments, again the Modified UCT system serving as a control.

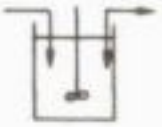
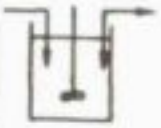
The anaerobic-aerobic IFFD system (IFFD3) was started up on day 6; the fully aerobic IFFD system (IFFD4) on day 30 and the fully aerobic CFCM system (CFCM4) on day 57, all with sludge from the MUCT system. Diluted SVI and MLSS concentration measurements on the 4 systems including the MUCT over a period of 120 days, are shown in Fig 7.1.

7.3.2 Results

In the anaerobic-aerobic IFFD3 system the DSVI remained approximately the same as in the MUCT system (i.e. between 160 and 220 mℓ/g) from start up to around day 95, i.e. for a period of 3 months or equivalently, 4,5 sludge ages. However, despite the similarities in the DSVI, the filamentous organism populations differed somewhat after about 2 weeks from start up. In the MUCT system *M.parvicella*, types 0092 and 0914 were the main filaments whereas in IFFD3, *M.parvicella* declined and 0092 became more abundant with 0914 and 0675 at common level. It would seem that in the IFFD3 system, under anaerobic/aerobic sequencing, the growth of *M.parvicella* was reduced, and that of 0092 was enhanced compared to their growth in the MUCT system.

After 3 months (day 95) the DSVI in the anaerobic-aerobic IFFD3 and MUCT systems began to diverge: Within 15 days, in the IFFD3 system, the DSVI increased from around 170 mℓ/g to around 250 mℓ/g with 0092 the dominant filament whereas in the MUCT system, the DSVI declined from about 160 mℓ/g to around 120 mℓ/g with *M.parvicella*, 0092 and 0914 the dominant filaments. No explanation for these differences can be advanced.

Table 7.1: Operating parameters and conditions for Modified UCT (MUCT) nutrient (N and P) removal system and 3 single reactor systems started with MUCT sludge viz. anoxic/anaerobic-aerobic intermittently fed fill-and-draw system (IFFD3), fully aerobic intermittently fed fill-and-draw system (IFFD4) and fully aerobic continuously fed completely mixed system (CFCM4).

System	MUCT	IFFD3	IFFD4	CFCM4
Operating conditions	Continuously fed multi-reactor	Single reactor IFFD	Single reactor IFFD	Continuously fed single reactor
Graphical representation				
Aeration	continuous in aerobic	6h off-16h on	continuous	continuous
DO concentration (mg/ℓ)	2-4	>6 when on	>6	>6
Feed	continuous (24h)	intermittent (once daily)	intermittent (once daily)	continuous (24h)
Sewage source	Mitchell's Plain raw sewage			
Mass of COD fed/d	15000 10000	1500	1500	1500
Volume (ℓ/d)	15* 10*↑	~2*	~2*	6
Concentration* (mg/ℓ)	1000 1000	~750	~750	250*
MLSS concentration	4350 2900	3250	3000	1500
MLVSS concentration	3500 2350	2600	2400	1200
F/M (mgCOD/(mgVSS.d)	0,22	0,20	0,20	0,20
Volume of reactors (ℓ)	6/2,5/4,5/9	3	3	6
Sludge age (d)	22	20	20	20
Nominal hydraulic retention time	35	22	22	24
Temperature (°C)	21	21	21	21

* Required COD concentrations were obtained by appropriate dilution of a stronger sewage with tap water.

↑ On day 99 (Fig 7.1) the MUCT system COD feed and sludge masses were reduced by 1/2 to (i) provide starter sludge for a second MUCT system and (ii) bring relief to the clarifier in the event of severe bulking.

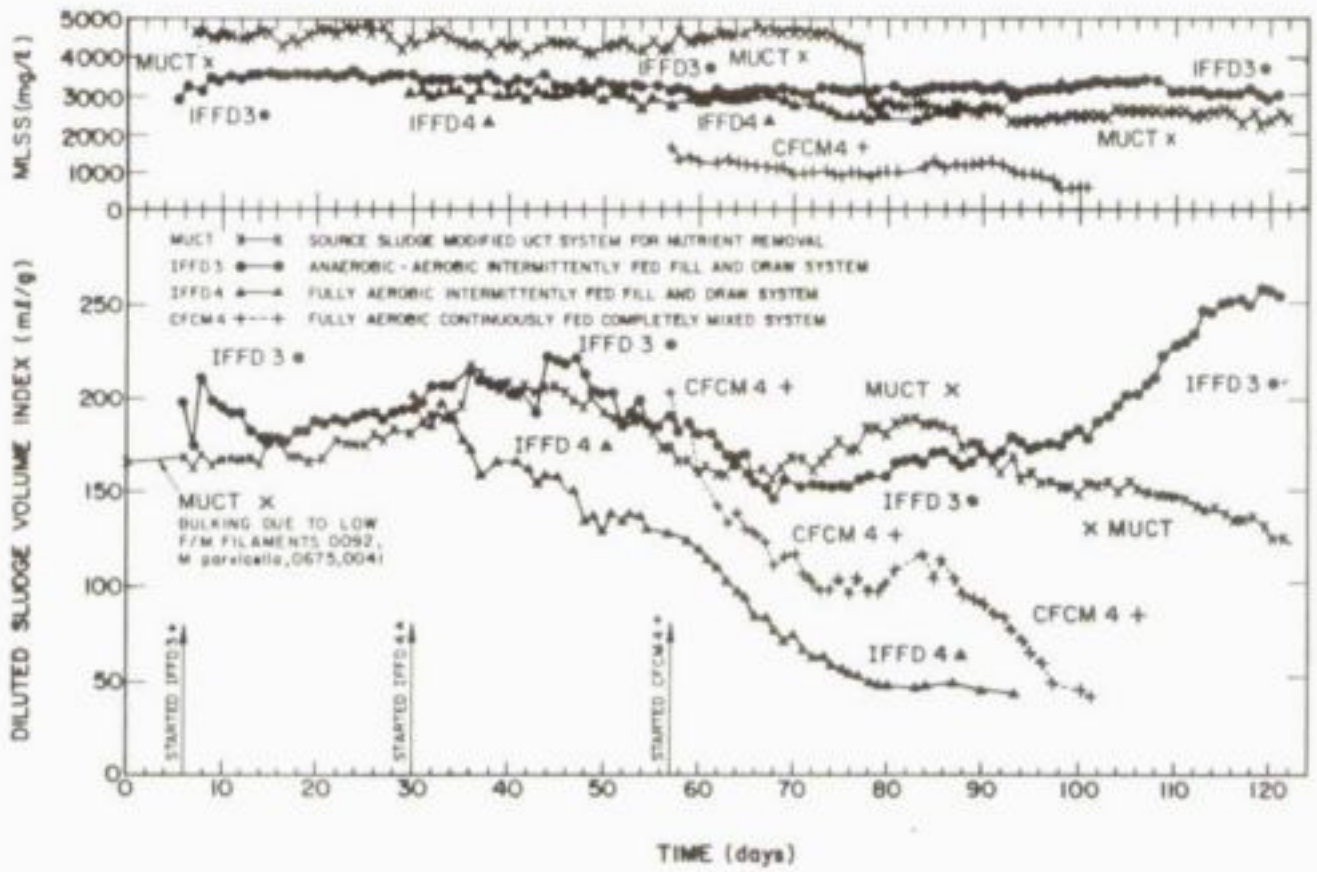


Fig 7.1: *Sludge settleability in DSVI (bottom) and MLSS concentration (top) with time in a Modified UCT nutrient (N and P) removal system (MUCT) and 3 single reactor systems started up with sludge from the MUCT system, all systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (20° C). Two of the single reactor systems (IFFD4, CFCM4), were fully aerobic, one intermittently fed fill and draw (IFFD4), the other continuously fed completely mixed CFCM4); the third single reactor system (IFFD3) was intermittently fed fill and draw with an anoxic (½ h) and anaerobic (5½ h) period for 6h after feeding and an aerobic period of 16h thereafter (and 2h settling). Note that the DSVI in the two fully aerobic systems i.e. IFFD4 and CFCM4 gradually declined from 200 to below 50 ml/g, while the DSVI in the systems with unaerated/aerated conditions i.e. MUCT and IFFD3, remained above 150 ml/g.*

In the fully aerobic IFFD system (IFFD4), the DSVI decreased steadily from a start-up value of 202 mℓ/g on day 30 to 47 mℓ/g on day 80 i.e. in 50 days. Over the same period the DSVI in the MUCT system remained between 160 and 200 mℓ/g (see Fig 7.1). Microscopic examination of the sludge, when the DSVI was low, showed large compact flocs with an almost complete absence of filamentous organisms.

In the fully aerobic CFCM system (CFCM4), the DSVI also decreased steadily from a start-up value of 200 mℓ/g to around 100 mℓ/g on day 72, i.e. in only 17 days. Thereafter the DSVI increased slightly. Microscopic examination of the sludge indicated that the *Sphaerotilus natans* had become the dominant filament. This was traced to *S.natans* seeding from the influent line (see Chapter 5). Following regular cleaning of the influent feed line, *S.natans* disappeared and the DSVI declined to 40 mℓ/g by day 101, with pin-point floc characteristic of such low DSVI sludges. Microscopic evaluation confirmed that the filaments *M.parvicella*, 0092 and 0914, present in the starter sludge, had been eliminated virtually completely from the sludge.

The results of these fully aerobic IFFD and CFCM systems confirm the results obtained in Chapters 5 and 6, that many of the low F/M filaments, in this case *M.parvicella*, 0092 and 0914, are eliminated under fully aerobic conditions irrespective of intermittently fed fill-and-draw or continuously fed completely mixed conditions, i.e. under fully aerobic conditions in the presence or absence of a selector effect.

7.3.3 Conclusions

From the results of this experiment, it was concluded that:

(1) During the whole period of the experiment, the MUCT system sustained the growth of the low F/M filaments at bulking level, i.e. sustained the growth of *M.parvicella*, 0092 and 0914.

(2) Continuous aeration inhibits the growth of the low F/M filaments *M.parvicella*, 0092 and 0914 irrespective of whether the mixing regime is intermittently fed fill and draw (IFFD) (with selector effect) or continuously fed completely mixed (CFCM) (without selector effect).

(3) In an IFFD system imposition of an initial anoxic-anaerobic period of 6 h (during which essentially all the RBCOD is removed, (some by denitrification but most by polyP organisms) followed by an aerobic period of 16 hours at a DO concentration above 6 mg/ℓ sustains the growth of some low F/M filaments; the growth of *M.parvicella* is reduced but the growth of 0092 is enhanced compared to the parent MUCT system.

(4) The aeration pattern i.e. whether or not the sludge is exposed to unaerated conditions, appears to play a significant role in whether or not low F/M filaments proliferate in a system.

7.4 ANOXIC/AEROBIC SYSTEMS

7.4.1 System set-up

From the above and the earlier experiments it appears that exposure of a sludge to alternating aeration and non-aeration cycles, is conducive to low F/M filament proliferation whereas continuous aeration is conducive to inhibiting low F/M filament

growth. In an attempt to grow low F/M filaments at laboratory scale in systems other than nutrient removal ones, two completely mixed continuously fed single reactor systems with intermittent aeration (denoted Experimental, EXP and Control, CTRL) were set up to simulate full scale Carousel, Orbal or ditch type plants. Both systems had the same sludge age (20 days), temperature (21°C), reactor volume (7,5ℓ), nominal hydraulic retention time (18h) and influent flow rate (10 ℓ/d). The influent feed to both systems was Mitchell's Plain raw sewage diluted to 500 mg/ℓ (see Table 7.2).

To mimic Carousel, Orbal and ditch type plants, the aeration cycle was set as follows: In a cycle time of 10 minutes, the air-on/air-off periods were set by trial and error such that the system was aerobic for 3-4 minutes and anoxic for 6-7 minutes. The duration of aeration depended on the OUR, nitrification and the MLSS concentration. The air-on/air-off period finally adopted once the systems had stabilized, was 55s on and 9m 5s off respectively. During the 55s air-on period, the DO increased to around 2,0 mg/ℓ; over the next 2 to 3 minutes the DO decreased to zero and for the remaining 6 to 7 minutes the systems were anoxic (nitrate was present throughout the cycle, see below). During the aerobic period it was found that the OUR is dominantly affected by the concentration of ammonia in the influent, consequently, in order to ensure a high OUR so that the DO would drop sufficiently rapidly after aeration ceases, additional ammonia was added to the influent (before sampling and therefore is reflected in the influent TKN concentration in Fig 7.2a and b) to stimulate a high nitrification OUR. The additional nitrate generated also ensured that denitrification did not reduce the nitrate concentration to zero by the end of the cycle.

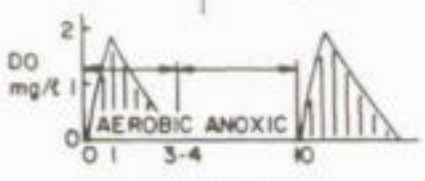
7.4.2 Results

The two systems were started up with Mitchell's Plain activated sludge which contained abundant levels of 0092 and *Nocardia* sp. and had a DSVI of about 140 mℓ/g. The overall performance of the systems was monitored by regularly measuring the influent and effluent (24h composite) COD, TKN, nitrate (as N) and total phosphorus (as P) concentrations; the data measured from day 20 to day 232 are shown in Fig 7.2a and b. The sludge settleability in Diluted SVI (DSVI), reactor mixed liquor suspended solids (MLSS) and filament populations were monitored regularly; the information collected in the investigation (day 1 to 362) are shown in Fig 7.3a, b and c.

During the first 28 days while the systems were stabilizing, the air-on time and airflow rates were adjusted to give the aeration pattern description above. During this period the DSVI in both systems increased to about 160 mℓ/g (Fig 7.3a). Over the next 47 days the DSVI in both systems increased gradually to about 200 mℓ/g (by day 76). Microscopic examination of the sludges on day 67 indicated that the levels of 0092 and *Nocardia* sp. had declined significantly, but that *M.parvicella*, a filament not observed in the starter sludge had become abundant. From day 76 to day 100, the DSVI in both systems increased sharply to around 500 mℓ/g, caused by proliferation of *M.parvicella*. Other filaments in the sludge were 1851, 0092 and 0914 (see Fig 7.3a).

On day 85 and 87, aerobic batch tests (with nitrification) were conducted on the Experimental and Control systems respectively to check whether or not the sludges had a selector effect; in these batch tests the OUR, soluble (0,45μm filtered) COD, TKN, nitrate (as N) and total phosphorus (as P) concentrations were measured over a 24 h period (see Figs 7.4 and 7.5). From the soluble COD concentration and OUR measurements (the latter appropriately corrected for nitrification) it was found that the

Table 7.2: Operating parameters and conditions for two single reactor continuously fed completely mixed intermittent aeration systems (Experimental, EXP and Control, CTRL).

System	EXP	CTRL
Operating conditions	Continuously fed, single reactor	
Graphical representation		
Aeration - day 1 - 103	intermittent	intermittent
104 - 176	continuous	intermittent
176 - 304	intermittent	intermittent
305 - 362	intermittent	continuous
DO concentration (mg/ℓ)		
when aeration intermittent	0 - 2	0 - 2
when aeration continuous	2 - 4	2 - 4
DO profile for intermittent		
Sewage source	Mitchell's Plain raw	
Mass of COD fed/d (mg/d)	5000	5000
Volume of feed (ℓ/d)	10	10
Concentration (mg/ℓ)	500	500
Influent TKN (mgN/ℓ)	60 - 100	60 - 100
Sludge age (d)	20	20
Temperature (°C)	21	21
Volume of reactor (ℓ)	7,5	7,5
MLVSS concentration (mg/ℓ)	2800	2800
MLSS concentration (mg/ℓ)	3500	3500
F/M [mgCOD/(mgVSS.d)]	0,24	0,24
Hydraulic retention time (h)	18	18
Underflow recycle ratio	1:1	1:1
pH of mixed liquor	7,3 - 7,5	7,3 - 7,5

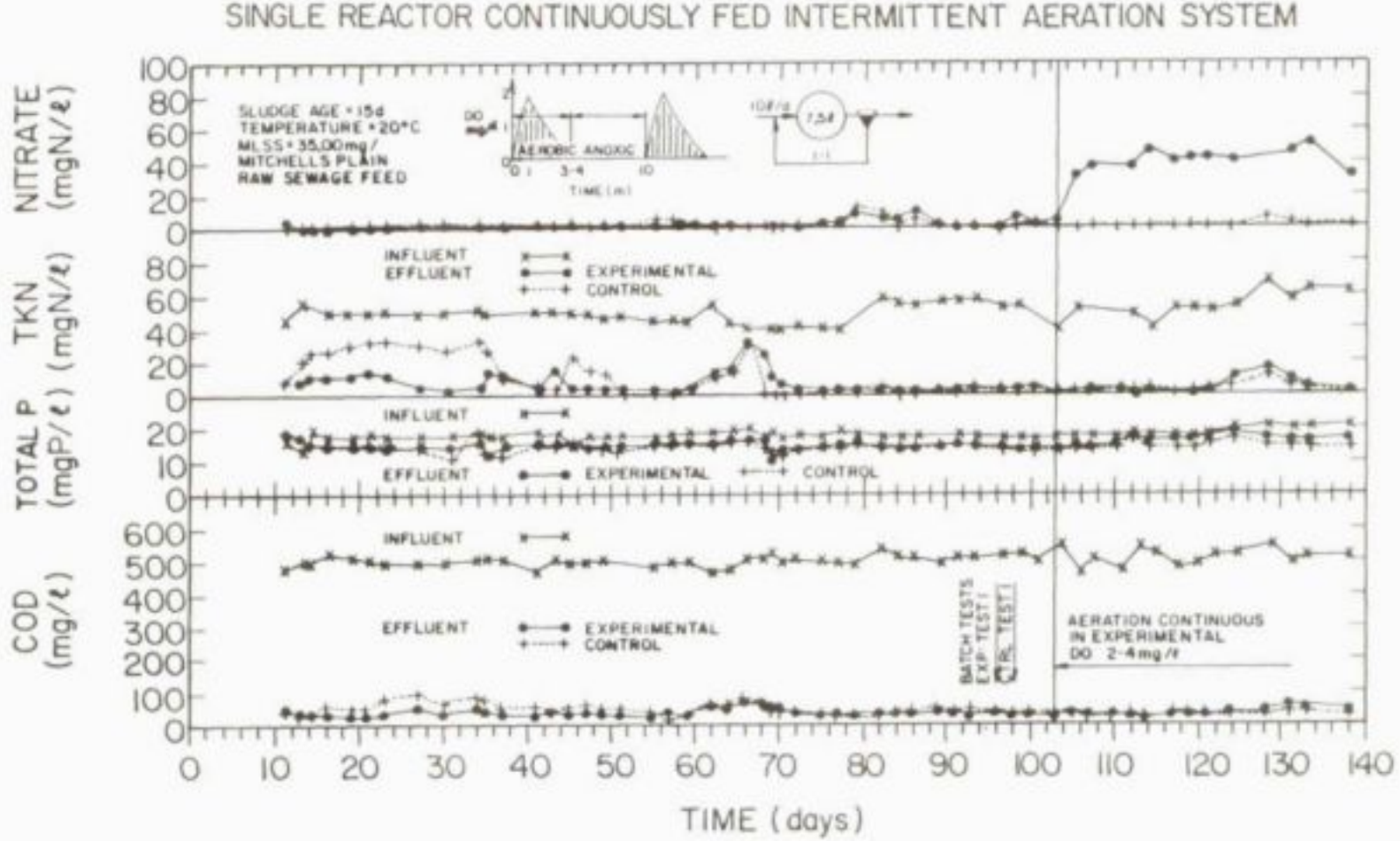


Fig 7.2a: *Influent and effluent COD (lower), total phosphorus (as P) (mid lower), nitrate (as N) (mid upper), and TKN (as N) (upper) concentrations with time in two, one Experimental (EXP) the other control (CTRL), single reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (21° C). Note the high effluent nitrate concentration from day 103 to day 176 (Fig 7.2b) due to the absence of denitrification, when the Experimental system was operated with continuous aeration.*

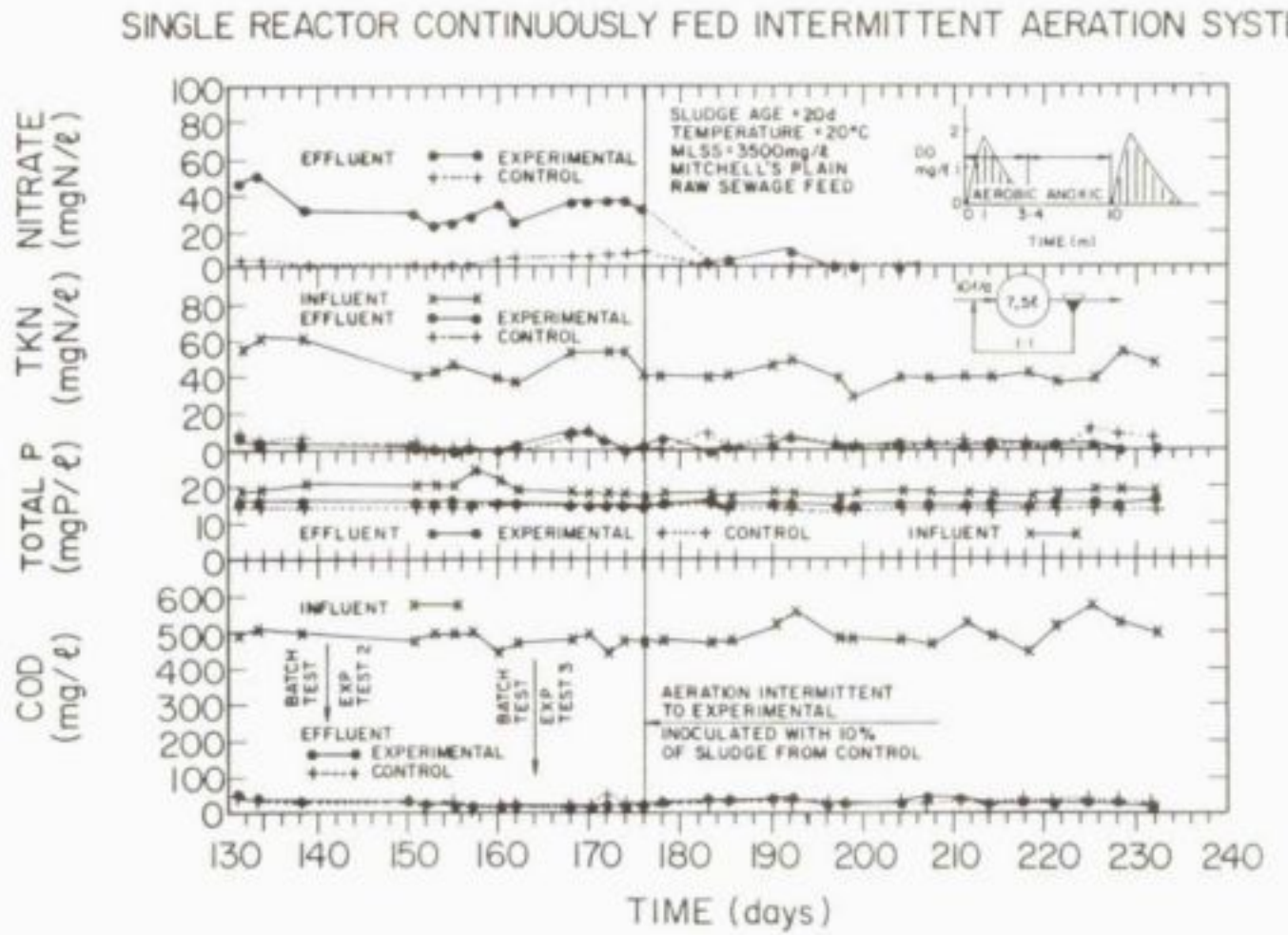


Fig 7.2b: *Influent and effluent COD (lower), total phosphorus (as P) (mid lower). nitrate (as N) (mid upper) and TKN (as N) (upper) concentrations with time in two, one Experimental (EXP) the other control (CTRL), single reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (21° C). Note the high effluent nitrate concentration from day 103 to day 176 (Fig 7.2a) due to the absence of denitrification, when the Experimental system was operated with continuous aeration.*

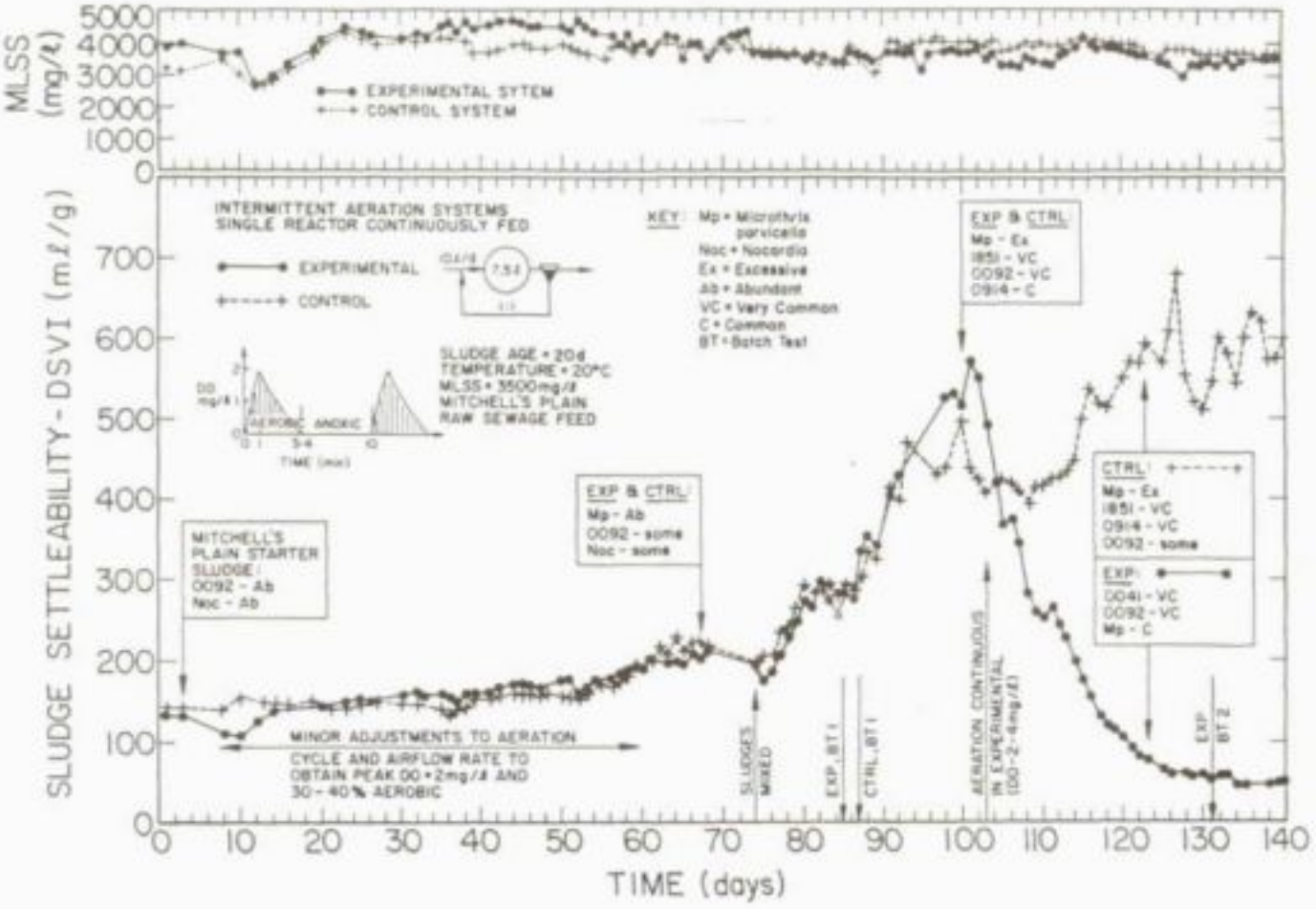


Fig 7.3a: *Sludge settleability in DSVI with time in two (one Experimental, EXP; one Control, CTRL) single reactor continuously fed intermittent aeration systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (20° C). Note (1) increase in DSVI and concomitant proliferation of low F/M filaments, in particular* M.parvicella *from day 0 to 103 when aeration is intermittent, (2) decline in DSVI (to below 100 mℓ/g) and in low F/M filaments from day 103 to 140 when aeration is continuous (DO = 2–4 mg/ℓ) in the Experimental system while the DSVI in the Control system remains high (> 300 mℓ/g).*

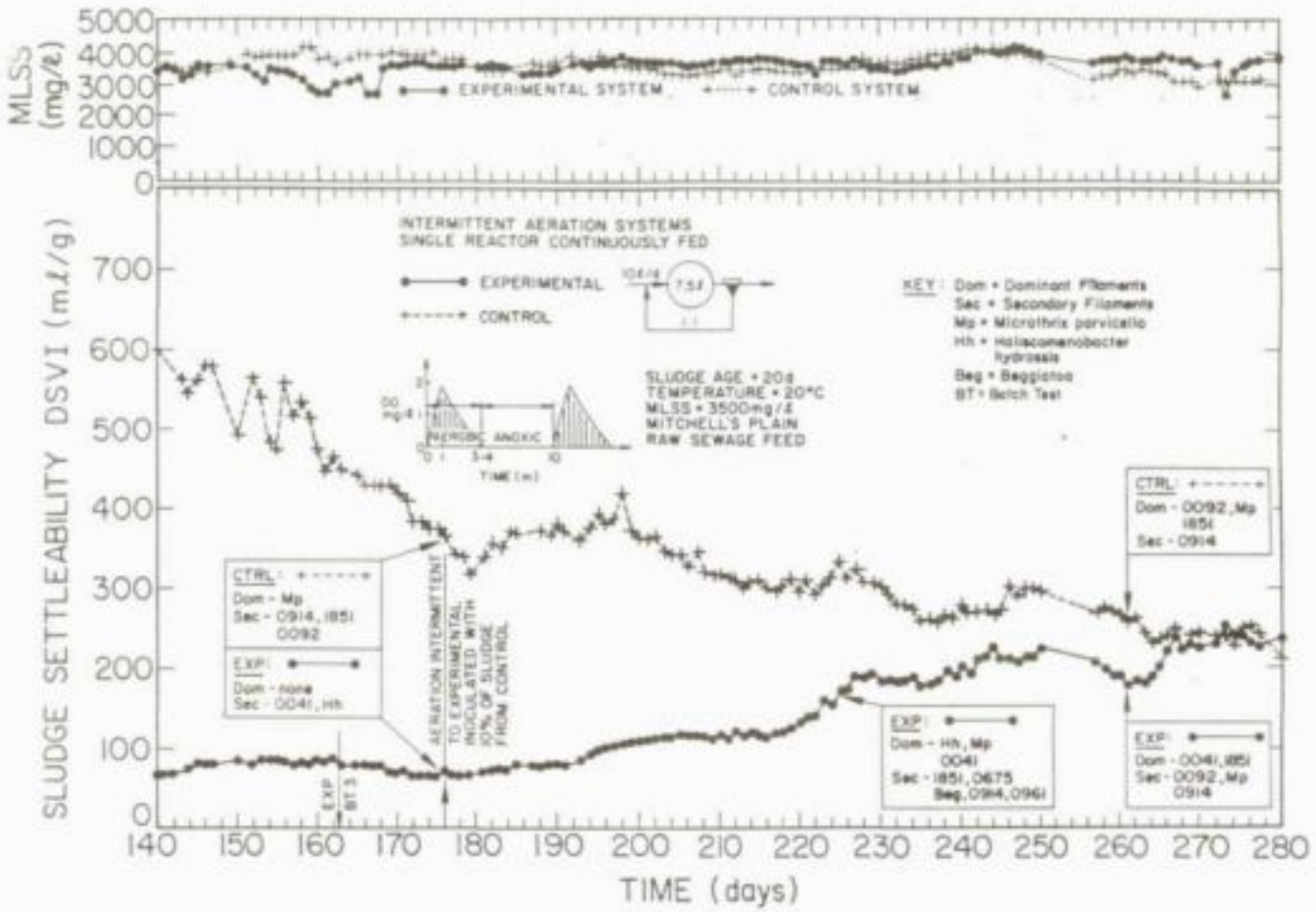


Fig 7.3b: *Sludge settleability in DSVI in two (one Experimental, EXP; one Control, CTRL) single reactor continuously fed systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (20° C). Note DSVI is low in the Experimental system when aeration is continuous whereas it is high in the Control system, caused by low F/M filaments, when aeration is intermittent (day 140 to 176). The DSVI in the Experimental system increases, with a concomitant proliferation in low F/M filaments, when aeration is changed from continuous to intermittent (day 176-280).*

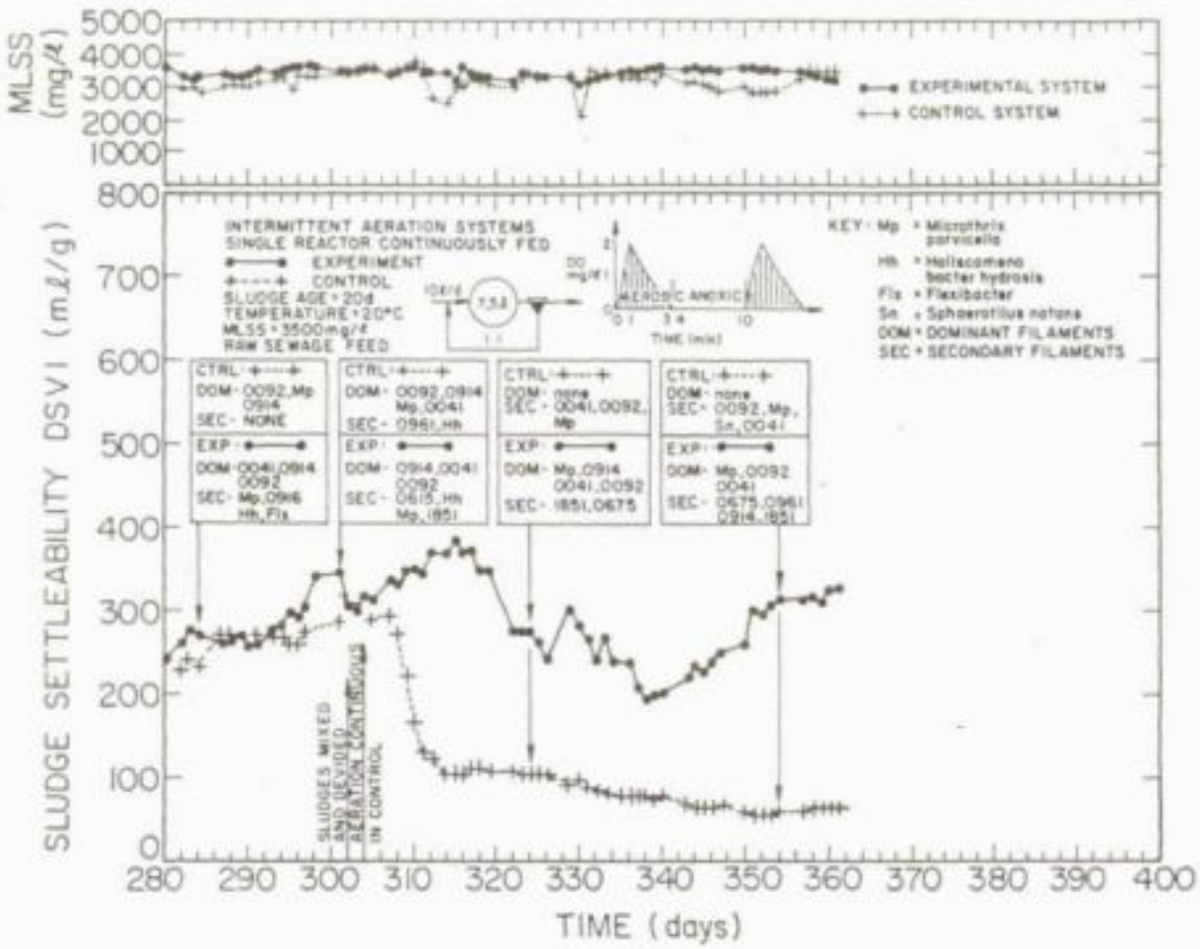


Fig 7.3c: *Sludge settleability in DSVI with time in two (one Experimental, EXP; one Control, CTRL) single reactor continuously fed intermittent aeration systems receiving the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (20° C). Note decrease in DSVI and concomitantly in low F/M filaments when aeration in the Control system is changed from intermittent to continuous (day 304 to 361) while in the Experimental system the DSVI remains high (> 200 mℓ/g) with intermittent aeration.*

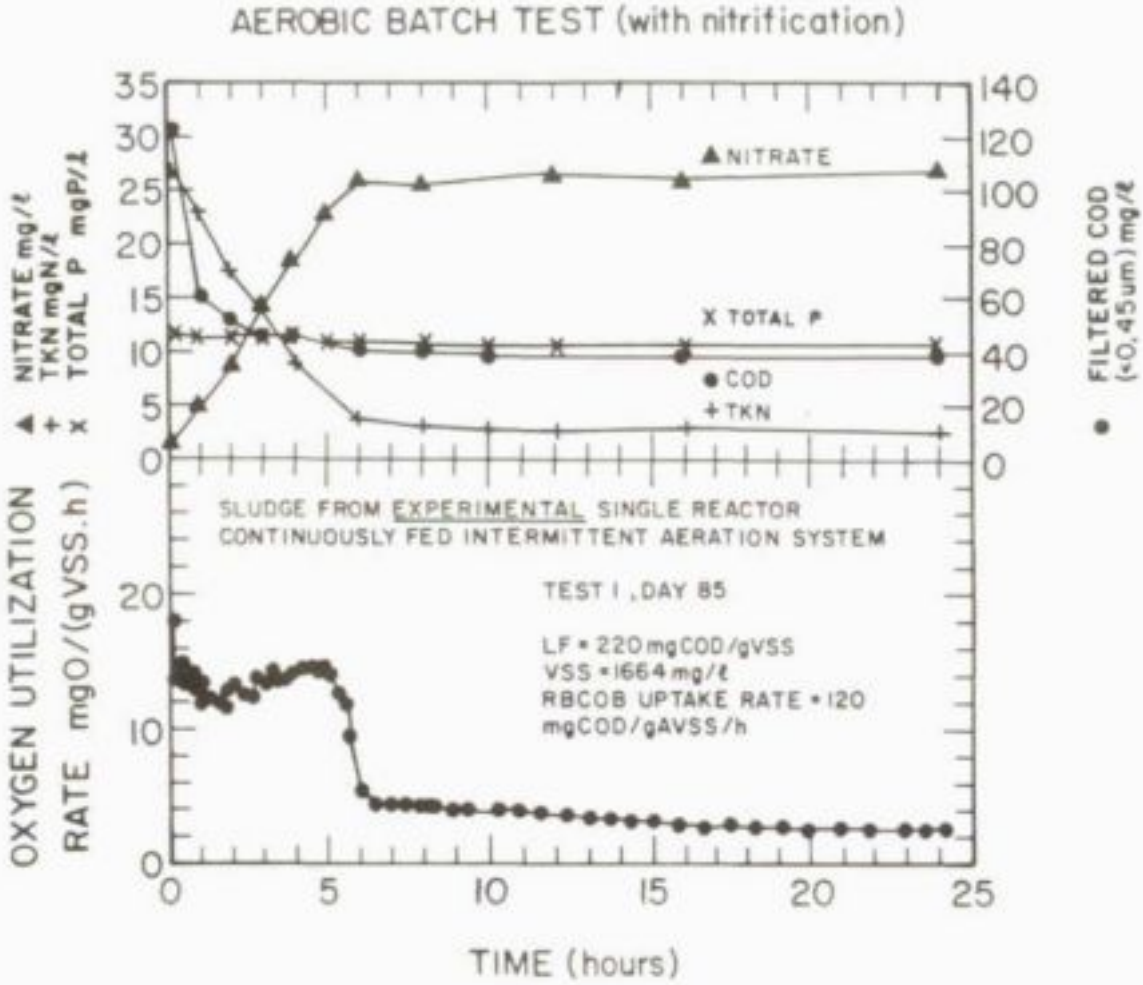


Fig 7.4: *Oxygen utilization rate [OUR in mgO/(gVSS.h)] (bottom), and soluble COD (<0,45μm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the first aerobic batch test (with nitrification) (day 85) at a load factor (LF) of 220 mgCOD/gVSS on sludge harvested from the Experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 120 mgCOD/(gAVSS.h) indicating the absence of a selector effect.*

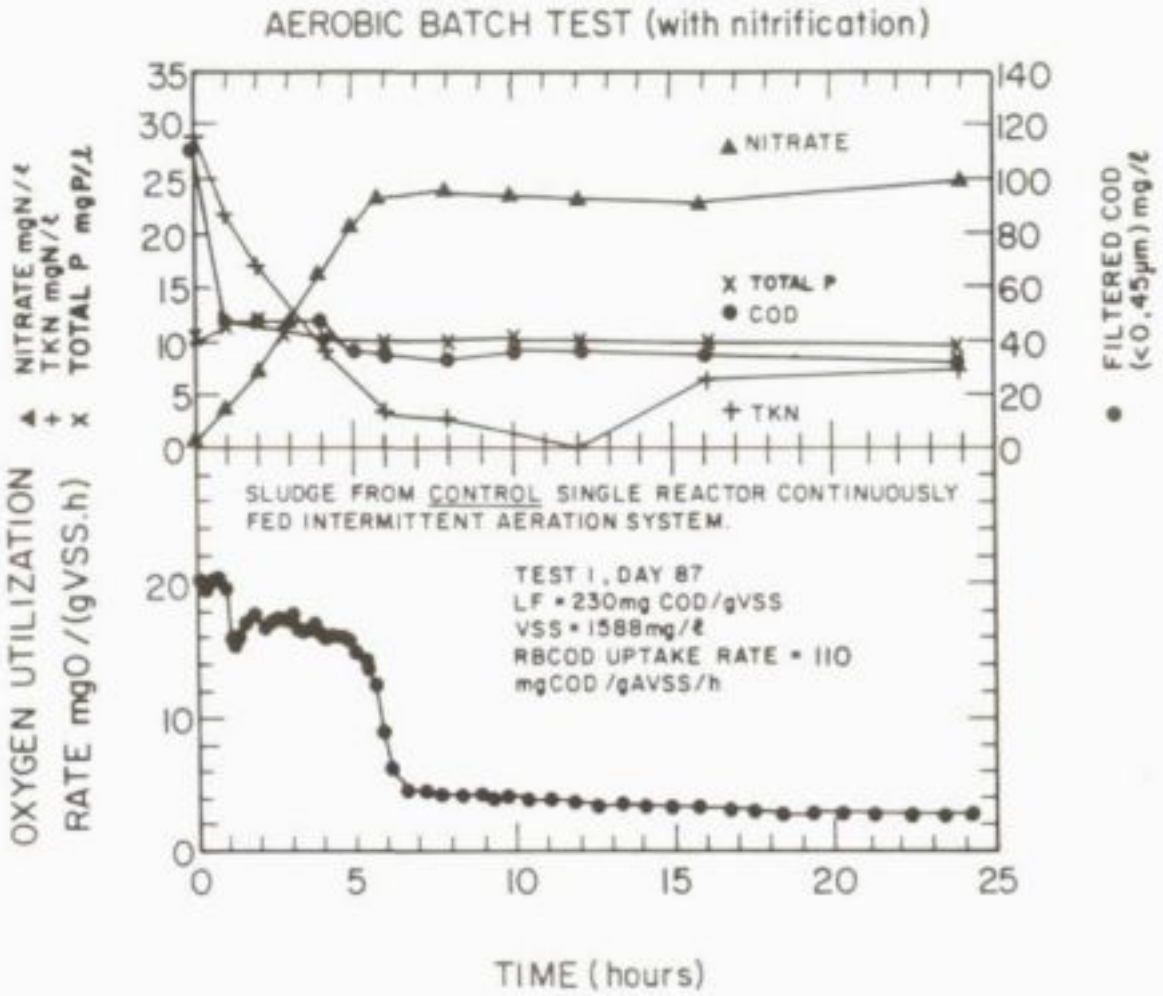


Fig 7.5: *Oxygen utilization rate [OUR in mgO/(gVSS.h)] (bottom), and soluble COD (<0,45µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the first aerobic batch test (with nitrification) (day 87) at a load factor (LF) of 230 mgCOD/gVSS on sludge harvested from the Control single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 110 mgCOD/(gAVSS.h) indicating the absence of a selector effect.*

RBCOD uptake rate was low [-110 mgCOD/(gAVSS.h) based on COD results; compare with Table 6.2] indicating that a selector effect was absent in both system sludges.

On day 103 the aeration to the Experimental system was changed from intermittent to *continuous* with the DO concentration controlled between 2 and 4 mg/ℓ. The system response to this is reflected in the effluent nitrate concentration which increased from about 3 to 5 mgN/ℓ to over 40 mgN/ℓ due to the absence of denitrification (Fig 7.2a and b). The DSVI immediately began to decrease at a rapid rate, falling from 480 mℓ/g to 92 mℓ/g in 20 days. The DSVI in the Control system, still intermittently aerated, remained at around 560 mℓ/g. On day 123, microscopic examination of the sludges indicated that: The Experimental system (*continuous* aeration) had large compact flocs with few filaments; the filaments, in decreasing order of abundance, were 0041, 0092 and *M.parvicella*; the Control system (*intermittent* aeration) had open and diffuse flocs with bridging; the filaments, in decreasing order of abundance, were *M.parvicella* at "excessive" level, types 1851 and 0914 at "very common" level and 0092 at "some" level.

On day 131 and 163, while the Experimental system had a low DSVI, aerobic batch tests (with nitrification) were conducted on the Experimental system sludge, with objective of checking whether or not the sludge had a selector effect; as in the earlier 2 batch tests, the OUR, soluble (0,45μm filtered) COD, TKN, nitrate and phosphate concentrations were measured over a 24 h period (see Figs 7.6 and 7.7). These tests show that the RBCOD uptake rate still is low [-100 mgCOD/(gAVSS.h) based on the COD results] indicating that a selector effect still is absent in the system. Consequently the reduction in DSVI and amelioration of low F/M filament bulking could not have been due to a selector effect.

On day 176 (Fig 7.3b) the continuous aeration in the Experimental system was changed back to intermittent. Because the filaments had been reduced to such a low level in the Experimental system (DSVI - 70 mℓ/g), 10% of the mixed liquor was wasted from this system and replaced with heavily filamentous sludge from the Control system. The system response again is reflected in the effluent nitrate concentration, which decreased back to 3-5 mgN/ℓ due to the reinstatement of denitrification (Fig 7.2b). The DSVI in the Experimental system began to increase slowly and on day 202 reached 120 mℓ/g, after which it ceased to increase. Inspection of the DO concentration profile during the 10 minute aeration cycle indicated the DO increased only to 1,3 mg/ℓ (not 2,0 mg/ℓ as earlier). Consequently on day 217 the airflow rate was increased so that the DO reached 2,0 mg/ℓ. Following this change, the DSVI in the Experimental system increased, attaining over 200 mℓ/g on day 238. In the Control system (intermittent aeration) the DSVI decreased slowly over this same period from about 550 mℓ/g around day 140 to below 300 mℓ/g around day 217. It is possible that this steady decline in the DSVI also was caused by the too low an airflow rate to give too low a peak DO concentration. On day 217 the air flow rate to the Control system also was increased, as for the Experimental system mentioned earlier. The DSVI in the Control system now remained relatively stable, but that of the Experimental increased slowly so that by day 270 (Fig 7.3b), the DSVI's of both systems were about the same at 240 mℓ/g. However, the filamentous organism populations were somewhat different: 0041 was the most dominant in the Experimental system whereas *M.parvicella* and 0092 were most dominant in the Control system.

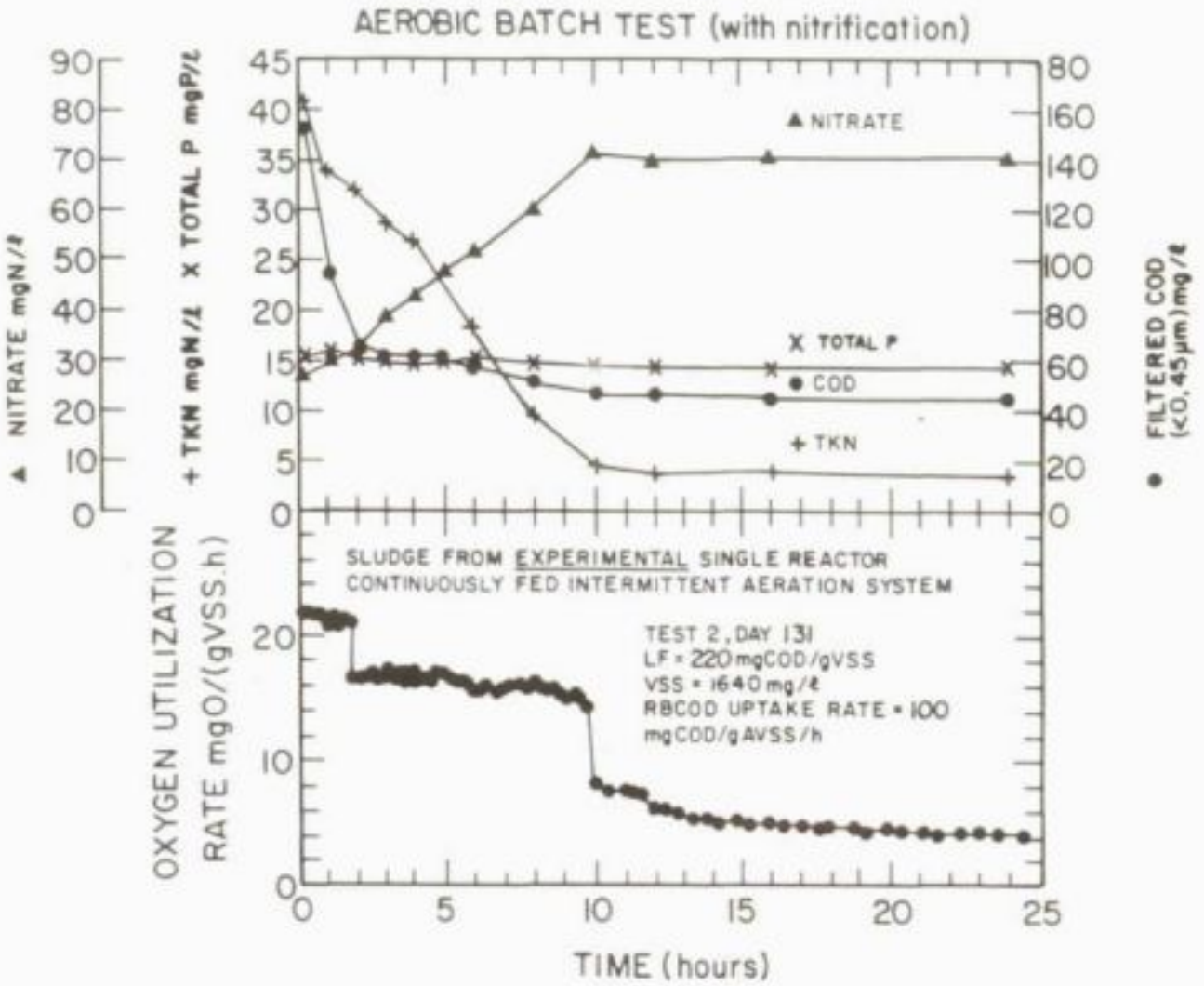


Fig 7.6: *Oxygen utilization rate [OUR in mgO/(gVSS.h)] (bottom), and soluble COD (<0,45µm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the second aerobic batch test (with nitrification) (day 131) at a load factor (LF) of 220 mgCOD/gVSS on sludge harvested from the Experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 100 mgCOD/(gAVSS.h) indicating the absence of a selector effect.*

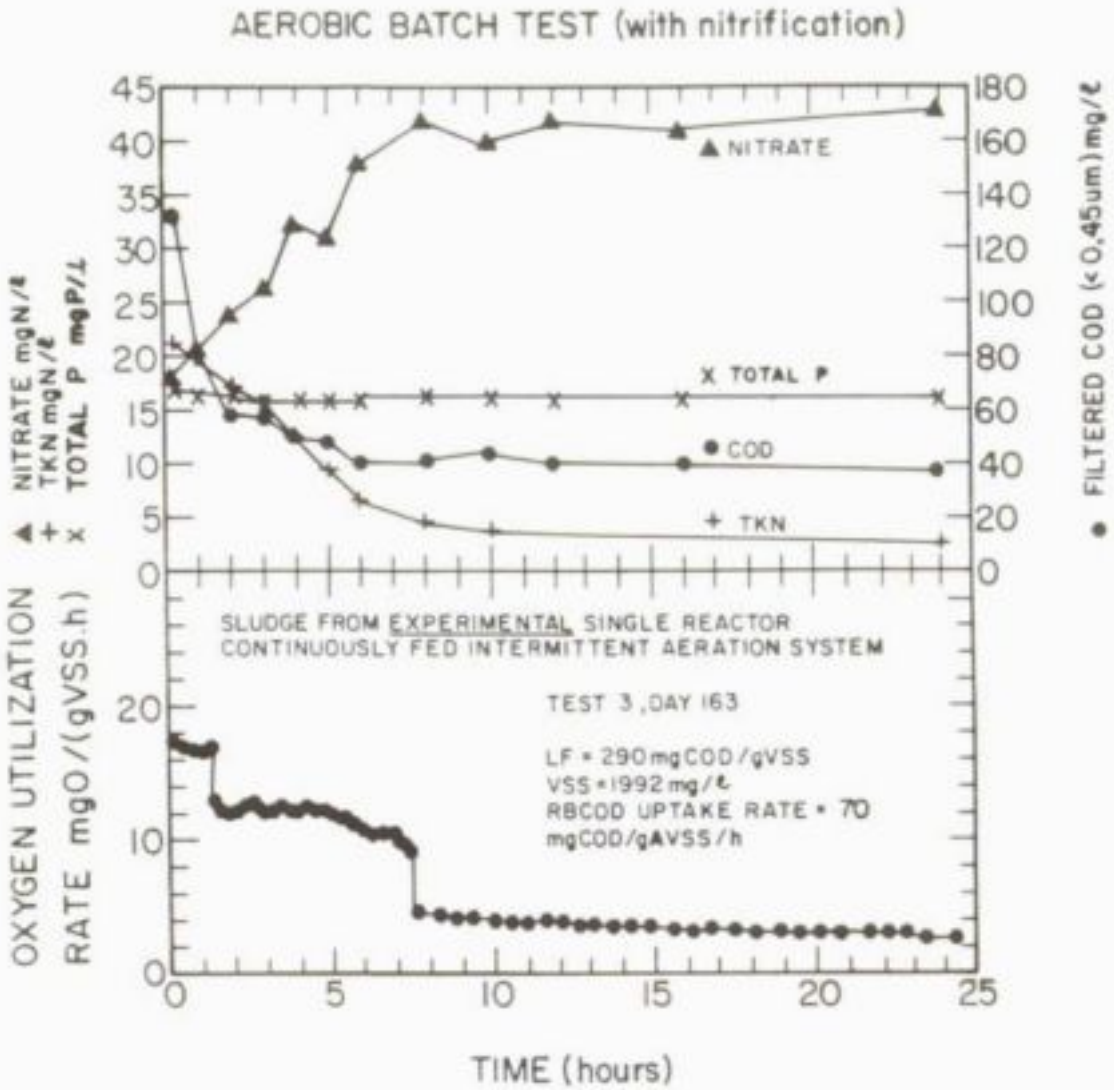


Fig 7.7: *Oxygen utilization rate [OUR in mgO/(gVSS.h)] (bottom), and soluble COD (<0,45μm), TKN, nitrate (as N) and total phosphorus (as P) concentrations (top) in the third aerobic batch test (with nitrification) (day 163) at a load factor (LF) of 290 mgCOD/gVSS on sludge harvested from the Experimental single reactor continuously fed intermittent aeration system. Note that the RBCOD uptake rate (calculated from the soluble COD concentrations) is slow at 70 mgCOD/(gAVSS.h) indicating the absence of a selector effect.*

For the next 32 days the systems were carefully observed to check whether or not the filamentous populations would become similar. When this did not happen, on day 302 the sludges were mixed and divided equally between the two systems. After mixing, the DSVI in both systems was around 310 mℓ/g (see Fig 7.3c).

On day 304 the air supply to one of the systems, in this instance the Control system, was changed from intermittent to continuous. The DSVI decreased rapidly from 317 mℓ/g to 104 mℓ/g in only 10 days and thereafter continued to decline, but more slowly so that by day 350 i.e. 46 days after changing to continuous aeration, the DSVI was 60 mℓ/g. The DSVI remained at this level until the end of the experiment on day 362. Over the same period, the DSVI in the Experimental system (intermittent aeration), initially increased to 371 mℓ/g, then decreased to around 200 mℓ/g and then increased again to 340 mℓ/g by the end of the experiment (day 362).

7.4.3 Conclusions

From the experiments with the single reactor continuously fed intermittent (on occasion continuous) aeration systems, the following was concluded:

(1) Intermittent aeration in continuously fed completely mixed systems, with short alternating anoxic-aerobic periods, sustain the growth of low F/M (long sludge age) filaments *M.parvicella*, 0092, 0041, 0675, 0914 and 1851, to give rise to DSVI's of 200 to 500 mℓ/g. The very high DSVI's usually were principally due to *M.parvicella*.

(2) changing from intermittent to continuous aeration (2-4 mgO/ℓ) reduces the low F/M filament abundance, to give DSVI's as low as 60 mℓ/g *in the absence of a selector effect.*

(3) No problems with *S.natans* bulking were encountered in the systems even when the feed lines were not regularly cleaned, indicating that long (-60-70%) anoxic conditions inhibit the growth of this filament even though the system is fed (and possibly seeded) during short aerobic periods.

(4) Having developed a laboratory scale system other than nutrient (N and P) removal ones, allowed checking whether or not the selector effect controls low F/M filament proliferation.

An investigation into the influence of the selector effect (as stimulated by aerobic selectors) on the low F/M filaments in continuously fed intermittent aeration systems is presented in the next chapter (8).

CHAPTER 8

AEROBIC SELECTORS IN ANOXIC/AEROBIC SYSTEMS

8.1 INTRODUCTION

Up to this stage of the investigation it has not yet been possible to come to explicit conclusions on the efficacy of selectors, aerobic or anoxic, for controlling bulking by low F/M filaments because these filaments could be sustained in aerobic laboratory scale systems wherein this could be tested (see Chapters 5 and 6). However, from the work reported in the previous chapter, it was found that continuously fed completely mixed (CFCM) single reactor systems operated with intermittent aeration (to induce short alternating anoxic-aerobic states), did produce bulking sludges with low F/M filaments, principally *M.parvicella* and 0092. These systems now provided an opportunity to test the effect of incorporating selectors on low F/M filament proliferation.

8.2 EXPERIMENTAL INVESTIGATION

8.2.1 System set-up

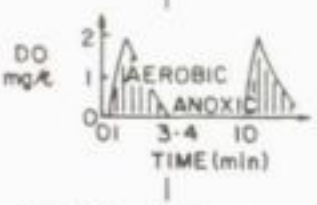
Two parallel systems were set up, both single continuously fed completely mixed reactor systems with volume 7,5ℓ, receiving a constant 10ℓ/d influent flow of raw sewage with a mean COD of 500 mg/ℓ from Mitchell's Plain plant (see Table 8.1). The systems were operated at sludge age 20 d and temperature 21°C with an aeration pattern to induce an aerobic state for 3-4 minutes and an anoxic state for 6-7 minutes in a 10 minute cycle (this set-up was the same as that in the intermittent aeration experiments described in Chapter 7, Section 7.4). To start up the systems, the two sludges from the intermittent aeration systems described in Chapter 7 were mixed and divided equally between the two systems. The initial DSVI's (day 1) in both systems were 190 mℓ/g (Fig 8.1). In operation, nitrification was virtually complete, and to ensure that sufficient nitrate was present so that the systems remained anoxic throughout the unaerated periods, ammonia was added to the influent (before sampling and therefore is reflected in the influent TKN concentration, Fig 8.2).

The two systems were operated for 130 days. The day to day performance of the two systems i.e. influent and effluent COD, total phosphorus (as P), nitrate (as N) and TKN concentrations, are shown graphically in Fig 8.2.

After 21 days of operation, the DSVI in both systems had increased from 190 to 340 mℓ/g (Fig 8.2). On day 21, two 250 mℓ aerated selectors were installed in series ahead of the intermittently aerated main reactor of one of the systems. The first selector received the influent and underflow streams: the effluent of the first selector passed to the second and the effluent to the second selector passed to the main reactor.

The size of the selectors was based on the uptake rate of RBCOD measured in the aerobic intermittently fed fill-and-draw (IFFD) system reported in Chapter 5. With the aid of this uptake rate, taking note of the concentration of RBCOD in Mitchell's Plain raw sewage and the system parameters, the fractional size of the selector to remove more than 95% of the RBCOD was calculated to be 1/30th of total process

Table 8.1: Operating parameters and conditions for two single reactor continuously fed completely mixed intermittent aeration systems, one with aerobic selectors (Experimental, EXP) and one without aerobic selectors (Control, CTRL) (Experimental, EXP and Control, CTRL).

System	EXP	CTRL
Operating conditions	Continuously fed, single reactor	
	with selectors (from day 21)	without selectors
Graphical representation		
Aeration - Main reactor	intermittent	intermittent
Selector	continuous	-
DO concentration (mg/ℓ)		
Main reactor	0 - 2	0 - 2
Selector	2 - 4	-
DO profile for main reactor		
Sewage source	Mitchell's Plain raw	
Mass of COD fed/d (mg/d)	5000	5000
Volume of feed (ℓ/d)	10	10
Concentration (mg/ℓ)	500	500
Influent TKN (mgN/ℓ)	60 - 100	60 - 100
Sludge age (d)	20	20
Temperature (°C)	21	21
Volume of main reactor (ℓ)	7,5	7,5
Selectors - from day 21	each 0,25	-
- from day 73	0,10; 0,25	-
MLVSS concentration (mg/ℓ)	2800	2800
MLSS concentration (mg/ℓ)	3500	3500
F/M [mgCOD/(mgVSS.d)]	240	240
Hydraulic retention time		
Main reactor (h)	18	18
Selectors - from day 21 (min)	each 36	-
- from day 73 (min)	14; 36	-
Underflow recycle ratio	1:1	1:1
pH of mixed liquor	7,3 - 7,5	7,3 - 7,5

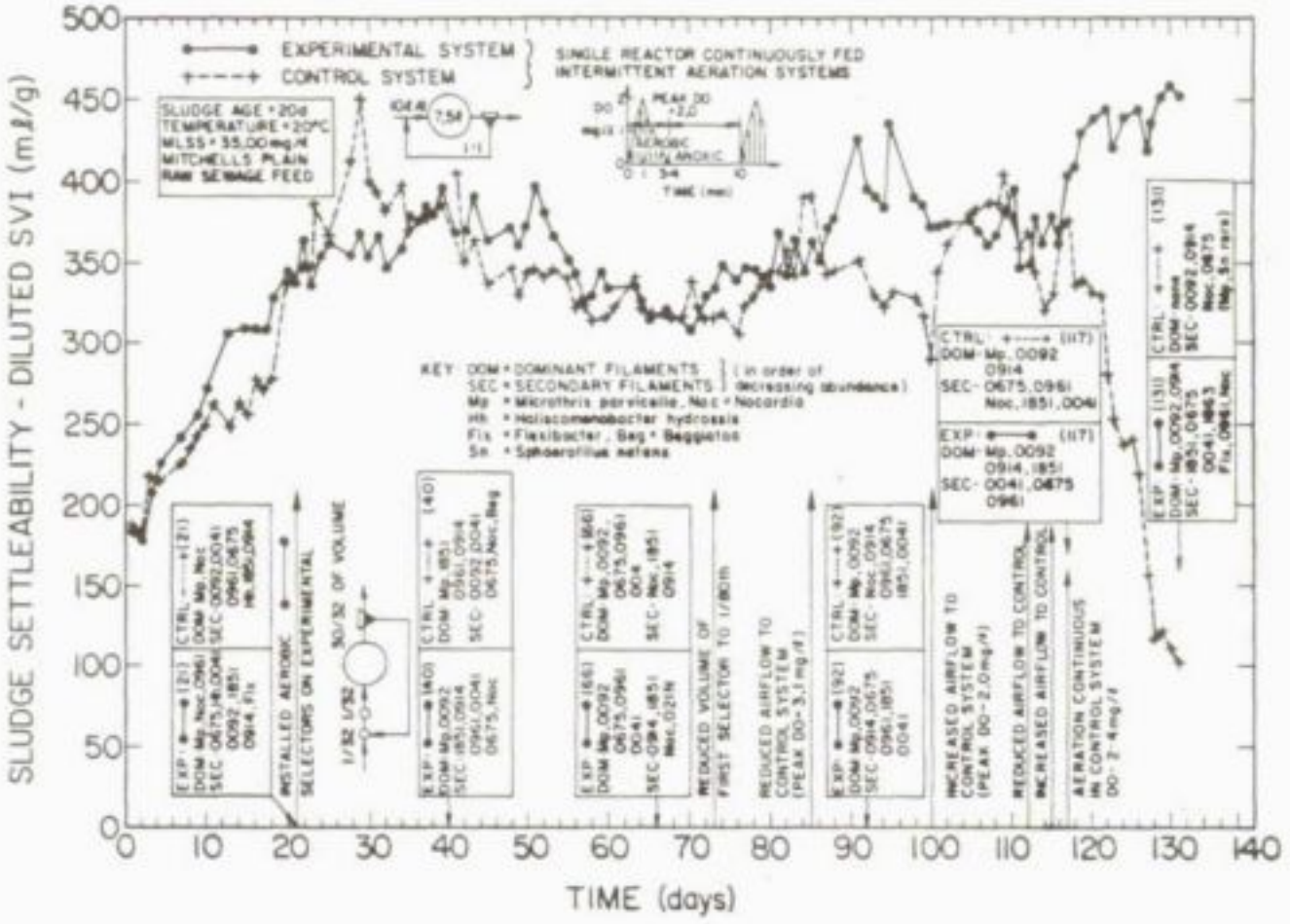


Fig 8.1: *Sludge settleability in DSVI with time in two (Experimental and Control) single reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20 days) and temperature (20° C). Note that installation of aerobic selectors in the Experimental system (correctly sized) (on day 21) did not ameliorate bulking by low F/M filaments over a period of 5 sludge ages (day 21-117) but changing the aeration in the Control system from intermittent to continuous, causes a sharp decline in DSVI in less than 1 sludge age (day 117 to 131) and a concomitant decrease in low F/M filaments.*

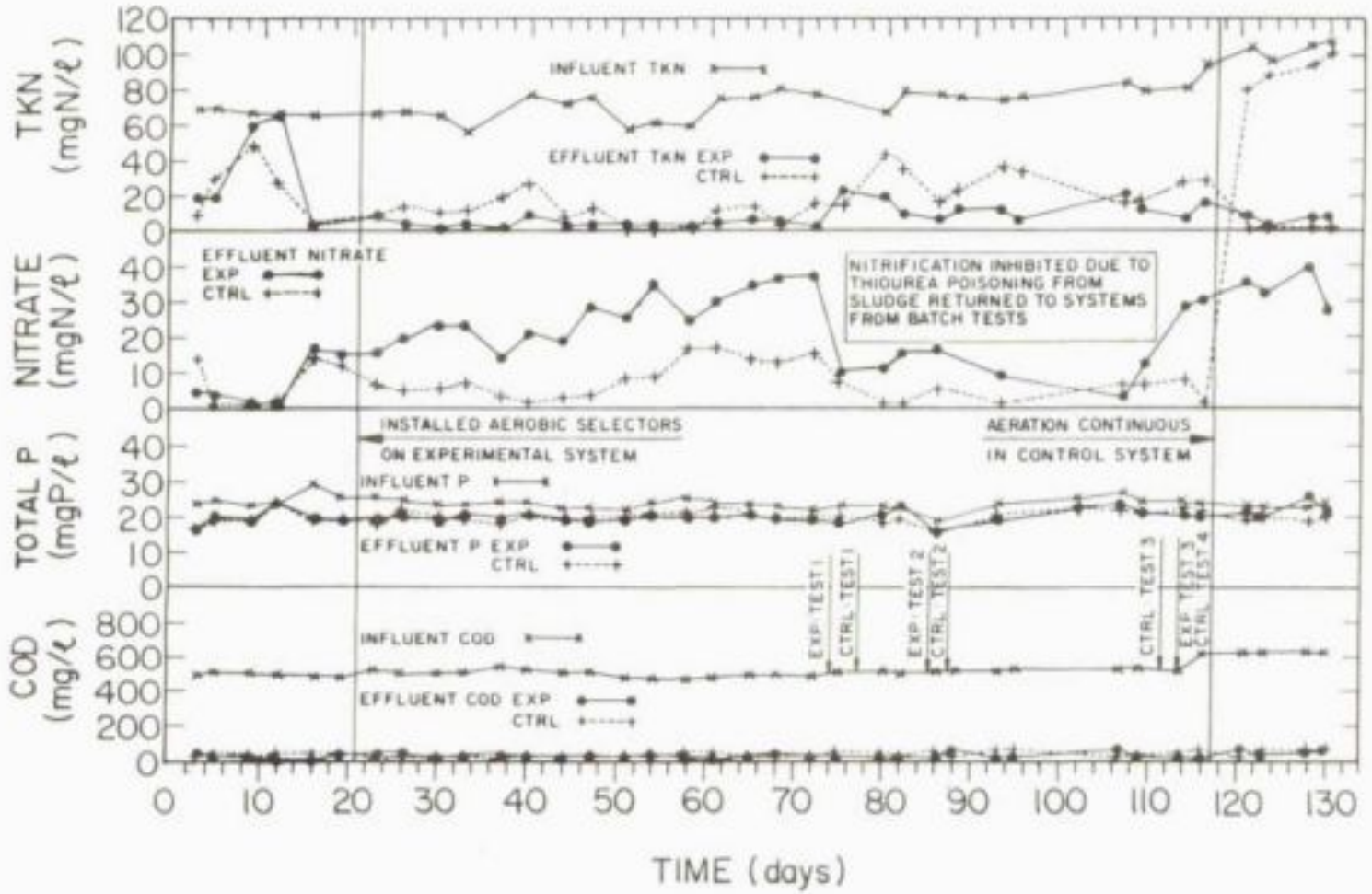


Fig 8.2:

Influent and effluent COD (lower), total phosphorus (as P) (mid lower), nitrate (as N) (mid upper) and TKN (upper) concentrations with time in two, one Experimental (EXP) and one Control (CTRL) single reactor continuously fed intermittent aeration systems fed the same sewage (Mitchell's Plain raw) and operated at the same sludge age (20d) and temperature (21° C). Note that (1) the installation of the aerobic selectors (day 21) causes an increase in effluent nitrate concentration in the Experimental system due to utilization of influent readily biodegradable COD in the aerobic selector, and (2) switching from intermittent to continuous aeration in the Control system (day 117) causes a dramatic increase in the effluent nitrate concentration due to the absence of denitrification.

volume i.e. 250 mℓ in 7,5ℓ. To take into account variability in the RBCOD uptake rate and in the influent RBCOD fraction of the sewage, *two* 250 mℓ selectors *in series* were installed without reducing the volume of the main reactor. Consequently two selectors were each 1/32nd fractional volume. The DO concentration in each selector was maintained between 2 and 4 mg/ℓ. For convenience the system with the selector reactors will be called the Experimental (EXP) system and the system without selector reactors the Control (CTRL) system.

8.2.2 Results

After installation of the aerobic selectors in the Experimental system, both Experimental and Control systems were operated for a period of 5½ sludge ages, from day 21 to 130. During this period (1) tests were undertaken to establish whether the selector effect had been induced in the Experimental system, and (2) the DSVI's and filament compositions of the two systems were monitored.

Selector effect:

Three criteria have been identified to assess whether or not a selector effect has been induced in a sludge, i.e.

(i) high removal of soluble biodegradable COD (or RBCOD) in the selector

(ii) presence of significant number of *Zoogloea* colonies

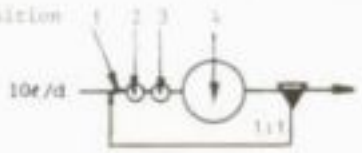
(iii) high initial OUR and soluble COD (RBCOD) uptake rate under batch conditions.

These three criteria were evaluated by (i) measuring the soluble (0,45μm filtered) COD profile through the Experimental system, (ii) microscopic examination of and (iii) a series of aerobic batch tests on sludge harvested from the Experimental and Control systems. On day a72, the soluble (0,45μm filtered) COD concentration was measured in the influent and each of the selector and main reactors of the Experimental system (see Table 8.2). From these measurements, a profile of soluble COD concentrations through the system was established, from which it was calculated that none of the soluble biodegradable COD entered the main reactor (Table 8.2). Microscopic examination of the sludges in the two systems on day 79 indicated the sludge in the Experimental system contained significantly more *Zoogloea* colonies compared to the sludge in the control system. On days 74 and 77 aerobic batch tests (nitrification inhibited) were conducted on sludges harvested from the Experimental and Control systems respectively during which the OUR was measured for 24 h (Fig 8.3); from these tests, it can be seen that the Experimental system sludge, the initial OUR was more than 1,5 times higher than that in the Control system sludge. From all these observations it was concluded that the selector effect had been induced in the Experimental system sludge.

In order to check that a reduced selector volume possibly may enhance the selector effect, the first selector reactor of the Experimental system was reduced in volume from 250 mℓ to 100 mℓ on day 72. [The batch tests (day 74) and microscopic examination (day 79) above were done so soon after this change (day 72) that it is unlikely that the smaller first selector volume significantly contributed to the results obtained]. After this change soluble COD profiles in the Experimental system were measured regularly (days 84, 104 and 121; see Table 8.2); as previously, these indicated that

Table 8.2: Soluble (<0,45µm filtered) COD (SCOD) concentration in the influent selector reactors and main reactor of the Experimental system on days 72, 84, 104 and 121 and soluble COD removals in these reactors.

Position/Day	72	84	104	121
	mgCOD/ℓ	mgCOD/ℓ	mgCOD/ℓ	mgCOD/ℓ
1) Into 1st selector	124,5	108	104	160
2) In 1st selector	65,7	76	74	90
3) In 2nd selector	57,5	54	66	74
4) In Main reactor	57,5	54	60	70
Reduction in				
1st Selector	57,8	32	30	70
2nd Selector	8,2	22	8	15
1st and 2nd Selector	66,0	54	38	87
Main reactor	0,0	0	0	4



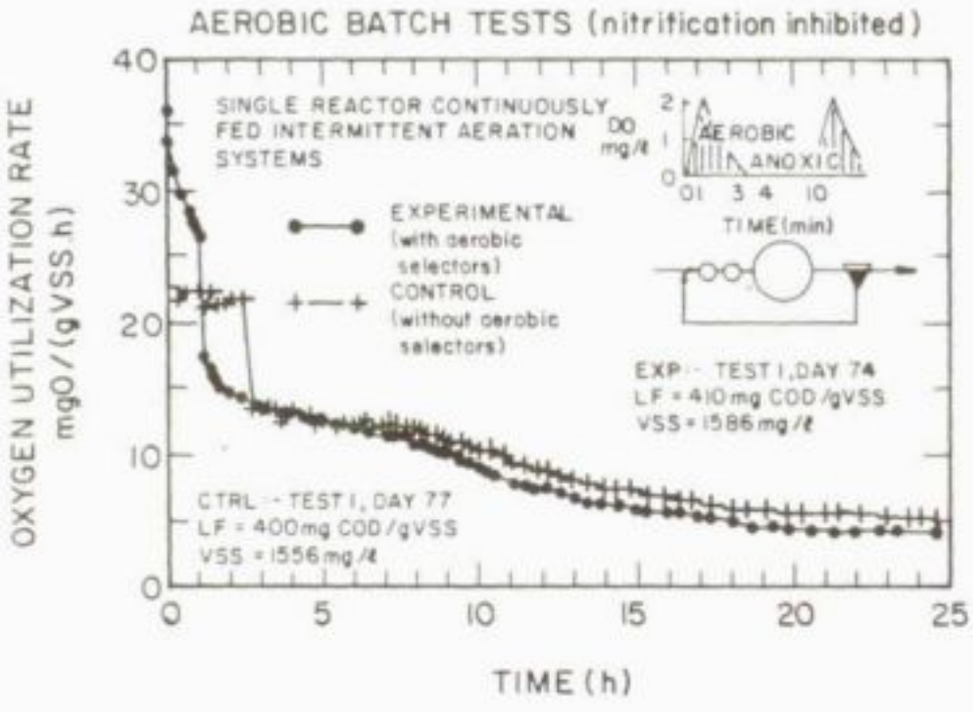


Fig. 8.3: *Oxygen utilization rate (OUR) in mgO/(gVSS.h) in the first set of aerobic batch tests (nitrification inhibited) on days 74 and 77 at the same Load Factor (LF ≈ 400 mgCOD added per gVSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (Experimental, EXP; •——•, day 74), the other without aerobic selectors (Control, CTRL; +----+, day 77). Note that the initial OUR is about 1,6 times higher in the Experimental system sludge (with selectors) than that in the Control system sludge (without selectors).*

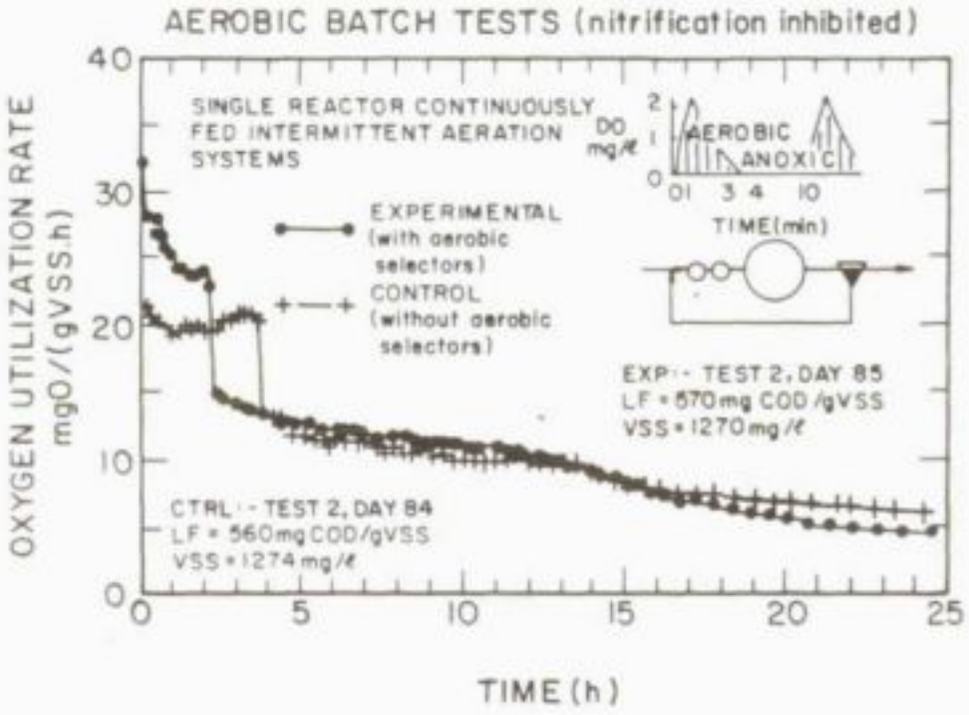


Fig. 8.4: *Oxygen utilization rate (OUR) in mgO/(gVSS.h) in the second set of aerobic batch tests (nitrification inhibited) on days 85 and 84 at the same Load Factor (LF ≈ 560 mgCOD added per gVSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (Experimental, EXP; ●——●, day 85), the other without aerobic selectors (Control, CTRL; +——+, day 84). Note that the initial OUR is about 1,6 times higher in the Experimental system sludge (with selectors) than that in the Control system sludge (without selectors).*

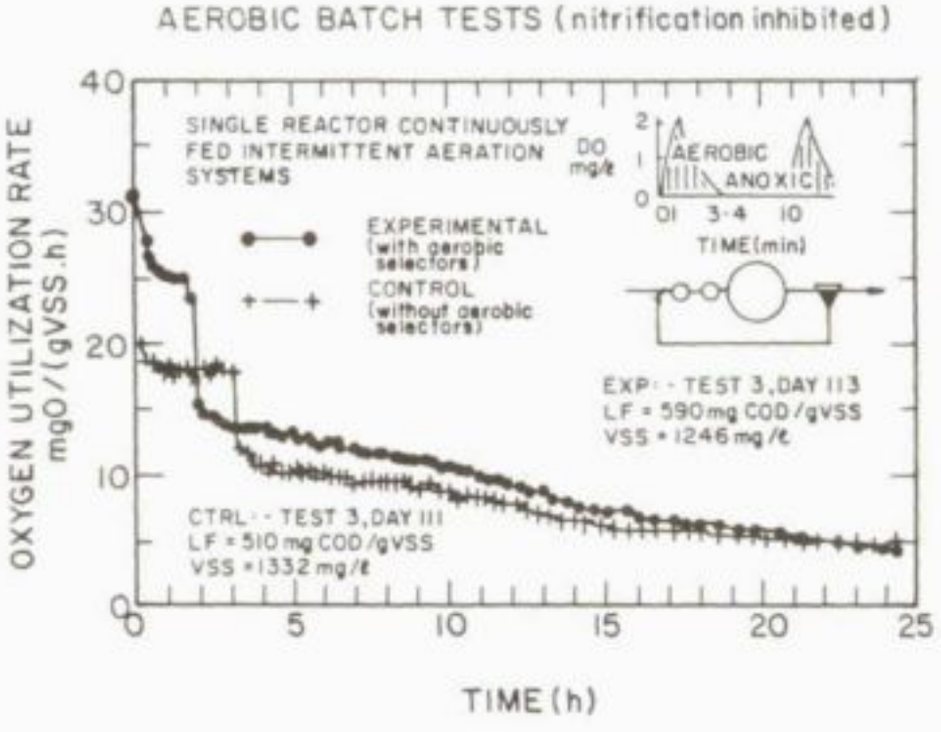


Fig. 8.5: *Oxygen utilization rate (OUR) in mgO/(gVSS.h) in the third set of aerobic batch tests (nitrification inhibited) on days 113 and 111 at the same Load Factor (LF ≈ 550 mgCOD added per gVSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (Experimental, EXP; •——•, day 113) the other without aerobic selectors (Control, CTRL; +----+, day 111). Note that the initial OUR is about 1,6 times higher in the Experimental system sludge (with selectors) than that in the Control system sludge (without selectors).*

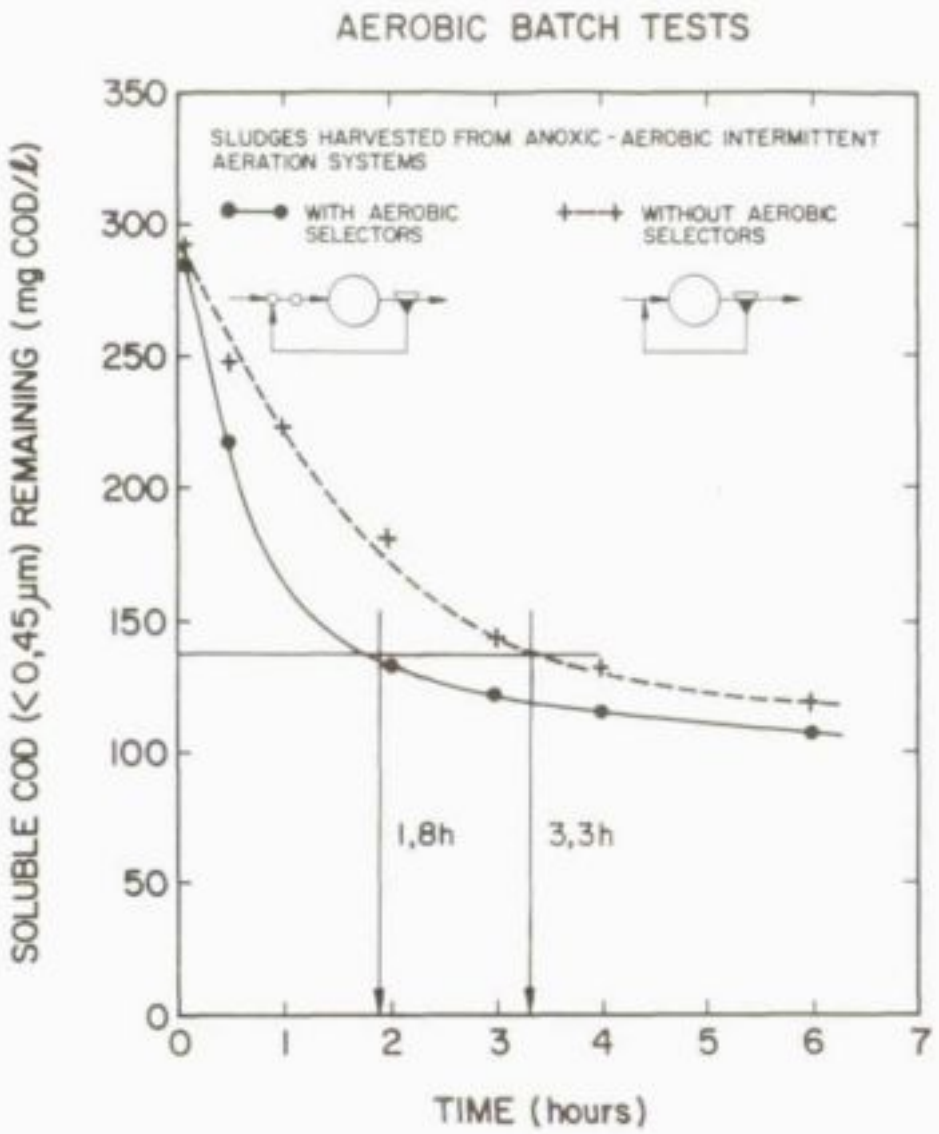


Fig 8.6: *Soluble COD (0,45µm filtered) concentration versus time in the fourth set of aerobic batch tests (nitrification inhibited) on day 113 at the same Load Factor (LF ≈ 570 mgCOD added per gVSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (Experimental, EXP; •——•, day 113), the other without aerobic selectors (Control, CTRL; +----+, day 113). Note that the soluble COD is taken up about 1,8 times faster by the Experimental system sludge (with selectors) than by the Control system sludge (without selectors) (see also Fig 8.7).*

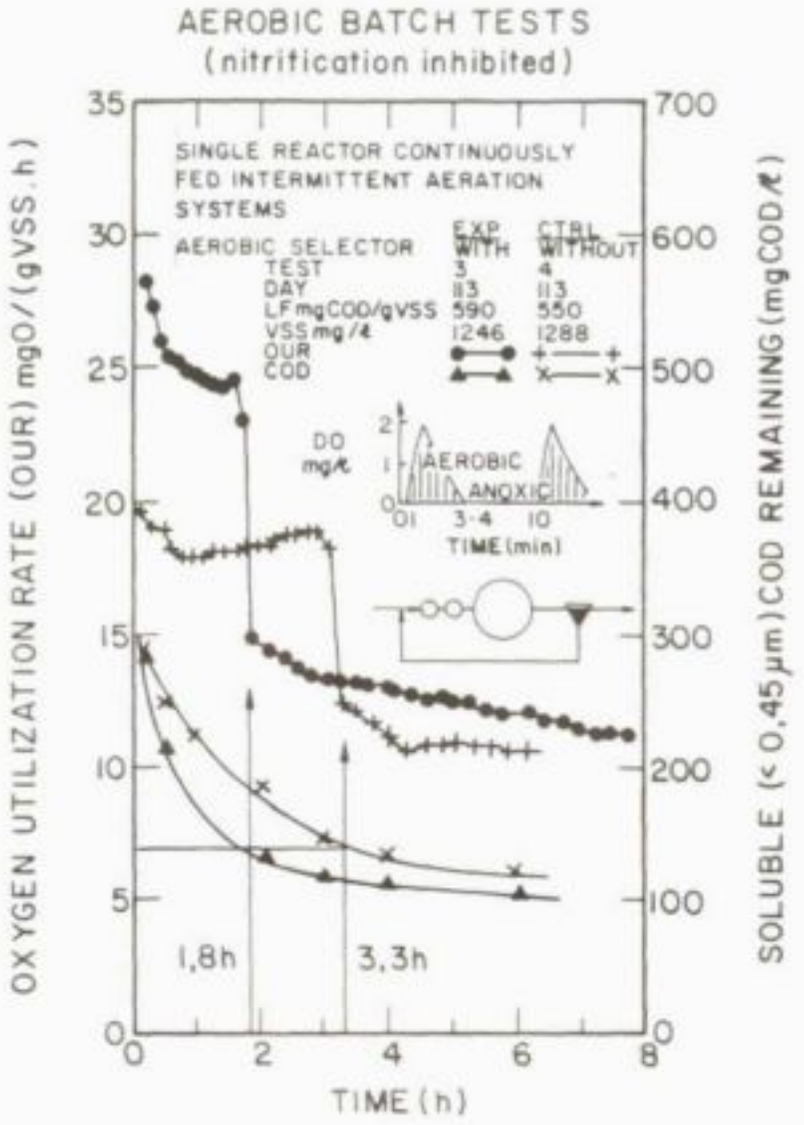


Fig 8.7: *Oxygen utilization rate [OUR, in mgO/(gVSS.h)] and soluble COD (<0.45µm) concentration in the fourth set of aerobic batch tests (nitrification inhibited) on day 113 at the same Load Factor (LF ≈ 570 mgCOD added per gVSS) on sludges harvested from two single reactor continuously fed intermittent aeration systems, one with aerobic selectors (Experimental, EXP; •——•, 113), the other without aerobic selectors (Control, CTRL; +----+, day 113). Note that (i) the initial OUR and soluble COD uptake is about 1,4 times faster in the Experimental system sludge (with selectors) than in the Control system sludge (without selectors) and (ii) the precipitous decrease in OUR occurs at approximately the time as the depletion of the biodegradable soluble (or readily biodegradable) COD.*

practically all the RBCOD was removed in the selector reactors. Batch tests nitrification inhibited) were conducted on the sludges harvested from the Experimental and Control systems (days 85 and 113 on the Experimental and 84 and 111 on the Control; see Figs 8.4 and 8.5. From these tests, the initial OUR in the Experimental system was more than 1,6 times that in the Control system. In the batch test on the Experimental system on day 113 and in an additional test on the Control system sludge on day 113, the soluble COD concentration and OUR was measured for the first 6 h (see Figs 8.6 and 8.7). These results confirm that not only is the initial OUR in the Experimental system sludge about 1,8 times higher than that in the Control system sludge, but also the soluble COD uptake rate. These tests (Fig 8.7) indicate that the initial high OUR in both the Experimental and Control systems decreased precipitously at approximately the same time as the RBCOD was depleted. Microscopic evaluation from days 92 to 131 indicated that the sludge in the Experimental system continued to contain significantly more *Zoogloea* colonies than the sludge in the Control system.

From the above it can be seen that in terms of the criteria for evaluating whether or not a selector effect is present in a sludge, the selector reactors in the Experimental system did indeed induce the selector effect and therefore it can be concluded that the selectors were correctly sized.

Sludge settleability

Two and a half sludge ages (50 d) after installing the selectors (that is, on day 71) the DSVI in both systems was still the same; each had a DSVI around 320 mℓ/g (Fig 8.1). Microscopic examination of the sludges indicated that the filaments in the sludge also were essentially the same and the dominant filaments, in decreasing order of abundance, were *M.parvicella*, 0092, k0675, 0961 and 0041 (see Fig 8.1).

After reducing the selector volume on day 72, the DSVI in the Experimental system increased from 349 to over 400 mℓ/g (by day 131). During this period, in the Control system the DSVI also increased and decreased (see below) but remained above 290 mℓ/g (see below.

Microscopic examination of the sludges from the Control and Experimental systems with reduced selector volume (on days 79, 92, 109, 117) indicated that the dominant filamentous populations in both systems remained essentially similar; in decreasing order of dominance, the filaments in the Control system were *M.parvicella*, 0092, 0914 and 0961 and in the Experimental system *M.parvicella*, 0092, 0914 and 1851 (see Fig 8.1).

In Chapter 7, in the intermittent aeration experiments, it was noticed that the mass of oxygen input per 10 minute cycle appeared to influence the sludge settleability. In an attempt to evaluate the influence of the oxygen input on the DSVI, on day 85 the airflow rate to the Control system was reduced so that during the air-on period the DO rose only to 1,3 instead of 2,0 mg/ℓ. The system responded with a decline in DSVI, from 392 to 289 mℓ/g by day 100 (Fig 8.1). On day 100, the airflow rate was increased so that the peak DO increased to 2,3 mg/ℓ. The system responded with an increase in DSVI from 289 to 386 mℓ/g on day 107. This behaviour was similar to that observed in the intermittently aerated systems discussed in Chapter 7. From this, it appears that too little oxygen input adversely affects the proliferation of some of the low F/M filaments, in particular *M.parvicella*. The lower oxygen input is reflected in

the higher effluent TKN concentration of the Control system (Fig 8.2) in that nitrification was not complete. However, part of increase in effluent TKN also is due to the return to the system of mixed liquor containing thiourea from the nitrification inhibited batch tests.

On day 117, the aeration pattern in the Control system was changed from intermittent to continuous and the DO was controlled between 2 and 4 mg/ℓ. At this time the dominant filaments in the Control system were *M.parvicella* (abundant), 0092 (very common) and 0914 (common) and the secondary filaments in decreasing order of abundance were 0675, 0961, *Nocardia* sp., 1851 and 0041 (see Fig 8.1). The DSVI in the Control system decreased rapidly from 376 mℓ/g on day 117 to 103 mℓ/g on day 132, (15 days) (see Fig 8.1), at which time the filaments in the Control system were 0092 (some to common), 0914 (some), *Nocardia* sp. (some), 0675 (some) and *M.parvicella* (few). Over the same period (day 117 to 132) in the Experimental system, in which intermittent aeration was maintained in the Main reactor, the DSVI remained high (> 400 mℓ/g), the dominant filaments were *M.parvicella*, 0092, 0914 with secondary filaments 1851, 9675, 0041, *Nocardia* sp. and 0961.

8.3 CONCLUSIONS

This experiment demonstrates that:

(1) In long sludge age single reactor completely mixed continuously fed (constant load) systems with intermittent aeration (7 min anoxic, 3 min aerobic), low F/M filaments proliferated.

(2) Incorporation of a correctly sized aerobic selector which stimulated a selector effect at the head of the system, receiving the influent and underflow recycle, did *not* control the proliferation of the low F/M filaments viz *M.parvicella*, 0092, 0914.

(3) The selector effect as stimulated by alternating feed-starve conditions imposed by the aerobic selectors does not appear to be valid for controlling bulking by low F/M filamentous organisms.

(4) Changing the aeration pattern from intermittent (anoxic/aerobic) to continuous (aerobic) causes amelioration (DSVI from 400 mℓ/g down to less than 100 mℓ/g) of bulking by low F/M filaments.

(5) Because aerobic selectors (and anaerobic reactors, see Chapter 5, Section 5.4.2) invoke removal of RBCOD by floc formers and this does not control low F/M filament proliferation, it would appear that the influent RBCOD does not play an important role in bulking by low F/M filaments.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 SCOPE OF RESEARCH

In this research, three areas of filamentous bulking control were investigated; (1) survey of severity of bulking in nutrient (N and P) removal plants and identification of causative filaments, (2) non-specific bulking control with chlorination in a nutrient removal system, and (3) specific bulking control methods to ameliorate bulking by the filamentous organisms causing bulking in South African activated sludge plants. The conclusions from this research are set out below.

9.2 SURVEY OF FILAMENTOUS BULKING

In the survey, which covered 33 out of about 45 nutrient (N and P) removal plants in south Africa, the six most frequently dominant filaments were found to be 0092 dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *Microthrix parvicella* in 33%, 0914 in 33% and 1851 in 21%. In a different order these 6 filaments are also the 6 most frequently dominant ones in all (96) activated sludge plants, most of which are nitrogen (N) or nutrient (N and P) removal plants (Blackbeard *et al.*, 1988). Four of these six filaments sort into the low F/M (low Food/Micro-organism ratio or long sludge age) group of filaments. Interestingly *Sphaerotilus natans* was not, and *Thiothrix* only rarely, identified as a dominant filament in South African plants.

9.3 CHLORINATION BULKING CONTROL IN A NUTRIENT REMOVAL SYSTEM

Chlorination bulking control was investigated on a Modified UCT (University of Cape Town) nutrient removal system with a bulking sludge caused by filaments typically found in nutrient removal systems i.e. 0092, *M.parvicella* and 0914. By following the procedure set out in the manual on the "Causes and Control of Filamentous Bulking and Foaming" by Jenkins *et al.* (1984), chlorination was found to be successful (DSVI decreased from 230 to 48 $m\ell/g$) and it did not significantly affect biological N and P removal even at a relatively high dosage rate of 8 $gC\ell/(kgMLSS.d)$. However, persistent dosing (19 days continuously) eventually did significantly reduce the denitrification and excess P removal (see Lakay *et al.*, 1988), but such persistent dosing is unlikely to be required in full scale application.

9.4 SPECIFIC BULKING CONTROL

The promoted specific bulking control method for low F/M filaments is system configuration 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 systems apparently affect control over the low F/M filaments is that under high readily biodegradable COD (RBCOD) concentrations the floc formers have, or develop, a

higher rate of RBCOD utilization than the filamentous organisms and hence preferentially remove available RBCOD from the filamentous organisms. These higher rates are developed in the 3 types of system described above. This mechanism for controlling the low F/M filaments, and the systems in which it develops were investigated and the following conclusions emerged from this work.

9.4.1 Stimulation of selector effect

The alternating feed-starve conditions imposed by (1) intermittent feeding (once daily) to completely mixed reactor systems (batch fed), either fully aerobic or anoxic-aerobic [intermittent non-aeration – 1 h anoxic (DO = 0 mg/ℓ), 3 h aerobic (DO = 2-4 mg/ℓ) with feed added alternatingly, on one day when aerobic, on the next when anoxic] and by (2) aerobic selector reactors incorporated in continuously fed completely mixed systems, either with fully aerobic or intermittently aerated (air on 1 min, off 9 min so that DO > 0,2 mg/ℓ for 3-4 min and < 0,2 mg/ℓ for 6-7 min in 10 m cycle main reactors, stimulated in the mixed liquor a high readily biodegradable (or dissolved, < 0,45μm filtered) COD (RBCOD) uptake rate. The RBCOD uptake rate was 2 to 3 times higher than that in systems which did not have alternating feed-starve conditions, such as continuously fed completely mixed systems without selectors. If the conditions during which the RBCOD was taken up rapidly were aerobic, the high RBCOD uptake rate gave rise to an associated high initial oxygen uptake rate under batch conditions; if the conditions were anoxic, it gave rise to an associated high (initial) nitrate uptake rate under batch conditions.

For convenience, a sludge in which a high RBCOD uptake rate has been stimulated, will be said to have acquired a "selector effect".

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

9.4.2 Purely aerobic conditions appear to ameliorate bulking by low F/M filaments

Low F/M filament bulking sludges (diluted sludge volume index, DSVI > 250 mℓ/g) containing, usually, in varying proportions 0092, *M.parvicella*, 0914, 0675, 1851 and 0041 filaments), from long sludge age full scale (N removal) plants, when used to start up laboratory scale long sludge age (> 15 d) activated sludge systems under *fully aerobic conditions*, invariably ceased bulking (DSVI < 80 mℓ/g) within a month irrespective of whether or not the system incorporated an aerobic selector or whether the system was intermittently fed or continuously fed, i.e. irrespective of whether or not the system stimulated a selector effect. This also was the case in two alternating non-aeration systems [anoxic 1 h (DO = 0 mg/ℓ) - aerobic 3 h (DO = 2-4 mg/ℓ], one continuously fed (no selector effect), the other intermittently fed (with selector effect) (batch fed once daily, with feed aded alternatingly, on one day when aerobic on the next when anoxic). Evidently, in long sludge *fully aerobic* systems, and in the particular alternating non-aeration systems, the selector effect was irrelevant because the low F/M filament growth was suppressed both when the selector effect was present or absent.

9.4.3 Bulking caused by *Sphaerotilus natans*

In the fully aerobic, and in the particular alternating non-aeration long sludge age (low F/M) systems, in which there was no selector effect (i.e. in continuously fed completely

mixed single reactor systems, either fully aerobic or anoxic-aerobic with 1 h non-aeration followed by 3 h aeration in a 4 h cycle), when bulking was observed, it was *not* due to proliferation of 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. *S.natans* has not, and *Thiothrix* only rarely, been observed to cause bulking in full scale long sludge age plants in South Africa, [most of which are nitrogen (N) or nutrient (N and P) removal ones].

9.4.4 *S.natans* bulking apparently caused by seeding

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

9.4.5 Selector effect controls *S.natans* and *Thiothrix*

Aerobic selectors and intermittent (batch) 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. 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 proliferation.

According to the literature, control of *S.natans* growth by aerobic selector reactors in systems with continuous feeding and in systems without selectors but with intermittent feeding i.e. in systems that stimulate a selector effect, probably takes place by competitive removal of soluble biodegradable COD [or equivalently the readily biodegradable COD (RBCOD)] by floc formers. Selector reactors and intermittent feeding cause the specific substrate uptake rate to increase up to 2-3 times higher than the rate in systems with continuous feeding but without selectors. The increase most likely is due to selection of floc formers with high RBCOD uptake rates, or adaptation of existing floc formers to acquire a high RBCOD uptake rate. The specific substrate uptake rate of *S.natans* is unlikely to change appreciably as it does not possess the diversity of the floc former population. Consequently the selected floc formers out-compete *S.natans* thereby effectively limiting substrate acquisition by *S.natans*, and curtailing their proliferation in the mixed liquor.

9.4.6 Low F/M filaments proliferated in nutrient removal systems but not *S.natans* and *Thiothrix*

From (9.4.2) above, low F/M filaments *did not* proliferate in the laboratory scale systems, neither in the fully aerobic ones (irrespective of whether these systems were continuouslу or intermittently fed), nor in the particular anoxic-aerobic ones [with alternating non-aeration (anoxic 1 h (DO = 0 mg/ℓ) – aerobic 3 (DO = 2-4 mg/ℓ) one continuously fed, the other intermittently fed (once daily) alternating on one day at the time when it was anoxic, on the next when it was aerobic]. In contrast, in nutrient removal systems (i.e. systems with anaerobic-anoxic-aerobic zones which follow sequentially in usually single or multi reactors in series and incorporating appreciable unaerated sludge mass fractions - 50%) both at laboratory and at full scale, low F/M filaments *did* proliferate and cause bulking problems; indeed, of the laboratory systems

operated at the time (which were the intermittently and continuously fed systems described above and nutrient removal ones) nutrient removal systems were the only ones wherein the low F/M filaments proliferated. In nutrient removal systems at laboratory scale, *S.natans* did not, and *Thiothrix* only rarely[1] cause bulking, even when the feed lines were not regularly cleaned; surveys on full scale nutrient removal plants also have indicated that *S.natans* did not, and *Thiothrix* only rarely cause bulking.

9.4.7 Anaerobic reactors appear to ameliorate or totally suppress *S.natans* (and *Thiothrix*) bulking

From (9.4.6) above, it can be hypothesized that the anaerobic reactor in nutrient removal plants operates as a kind of selector reactor against *S.natans* (and possibly also *Thiothrix*) proliferation. This hypothesis finds support from the laboratory experiments of Wanner *et al.*, (1987a, 1987b). A possible explanation for this is that *S.natans* is an obligate aerobe (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 by either (1) removing RBCOD under conditions in which *S.natans* cannot function (anaerobic or anoxic reactors) or (2) stimulating high RBCOD uptake rates 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, and anoxic and aerobic *selectors* (though not anoxic reactors) 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).

9.4.8 Selectors as a means of ameliorating bulking by low F/M filaments falls into question

It was pointed out above that aerobic and anoxic selectors and anaerobic reactors control the proliferation of the filaments *S.natans* and *Thiothrix* (021N probably can be included because this filament is controlled by aerobic and anoxic selectors; van Niekerk, 1985; Shao, 1986). The suggested mechanism for this is soluble COD, or more correctly RBCOD, removal by floc-formers; in the selectors the RBCOD is removed at a high rate so that the filaments are unable to successfully compete for

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[1]On one occasion when *Thiothrix* (I and II) caused bulking (DSVI - 150 mℓ/g) it was in a modified UCT system receiving sewage that was first passed through an acid fermentation reactor; the acid fermentation significantly increased the sulphide concentration of the influent and probably was the cause of the proliferation of the sulphur containing *Thiothrix* filaments. Low F/M filaments were present also (0914, 0092, 0041, 0675) but were secondary in comparison to the *Thiothrix* spp. (Bagg *et al.*, 1985) (Also see footnote 2 on page 9.5).

RBCOD and in the anaerobic reactor, the RBCOD is removed by polyP organisms, the only organisms that can do this in the absence of oxygen and nitrate. It was also pointed out that low F/M filaments proliferate in nutrient removal systems which means that the anaerobic reactor, and the RBCOD removal that it promotes, is unable[2] to control the proliferation of these filaments. This raises the question whether or not aerobic (and anoxic) selectors, and the RBCOD removal that these promote, are able to control proliferation of low F/M filaments. The literature suggests that aerobic selectors are able to control low F/M filament proliferation but little unambiguous[3] verification of this is available in the literature. Because of the prevalence of low F/M filaments in South African activated sludge plants it was important to check whether or not aerobic (and anoxic) selectors can control low F/M filament proliferation. Before this could be done, it was necessary to devise laboratory systems other than nutrient removal ones, wherein low F/M filaments proliferate. To do this attention was focussed on unaerated/aerated systems, because it was evident that low F/M filaments proliferated in full scale unaerated/aerated systems.

9.4.9 Unaerated/aerated conditions promote bulking by low F/M filaments and confirmation that purely aerobic conditions ameliorate this

Three single reactor systems were started up with a bulking sludge, caused by low F/M filaments, from a laboratory scale nutrient removal (Modified UCT) system. All three systems were operated at the same sludge age (20d) 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

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[2]Albertson (1987), suggests that bulking in many South African nutrient removal systems arises because the anaerobic, anoxic and aerobic zones in these systems are in the form of single completely mixed reactors; if these zones were compartmentalized, bulking would be controlled because F/M gradients would be imposed in the various zones. He does not qualify which filaments are likely to be controlled by this method, but, from experimental evidence on laboratory scale modified UCT systems, this approach is unlikely to be successful for controlling bulking by low F/M filaments: When the anaerobic zone with a mass fraction of 0,16 was compartmentalised into 4 equal sized completely mixed reactors, the DSVI increased steadily from 88 mℓ/g to 164 mℓ/g over a period of 3 sludge ages, caused by the proliferation of low F/M filaments 0092, 0914, *M.parvicella*, 0675, (Bagg *et al.*, 1985); when the first anoxic zone with a mass fraction of 0,14 was in the form of a plug flow reactor, DSVI's over 200 mℓ/g were obtained for periods well in excess of 5 sludge ages, caused by the low F/M filaments 0092, 0041, *M.parvicella* and 0675 (Clayton *et al.*, 1989). In the Kelowna plant, which is a completely compartmentalized nutrient removal system, DSVI's in the range of 200 mℓ/g are obtained. As Albertson suggests this may be due to the practice of acid fermenting primary sludge to augment biological P removal; if septic sewage filaments like *Thiothrix*, 021N or *Beggiatoa* cause the bulking, then this is an acceptable explanation, but if low F/M filaments cause the bulking it would mean that compartmentalization does not control low F/M filaments.

[3]For example, Wheeler *et al.* (1983) report the successful control of low F/M filament 0041 with aerobic selectors in a full scale system. The aeration in the aerobic selector was provided by *additional* aeration so it is possible that the increased aeration may have led to the reduction in 0041 and improvement in settleability.

anaerobic for the first 6 h after feeding and aerobic for 16 h, and finally settling for 2 h. The other intermittently fed system, and the continuously fed system, were maintained aerobic for 24h. In the two aerobic systems (one intermittently fed, the other continuously fed) the DSVI declined steadily from a start-up value of around 200 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 Modified UCT system remained high between 180 and 200 mℓ/g.

These experiments indicate 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 the mixing regime is plug flow (intermittently fed) or completely mixed (continuously fed), and (2) an initial anoxic-anaerobic period of 6 h (principally anaerobic) during which all the RBCOD is removed from the liquid phase, followed by an aerobic period of 16 hours (with 2 hours settling) at a DO of 6 mgO/ℓ, and the anaerobic (9,6 h), anoxic (11,2 h), aerobic (14,4 h) sequence of the parent MUCT system, allows low F/M filaments to proliferate and cause bulking (DSVI remained between 180 and 200 mℓ/g). It is not clear how the continuation of bulking by low F/M filaments in the intermittently fed anaerobic/aerobic systems fits in with the amelioration of bulking observed in the intermittently and continuously fed systems with intermittent non-aeration (1 h anoxic — 3 h aerobic cycles) described earlier in section 9.4.2 above.

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 (as in nitrogen or nutrient removal plants) or in different stages of the same reactor (as in Carousel, Orbal or ditch type plants).

9.4.10 Low F/M filaments proliferate in intermittent aeration systems

In an attempt to grow low F/M filaments in laboratory systems other than nutrient 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 mg/ℓ) were set up to mimic Carousel and Orbal type plants. It was found that in such systems most (but not necessarily all together) of the low F/M filaments proliferated (DSVI > 300 mℓ/g), in particular *M.parvicella* and 0092 but also 0914, 0041, 0675 and 1851.

To check the response of the system when changed to continuous aeration, two intermittent aeration systems were set up, one a control system (maintained intermittently aerated) the other an experimental system. Switching the experimental system from intermittent aeration to continuous aeration caused a sharp decline in bulking (DSVI < 80 mℓ/g in under one sludge age) 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 (DSVI > 300 mℓ/g) (slowly over a long period of time, 3-4 sludge ages). In the control system the DSVI remained high. The experiment was repeatable using the same two systems but with interchanged roles, the experimental becoming the control, and *vice versa*.

9.4.11 Evaluate aerobic selectors for controlling low F/M filaments

Having established that low F/M filaments proliferate in laboratory intermittent aeration systems, it became possible to check, by setting up an experimental and a

The finding that selectors do not control bulking by low F/M filaments places research in this field back into an exploratory stage. As a consequence, the main task of a bulking control research program will be to establish and pursue a new research direction for dealing with bulking by low F/M filaments. More specifically the following aspects need to be addressed:

1. Establish 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, investigate the influence of the influent particulate biodegradable COD (PBCOD). It is expected 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, anoxic or anaerobic) anaeration reactors.

   For this purpose 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.

2. If PBCOD only supports the growth of the low F/M filaments, do the filaments utilize hydrolysis products of the PBCOD in the liquid generated by other organisms or are they able to hydrolyse and utilise 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)?

3. Due to the strong influence of unaerated conditions (most likely anoxic because the low F/M filaments proliferate in both nitrogen and nutrient removal unaerated-aerated systems), investigate the possibility of low F/M filaments being denitrifiers (interestingly *M.parvicella* is reported to be an obligate aerobe). Investigate the effect of the nitrate concentration in the anoxic zone on low F/M filament proliferation.

4. 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?

5. Establish the minimum sludge age for proliferation of low F/M filaments. Is nutrient removal possible at this sludge ?

6. 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 in all likelihood these were low F/M ones because *S.natans*, *Thiothrix* or 021N are rarely found in laboratory unaerated-aerated systems.

control system, whether or not aerobic selectors control low F/M filaments. With a correctly sized selector installed on the experimental system, (tests were conducted to check that the selector stimulated the selector effect and removed most of the RBCOD) it was found that the selector effect did not control most of the low F/M filaments; the DSVI in both the control and the experimental systems remained above 250 $m\ell/g$. Switching the control system to continuous aeration (DO between 2 and 4 mgO/ℓ) caused the DSVI to decreaae, with a concomitant decline in low F/M filaments, while the DSVI in the experimental (selector) system remained high.

9.4.12 Low F/M filaments appear more sensitive to alternating unaerated/aerated conditions than to the selector effect

From (9.4.6), (9.4.9) and (9.4.10) above it would appear that many of the low F/M filaments proliferate in (1) nutrient removal systems, (2) intermittently fed alternating anaerobic-aerobic systems and (3) continuously fed completely mixed systems with intermittent aeration irrespective of whether or not these systems incorporate an aerobic selector. When these systems are made purely aerobic by continuous aeration, the filaments are reduced and bulking is ameliorated. It would appear that the presence of unaerated conditions (anaerobic or anoxic, but probably anoxic, although this is uncertain) is conducive to low F/M filament proliferation irrespective of the presence of an aerobic selector or intermittent feeding. However, factors to which no answer can be given at this stage are the effects of magnitude of unaerated mass fraction, length of retention time (actual or nominal) under unaerated conditions, whether it is the anaerobic or anoxic condition that has the greater effect, the duration of the anoxic-aerobic cycles in intermittent aeration systems, and the concentration of nitrate during the anoxic periods.

9.4.13 Consistency of behaviour of anaerobic reactors and aerobic selectors

Having established that aerobic selectors do *not* control bulking by low F/M filaments resolves the inconsistency in behaviour of anaerobic reactors and aerobic selectors. It would appear that neither anaerobic reactors, nor aerobic selectors (and anoxic selectors presumably also), and the preferential RBCOD removal by floc formers these stimulate, do not control bulking by low F/M filaments. Because removal of RBCOD by floc formers does not control low F/M filament proliferation, it would appear that the influent readily biodegradable COD does not play an important role in controlling bulking by low F/M filaments.

9.5 RECOMMENDATIONS FOR FURTHER RESEARCH

The research reported above provides strong evidence that the promoted specific control methods against low F/M filaments i.e. selectors (whether anaerobic, anoxic and aerobic) and intermittent feeding (sequencing batch reactors) do not control these filaments in intermittent aeration systems (like Carousel and Orbal plants) for nitrification-denitrification and multi-reactor anaerobic-anoxic-aerobic systems (like UCT and Bardenpho systems) for biological N and P removal. It would appear that the environmental conditions created for biological nutrient removal, (either N or N and P), i.e. sequential unaerated-aerated zones, are conducive to proliferation of low F/M filaments; completely aerated systems cure bulking by low F/M filaments, but also preclude biological nutrient 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 effecting biological nutrient removal. At this stage these an environmental conditions are not known.

7. Attempt to control bulking by low F/M filaments in different system configurations which incorporate nitrification-denitrification and nutrient removal. For example, a system configuration which minimises utilisation 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.

The above research will be time consuming because all experiments will need to be conducted in conjunction with a control experiment and operated for at least 3 sludge ages after a change. The control experiment is particularly important in exploratory experiments of this nature where the causes for proliferation and elimination of the low F/M filaments are not well understood.

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GLOSSARY

DEFINITION OF TERMS

AVSS	Active Volatile Suspended Solids. The volatile suspended solids (VSS) comprise active organisms and inert organic mass. The active organisms mass is the live biological mass which performs the biological reactions; the inert mass originates from two sources (i) from inert organic material in the influent and (ii) endogenous residue. The active fraction of the VSS is a function of the sludge age of the system and sewage characteristics. It is an empirical estimate that has found acceptability because of the consistency it brings to kinetic rates observed in activated sludge systems e.g. based on active mass the specific endogenous mass/respiration rate and specific denitrification rates are constant with sludge age from 3 to 72 days. Because of this consistency, the readily biodegradable COD (RBCOD) uptake rates also are reduced to specific rates with respect to AVSS so that rates in different sludge age systems can be compared. For details on calculation of the AVSS, see Marais and Ekama, 1976 and Ekama, Dold and Marais, 1986
BT	Batch test; a test conducted by mixing sewage containing a known mass of COD with sludge containing a known mass of VSS in a completely mixed reactor
CFCM	Continuously fed completely mixed; an activated sludge system comprising a single completely mixed main reactor receiving influent at a constant rate continuously over a 24h period
COD	Chemical oxygen demand
CTRL	Control; abbreviation for the laboratory system serving as the control system
DO	Dissolved oxygen
DSVI	Diluted sludge volume index, a modified SVI sludge settleability test [see Ekama and Marais (1984) Two improved sludge settleability parameters, IMIESA, 9, 6, 20-25]
d	day
EPA	Environmental Protection Agency (of USA)
EXP	Experimental; abbreviation for the laboratory system serving as the experimental system i.e. the one on which changes are made

g	gram
GLUMRB	Great Lakes — Upper Mississippi River Board of State Sanitary Engineers (Commonly known as Ten States Standards)
h	hour
IFFD	Intermittently fed fill and draw; an activated sludge system comprising a single completely mixed reactor receiving influent intermittently (batchwise) e.g. once daily, on a draw and fill basis
IWPC	Institute for Water Pollution Control (South African Branch); known as the Water Institute of South Africa since 1987
LF	load factor; mass influent sewage COD applied per day per mass MLSS (MLVSS) on activated sludge system or batch test
LR	loading rate; same as LF
low F/M	low food to micro-organism ratio; equivalent to low load factor, or low loading rate or long sludge age
m	minutes
MUCT	Modified University of Cape Town system for biological removal of nitrogen and phosphorus
M.parvicella	*Microthrix parvicella*; one of the filamentous micro-organism common in nutrient removal activated sludge plants
MLVSS	mixed liquor volatile suspended solids; same as VSS, the organic part of the suspended solids in activated sludge plants
MLSS	mixed liquor suspended solids; the organic and inorganic suspended solids in activated sludge plants, also referred to as Total Suspended Solids
N	nitrogen; all nitrogen concentrations i.e. nitrate, nitrite or TKN are expressed as mgN/ℓ
NUR	nitrate utilization rate; mass nitrate as N denitrified per unit reactor volume per unit time, or per unit VSS mass per unit time e.g. mgNO_3-N/(gVSS.h)
OUR	oxygen utilization rate; mass oxygen utilized per unit reactor volume per unit time, or per unit VSS mass per unit time e.g. mgO/(gVSS.h)
P	phosphorus; all phosphorus concentrations are total phosphorus concentrations and expressed as mgP/ℓ

RBCOD	readily biodegradable COD
s	seconds
S.natans	*Sphaerotilus natans*; a filamentous organism rarely observed in nutrient removal activated sludge systems
SVI	Sludge Volume Index
$SSVI_{3,5}$	Stirred specific volume index at the standard MLSS concentration of 3,5 g/ℓ; the sludge settleability measure developed by White (1975) [for details see Ekama and Marais (1984) Two improved sludge settleability parameters. IMIESA, 9, 6, 20-25]
TEFL	Total extended filament length
TKN	Total Kjeldahl nitrogen
UCT	University of Cape Town activated sludge system for biological removal of nitrogen and phosphorus
VFA	Volatile fatty acids
V_o/n	The flux theory settleability measure where V_o and n are the parameters in the empirical zone settling velocity (V_s) – MLSS concentration (X_o) relationship $V_s = V_o \exp(-nX_o)$
<0,45μm COD	soluble COD; the COD concentration which passes through a 0,45 μm filter membrane