Filamentous organism bulking in nutrient removal activated sludge systems. Paper 2: Stimulation of the selector effect under aerobic conditions

Still DA, Ekama GA, Wentzel MC, Casey TG and Marais GvR
University of Cape Town, Department of Civil Engineering, Rondebosch 7700, Cape, South Africa

Abstract

The Monod kinetic based selector theory for filamentous bulking control has guided research and application for the past two decades. This approach, which in its broadest sense recommends modification of system configuration or operation to introduce alternating feed starve conditions, is evaluated for control of the low F/M filament group which are ubiquitous and cause most of the bulking problems in N and N & P removal systems. In agreement with the literature, it was found that this approach induces in the sludge a rapid uptake of influent readily biodegradable COD and oxygen under batch fed conditions (selector effect), but it could not be demonstrated that this controlled low F/M filament proliferation because the control systems without the selector effect also did not bulk with low F/M filaments. However, the selector effect did control *Sphaerotilus natans* and *Thiothrix* sp. proliferation, the former of which was found to grow in the laboratory systems as a result of seeding from influent feed line wall growths. Batch test results could be adequately interpreted with existing activated sludge kinetic models, and based on these, a design method for aerobic selectors is presented. A selector designed with this method is shown to induce a selector effect and control filaments *S. natans* and *Thiothrix* sp.

List of symbols

ADWF = average dry weather flow
ATV = Abwassertechnischen Vereinigung
b_H = heterotrophic organism endogenous respiration rate (/d)
= 0.24/d at 20°C
CFCM = continuously fed completely mixed
COD = chemical oxygen demand
d = day
DO = dissolved oxygen (mg O/ℓ)
DSVI = diluted sludge volume index
DW = dry weather
f = endogenous residue fraction = 0.20
f_{av} = fraction of VSS mass that is active organisms
f_{cv} = COD/VSS ratio of the sludge mass synthesised
F/M = food to micro-organism ratio
f_s = fraction of the underflow recycled to the selector zone
f_{ts} = fraction of the total influent COD (S_{ti}) that is readily biodegradable (S_{bsi})
f_{vs} = volume fraction of the selector reactor, i.e. the volume of the selector as a fraction of the total biological reactor volume including the selector
f_{xs} = selector sludge mass fraction, i.e. fraction of the mass of VSS in the system that is in the selector reactor(s)
h = hour
IAWQ = International Association for Water Quality
IFFD = intermittently fed fill and draw
K_{ms} = maximum specific substrate utilisation rate [mg COD/(mg AVSS·d)]
K_s = half-saturation coefficient in the Monod equation (mg/ℓ)
L_r = peak to average COD load ratio under dry weather conditions
M = symbol denoting mass of compound following it, i.e. MS_{ti} = mass of COD load per day = $Q_i.S_{ti}$
MX_v = mass of VSS in biological reactor = $V_p X_v$
MLSS = mixed liquor suspended solids
MLVSS = mixed liquor volatile suspended solids
N = nitrogen
OUR = oxygen utilisation rate in mg O/(ℓ·h) or mg O/(g AVSS·h). Subscripts RBCOD and SBCOD denote the OUR for RBCOD and SBCOD utilisation respectively. Subscript Het is the heterotrophic OUR which is the sum of OUR_{RBCOD} and OUR_{SBCOD}
p = phosphorus
PDWF = peak dry weather flow
Q_i = influent flow at ADWF (ℓ/d)
Q_r = underflow rate (ℓ/d)
RBCOD = readily biodegradable COD
R_s = sludge age (d)
s = underflow recycle ratio (Q_r/Q_i)
S = general symbol for COD concentration (mg COD/ℓ). Subscripts b and t refer to biodegradable and total respectively and additional subscripts i and s refer to influent and soluble respectively
SBCOD = slowly biodegradable COD
S_{bs} = readily biodegradable COD concentration (mg COD/ℓ)
Additional subscript i denotes influent
SEL = selector
t = time

* To whom all correspondence should be addressed.
☎ (021) 650-2588; fax (021) 650-2603; e-mail ekama@engfac.uct.ac.za
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TKN	=	total Kjeldahl nitrogen
UCT	=	University of Cape Town
V_p	=	total volume of biological reactor (ℓ)
V_s	=	volume of selector (ℓ)
VSS	=	volatile suspended solids
X_H	=	active heterotrophic organism concentration (mg AVSS/ℓ)
X_v	=	volatile suspended solids concentration (mg VSS/ℓ)
Y_H	=	sludge growth yield coefficient (mg VSS/mg COD)
μ_H	=	maximum specific growth rate of heterotrophs, (/d)
μ_N	=	maximum specific growth rate of nitrifiers (/d)
μm	=	micro (10^{-6}) meters

Introduction

Chudoba's selector theory

Chudoba et al. (1973a;b; 1974) proposed an organism selection criterion as an explanation for the occurrence or non-occurrence of filamentous organism bulking. This criterion is based on competition between the floc-formers and the filaments for the mutually limiting soluble substrate, as follows: In the Monod formulation for the specific rate of growth of organisms, filamentous organisms have lower values for both the maximum specific growth rate (μ_H) and the half saturation coefficient (K_s) than do floc-formers. Consequently, at low substrate concentrations filamentous organisms have a higher specific growth rate than floc-formers and at high substrate concentrations, a lower specific growth rate, as illustrated in Fig. 1.

Over the past two decades the selection criterion has provided a framework for research into the causes of bulking and its control by specific methods. Results reported by a number of investigators who have measured the Monod constants of various filaments and floc-formers, appear to fit within the structure of the selection criterion: Van den Eynde et al. (1982a;b) showed that in general, organisms with high μ_H have high K_s values and ones with low μ_H have low K_s values. Slijkhuis (1983) measured the μ_H of *Microthrix parvicella* (one of the principal filaments causing low F/M filament bulking) to be 1.66/d; this is considerably lower than a μ_H of 4.33/d measured by Richard et al. (1982) 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 dissolved oxygen, DO ones) the limiting nutrient apparently is oxygen, whereas for others the limiting nutrient is the soluble substrate concentration surrounding the organism, as originally conceived by Chudoba et al. (1973a;b). Hao et al. (1983) and Lau et al. (1984) confirmed the work of Palm et al. (1980). From dual species studies they showed that low DO filaments (*Sphaerotilus natans*, type 1701) and floc-formers can be selectively grown by manipulating the DO concentration - if high, the floc-former dominates, if low, the filament dominates.

With regard to bulking in long sludge age (low F/M) systems, Chudoba et al. (1973a;b; 1974) 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 completely mixed single reactor 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. In the aerobic completely-mixed single-reactor systems, filamentous organisms proliferated, causing bulking, whereas in the aerobic multi-reactor plug-flow systems, filamentous organisms did not proliferate and a good settling sludge was maintained. From this work, Chudoba et al. (1973b) developed the selector reactor for bulking control.

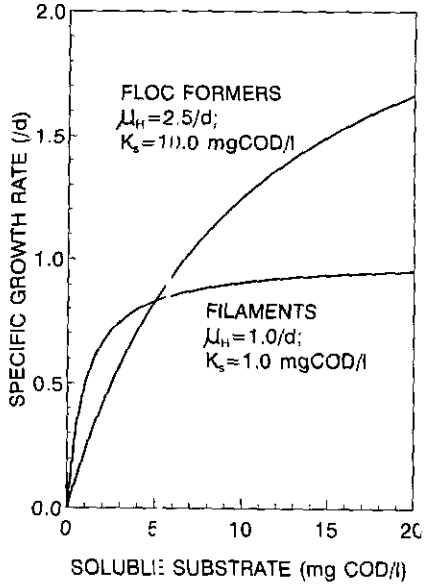


Figure 1
Monod specific growth rate functions for filament and floc-forming organisms in accordance with the selection criterion of Chudoba et al. (1973a;b)

The selector reactor is a small aerated reactor upstream of the main aeration reactor and receives the influent and underflow recycle. In the selector reactor, the substrate concentration is high and, in terms of the selection criterion, the floc-formers should grow faster than the filaments and utilise practically all of the soluble substrate. Should any soluble substrate pass through the selector unutilised it would be a very small fraction of that available to the floc-formers in the selector so that filament growth will be restricted and insufficient to cause bulking.

The findings of Chudoba were supported by a number of investigators; non-bulking sludges were produced in **completely aerobic** systems with:

(1) Selectors ahead of the main reactor (Grau et al., 1982; Lee et al., 1982; Jenkins et al., 1983; Van Niekerk, 1985; Van Niekerk et al., 1987);
(2) compartmentalisation of the aeration reactor while maintaining continuous feeding of waste water (Chudoba et al., 1973b; Rensink et al., 1982; Wu et al., 1984);
(3) batch or intermittent feeding to completely mixed aeration basins (Houtmeyers 1978; Houtmeyers et al., 1980; Verachtert et al., 1980; Van den Eynde et al., 1982a;b; Eikelboom, 1982; Rensink et al., 1982; Goronszy, 1979; Goronszy and Barnes, 1979; Barnes and Goronszy, 1980; Chiesa and Irvine, 1985; Jenkins et al., 1983; Van Niekerk, 1985; Van Niekerk et al., 1987).

A common feature found in all these investigations, using either selectors, plug-flow reactors or intermittent feeding to single-reactor completely mixed aerobic systems, is that the systems stimulated in the sludge a high utilisation rate of soluble (<0.45μm) COD (i.e. readily biodegradable COD, RBCOD). These rates were

observed in aerobic batch tests by drawing sludge from the system and spiking it with influent and measuring the <0.45µm COD concentration reduction with time, and/or the oxygen utilisation rate (OUR) associated with the soluble COD reduction. Where this effect was present, for example, in a single reactor system with a selector upstream of the reactor, the rates of these two parameters are 2 to 3 times higher than for the system that did not exhibit the effect, i.e. in single reactor completely mixed systems without a selector (*inter alia* Houtmeyers, 1978; Houtmeyers et al., 1980; Verachtert et al., 1980; Van den Eynde et al., 1982a; Grau et al., 1982; Eikelboom, 1982; Jenkins et al., 1983; Van Niekerk, 1985; Daigger et al., 1985 and Van Niekerk et al., 1987). For convenience, a sludge with high soluble COD and oxygen uptake rates will be described as one exhibiting a selector effect.

Selector effect and control of low F/M filaments

From the literature there is strong evidence that where the selector effect is induced, proliferation of the filamentous organisms *S. natans*, *Thiothrix* sp. and type 021N is controlled.

Plants in Europe and the United States have been predominantly aerobic and modification of these to induce the selector effect has been accompanied by considerable success in controlling bulking by the filaments given above. However, these filaments are rarely encountered in South African plants which predominantly include unaerated zones in their configuration. The ATV Working Report (1989) and other European researchers (Pujol and Canler, 1993, Kruit et al., 1993) support this approach for bulking control: "On the basis of the information available today, the use of a 'selector', i.e. a high-load preliminary tank, can be recommended as the most promising measure for preventing and controlling bulking, regardless of the waste water." (ATV Working Report, 1989).

Reviewing the investigations into control of bulking in low F/M systems by the selector effect cited under points (1) to (3) above, where filament identifications were performed, which were predominantly in laboratory-scale investigations, bulking was caused not by low F/M filaments but by *S. natans*, which (as indicated in Table 1 of Casey et al., 1995) is not a low F/M filament. This generated considerable uncertainty regarding the appropriateness of the selector effect for controlling bulking by low F/M filaments in South African plants and this uncertainty was one of the motivations for the current research into the efficacy of selector reactors.

Methods for inducement of the selector effect

Because the principal objective of our research investigation was to identify specific control methods for the low F/M filament category, and as a consequence of finding in the literature that the selector effect had not been unequivocally demonstrated to be effective for controlling these filaments, it was decided to repeat the experiments undertaken by the researchers cited above but focus specifically on the influence of the selector effect on the low F/M filaments. Consequently, experimental work was conducted to examine two means which have been found to induce the selector effect: by changing the feeding pattern from continuous to batch; and through addition of selector reactors ahead of the main aeration reactor.

As mentioned above, many investigators have shown that sludges subjected to different COD feeding patterns have different soluble COD and oxygen uptake rates. Of particular note, Jenkins et al. (1983) demonstrated that alternating feed-starve conditions resulting from IFFD systems; or continuous feeding to completely mixed systems with selector reactors (CFCM/SEL), promote higher soluble COD and oxygen uptake rates than do continuously fed completely mixed (CFCM) systems. Because filaments did not develop in the systems with the selector effect, it was concluded that this effect is important in creating environmental conditions which act against the proliferation of filamentous organisms. Therefore as the starting point of our investigation, the experiments of Jenkins et al. (1983) were repeated but were focused on the influence of the selector effect on the low F/M filament category as distinct from the filaments *S. natans*, *Thiothrix* sp. and Type 02IN. The experiments described below were designed to examine this aspect and are divided into four parts as follows:

- Part 1: Experimental investigation - Comparison of RBCOD and oxygen uptake rates (or equivalently maximum specific heterotrophic growth rates μ_H) developed in IFFD and CFCM systems and their effect on sludge settleability.
- Part 2: Interpretation of results - Comparison of RBCOD and oxygen uptake rates with those measured at the University of California at Berkeley with respect to the role of storage of substrate in control of bulking.
- Part 3: Design of selectors - Development of procedures for design of aerobic selector reactors.
- Part 4: Testing selectors - Experimental examination of aerobic selectors in aerobic systems.

The outcome of this research is presented in this paper.

Experimental investigation

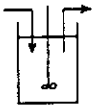
Part 1: Comparison of maximum specific heterotrophic growth rates (μ_H) developed in IFFD and CFCM systems and their effect on sludge settleability

Relationship between maximum specific OUR and sludge settleability

Two single-reactor aerobic systems were operated with settled sewage from Mitchell's Plain as influent. One was operated as an IFFD, the other as a CFCM system. The operating conditions of the two systems are shown in Table 1. Both systems were started with a bulking sludge (DSVI~250 m*l*/g) from Mitchell's Plain treatment works (Cape Town, South Africa). Microscopic examination of the starter sludge indicated the presence of the following filaments and their abundance on a 0 (none) to 6 (excessive) scale: 5 - type 1851; 4+ - *M. parvicella* and type 0914; 4 - type 0092, type 0675 and *Nocardia* spp.; 3 - type 0803. All the observed filaments are low F/M types.

Measurement of COD, TKN, MLVSS and MLSS concentrations was done in accordance with *Standard Methods* (1985); dissolved oxygen (DO) concentration with a Yellow Springs Inc. (YSI) DO meter; pH with a radiometer pH meter model No. PHM80; and nitrate and nitrite concentrations with the Auto Analyser automated industrial method No. 33.69W. Oxygen utilisation rate (OUR) was calculated from the DO versus time slope generated on a strip chart recorder and measured directly in the reactor during the aeration off period while maintaining mixing. The aeration on-off cycle was automated with a DO-controller in accordance with Johnston and Buhr (1982) and later completely automated by Randall et al. (1991). Diluted sludge volume index (DSVI) was measured as outlined by Lee et al. (1983) or Ekama and Marais (1984). Filament identifications were done in accordance with

TABLE 1
OPERATING PARAMETERS AND CONDITIONS OF INTERMITTENTLY FED FILL AND DRAW (IFFD) AND CONTINUOUSLY FED COMPLETELY MIXED (CFCM) SYSTEMS

SYSTEM	IFFD	CFCM
Operating conditions	Intermittently fed fill and draw	Continuously fed completely mixed
Graphical representation		
Aeration	Fully aerobic	Fully aerobic
DO concentration (mgO/ℓ)	2 - 4	2 - 4
Feed	Intermittent (once daily)	Continuous (24h)
Sludge source	Mitchell's Plain	
Sewage source	Mitchell's Plain settled	
Mass of COD fed (mg/d)	3500	3500
Volume of feed (ℓ/d)	5.4	10
Concentration (mgCOD/ℓ)	650	350
Mass of TKN fed (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
Load factor (F/M) [mgCOD/(gVSS.d)]	280	280
Nominal hydraulic retention time (h)	44	24
pH	7 - 8	7 - 8

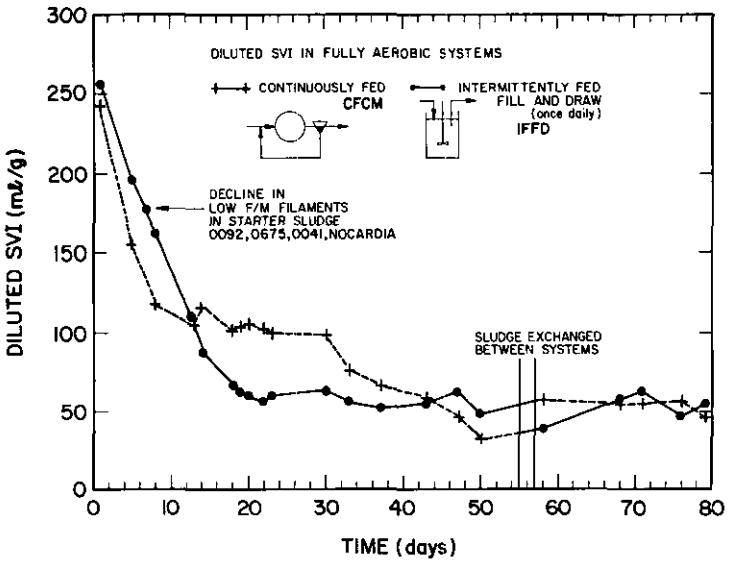


Figure 2
Sludge settleability expressed as Diluted SVI (DSVI) of sludges in two fully aerobic single reactor systems fed (1) intermittently (batch) once daily (IFFD, •——•) and (2) continuously (CFCM, +------+) receiving the same feed (Mitchell's Plain settled sewage) and operated at the same sludge age (30 d) and temperature (20°C). Note that in the first 20 d the DSVI of 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.*

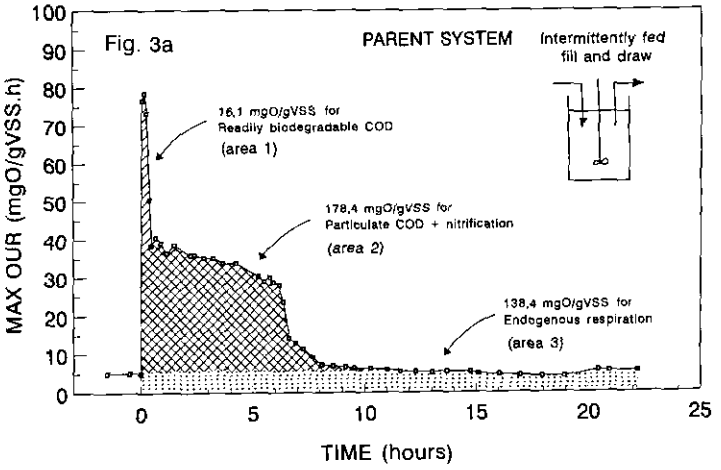
Eikelboom and Van Buijsen (1981) and Jenkins et al. (1984). Readily biodegradable COD uptake rates (RBCODUR, K_{ms}) and maximum specific growth rates of heterotrophs (μ_H) were calculated by means of the method of by Ekama et al. (1986) (see Appendix 1).

Both systems were operated for 80 d. The change in DSVI with time is illustrated in Fig. 2. In both systems the DSVI decreased from 250 mℓ/g at start-up to less than 100 mℓ/g after a month. After about 30 d the IFFD system had a pin-point floc structure and turbid effluent while the CFCM system had a better developed floc structure and clear effluent.

At regular intervals, sludge was abstracted from both systems and aerobic batch tests were conducted to determine

- the soluble COD (< 0.45 μm) uptake rate, and
- the OUR response over a 24 h period.

An example of a batch test conducted on sludge abstracted on day 78 from the IFFD system and on day 79 from the CFCM system is given in Figs. 3a and 3b respectively. Apart from the initial high value of maximum specific OUR [mg O/(g VSS·h)] indicating that a selector effect had been induced, the shape of the OUR profile provides a considerable amount of additional information.



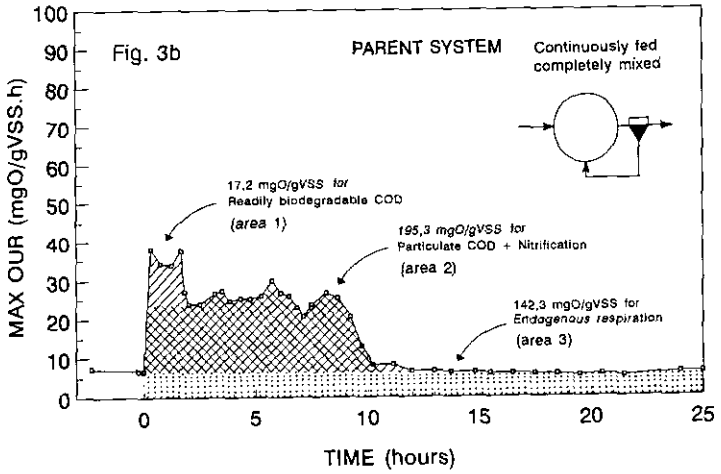


Figure 3

OUR response in mg O/(g VSS·h) observed under aerobic batch test conditions at the same COD load per g VSS on sludges harvested from aerobic single reactor systems fed (1) intermittently (batch) once daily (Fig. 3a, IFFD, upper) and (2) continuously (Fig. 3b) CFCM, lower) both receiving the same sewage feed (Mitchell's Plain settled) and operated at the same sludge age (30 d) 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.

Initial high OUR response

The area below the initial high OUR response curve, (area 1, Figs. 3a and b) represents the oxygen consumed in utilising the influent readily biodegradable COD (RBCOD) - the larger this area with respect to the total area under the curve, the greater the fraction of readily biodegradable COD concentration in the influent (Ekama et al., 1986). The point at which the OUR drops rapidly the first time indicates the point at which the influent RBCOD is completely utilised. The shape of the initial OUR response rectangle reflects the rate of RBCOD utilisation. A high initial OUR response present for a short time reflects a high K_{ms} (specific RBCOD uptake) rate (proportional to μ_H through the yield coefficient Y_H i.e. K_{ms} i.e. = μ_H/Y_H) indicating that the RBCOD is utilised rapidly (Fig. 3a), and a low initial OUR response present for a comparatively longer time reflects a low K_{ms} rate indicating that the RBCOD is utilised slowly (Fig. 3b). Clearly the IFFD sludge has a much higher K_{ms} (Fig. 3a) than that in the CFCM sludge (Fig. 3b) indicating that in the former a selector effect was present (Jenkins et al., 1983). However, note from Figs. 3a and 3b that the area of the initial high OUR rectangle is virtually the same for both the IFFD and CFCM systems. In the absence of intracellular storage of RBCOD, these two areas should be equal because they are directly proportional to the influent RBCOD concentration (Ekama et al., 1986).

Comparing the RBCOD uptake rates (K_{ms}) calculated from batch test soluble (<0.45 μm) COD profiles and the high initial OUR at the start of the batch test, it was found that these were generally related through the active heterotrophic organism yield coefficient (Y_H) and COD/VSS ratio (f_{cv}) (Ekama et al., 1986). This indicated that intracellular storage of RBCOD was generally negligible and that the RBCOD uptake rate can be measured indirectly by monitoring the initial high OUR. Intracellular storage was negligible probably because the COD loading rates [mg COD/(mg VSS·d)] of the batch tests were not greater than twice the loading rates of the parent systems from which the batch test sludge was harvested.

Second OUR plateau

The area below the second plateau in the OUR profile (area 2 in Figs. 3a and 3b), represents the concentration of oxygen required for solubilisation and utilisation of particulate slowly biodegradable COD (SBCOD) and nitrification (in non-nitrification inhibited tests). Because the solubilisation and utilisation of SBCOD is not influenced significantly by environmental conditions in the plant, e.g. selector effect (see below) and unaerated conditions (Clayton

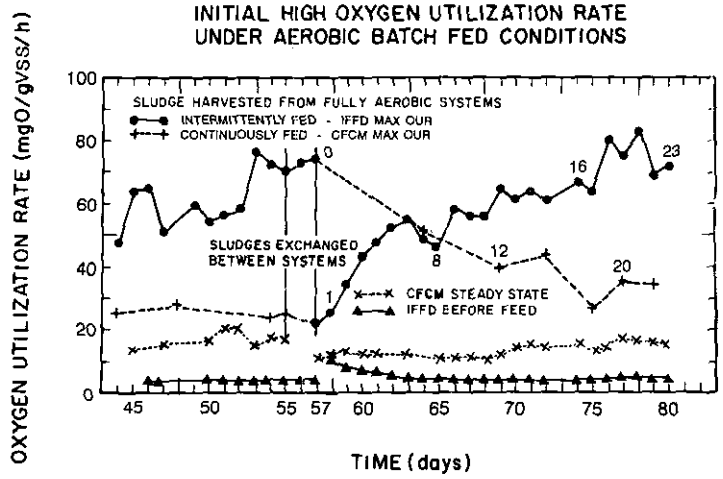


Figure 4

Initial high OUR, [in mg O/(g VSS·h)] with time observed in aerobic batch tests under identical COD loading per g VSS on sludges harvested from aerobic single reactor systems fed intermittently (batch) once daily (IFFD, •—•) and (2) continuously (CFCM, +----+) both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (30 d) and temperature (20°C). Note the higher initial OUR in the intermittently fed system than in the continuously fed system as in Fig. 3. 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. The OUR in the IFFD system just prior to feeding (▲----▲) and the steady state OUR in the CFCM system (x----x) are also shown.

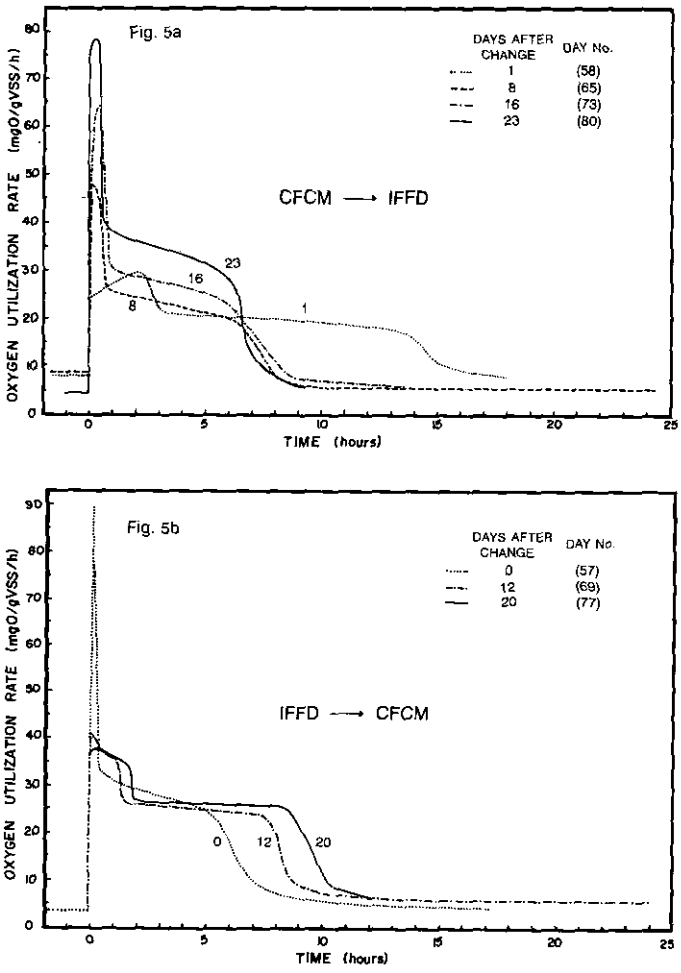


Figure 5

Changes in 24 h batch OUR profile after switching sludges from CFCM conditions to IFFD conditions (Fig. 5b, top) and vice versa *(Fig. 5b, bottom). Note that as IFFD (or CFCM) conditions become established the OUR areas associated with RBCOD utilisation and nitrification (i.e. areas 1 and 2 respectively in Figs. 3a and b) become taller and narrower (shorter and wider) indicating increasing (decreasing) maximum specific growth rate of heterotrophs (area 1) and nitrifiers (area 2).*

et al., 1991; Wentzel et al., 1994), changes in this second plateau of the OUR profile arise principally from changes in the maximum specific growth rate of the nitrifiers (μ_N). For high μ_N, the OUR profile of the area is high and narrow and for low μ_N the profile is low and wide (see **Appendix 1**).

The second precipitous drop in OUR is a consequence of a cessation of nitrification when the ammonia concentration is depleted. In Figs. 3a and 3b it is clear that for some reason (see below) the μ_N value is greater for the IFFD system sludge than for the CFCM system sludge in that nitrification was complete in 6.5 h in the former and 9.5 h in the latter. In particular, note that in Fig. 3a for the IFFD system, after nitrification has ceased, the OUR continues to decrease from 15 mg O/(g VSS·h) to 5 mg O/(g VSS.h) (See also Fig. 3 in Ekama et al., 1996a). This is because the SBCOD was not completely utilised by the heterotrophic organisms before nitrification was complete. This is not observed in the CFCM OUR profile (Fig. 3b) because in this case nitrification took longer to complete so that the utilisation of SBCOD by the heterotrophs was complete while nitrification was still continuing.

The change in the second plateau OUR area, i.e. that associated with the utilisation of SECOD and nitrification, is principally attributed to changes in μ_N because:

- Chudoba et al. (1986) report a similar effect on μ_N stimulated by plug-flow reactor configuration.
- Simulations of the results of batch tests with and without nitrification inhibition with the UCT dynamic activated sludge model (Dold et al., 1991). Both the experimental and simulated nitrification inhibited batch test results did not show a well-defined second precipitous decrease in OUR but rather a progressive decrease to the endogenous respiration OUR as the SBCOD was utilised.

Third OUR area

Only when both nitrification and influent SBCOD utilisation is complete does the OUR reach a third plateau. This is the OUR associated with endogenous respiration, which represents the oxygen required for solubilisation and utilisation of substrate released via organism death and lysis (area 3 in Figs. 3a and b).

Inducement of selector effect

The magnitude of the maximum specific OUR indicates whether or not a selector effect has been induced in the sludge. The high initial OUR values measured in the batch tests during the second half of the 80 d investigation are shown in Fig. 4. From day 45 to day 57 the IFFD sludge had an initial high OUR 2 to 2.5 times greater than that of the CFCM sludge indicating that a selector effect was induced by the IFFD conditions, but not by CFCM conditions. On day 57, the sludges in the IFFD and CFCM systems were interchanged and regularly thereafter the 24 h OUR profile was monitored in batch tests to observe the rate at which the selector effect is induced in and lost by the sludge (Fig. 4). The ex-IFFD sludge progressively lost its selector effect (days 59 to 80) under CFCM conditions while the ex-CFCM sludge developed a selector effect under IFFD conditions. It appears that the development or loss of the selector effect takes place over a period shorter than the sludge age - about 20 d in the 30 d sludge age systems.

The changes in the batch 24 h OUR profile after the switching of the sludges on day 58 are shown in Figs. 5a and 5b. For the ex-CFCM sludge under IFFD conditions, it can be seen that the area related to the utilisation of the RBCOD fraction changes with time from a low wide rectangle to a high narrow rectangle as the selector effect is induced (Fig. 5a). The rectangle associated with the utilisation of SBCOD and nitrification changes shape with time in the same way and because this is principally a result of changes in nitrification behaviour, indicates that the maximum specific growth rate of the nitrifiers (μ_N) has increased under the IFFD conditions. For the ex-IFFD sludge under CFCM conditions the changes are opposite. The area related to the utilisation of the RBCOD fraction changes with time from a high narrow rectangle to a low wide rectangle (Fig. 5b) indicating that the selector effect is progressively lost with time. Similar changes in the shape of the area associated with utilisation of SBCOD and nitrification indicate a decrease in μ_N for the reasons given above. Calculation of influent readily biodegradable COD fraction and kinetic constants K_{ms} (or μ_H) and μ_N from the 24 h batch test OUR response is given in **Appendix 1**.

Reconciling the selector effect with Chudoba's selection criterion

It is difficult to reconcile the experimental results above with Chudoba's selection criterion. It may be argued that the μ_H of the mixture of filaments and floc-formers increases because filaments with a low μ_H value are being eliminated. While this influence is possible, it does not explain why the μ_H values of the ex-CFCM and ex-IFFD increased and decreased respectively under IFFD and CFCM conditions between days 45 and 80 (Fig. 4) when both sludges were already settling well (Fig. 2). Therefore the changes in μ_H resulting from the different feeding conditions is a consequence of changes in the floc-former organism population. The observation that introduction or removal of alternating feed-starve conditions either changes the maximum specific growth rates (μ_H) of the existing floc-forming heterotrophic organisms or results in the development of a floc-forming population with a higher μ_H is a phenomenon not recognised by Chudoba's selection criterion.

Chudoba's selection criterion (Fig. 1) accepts different Monod constants for the filaments and floc-formers, and for different feeding patterns and system configurations these constants remain unchanged, only the readily biodegradable COD concentration in the bulk liquid changes. However, from the experiments it would appear that with increases in RBCOD in the liquid, the maximum specific growth rate (μ_H) of the floc-formers increases. This results in an upward shift in the floc-former specific growth rate - readily biodegradable substrate curve in Fig. 1. This phenomenon does not invalidate Chudoba's selection criterion but does indicate that it requires revision. It is possible that with the increase in μ_H stimulated by alternating feed-starve conditions in the floc-formers, there is now no longer a cross-over point in the floc-former and filament specific growth rate curves at any substrate concentration, resulting in elimination of the filaments (Ekama and Marais, 1986).

More importantly, it is not possible to state unequivocally from the experimental results that the presence of the selector effect was the reason for the low DSVI values (few filaments) measured in the IFFD system, since low DSVI values were also measured in the CFCM system in which the selector effect was absent. Nevertheless despite this inconclusive result, the research project was continued by evaluating the feasibility of integrating selector reactor design procedures with activated sludge kinetic models because of the considerable attention the selector effect had attracted as a means for controlling bulking by low F/M filaments.

Interpretation of results

Part 2: Integration of selector reactor design procedures with activated sludge kinetic models

Jenkins et al. (1983) at Berkeley have conducted extensive investigations into low F/M bulking and formulated design procedures for selector reactors. To evaluate the role of selector reactors and their design in the control of bulking sludges, Van Niekerk (1985); and Van Niekerk et al. (1987) conducted sludge settleability and substrate uptake tests on activated sludges grown in three types of systems: IFFD, CFCM and CFCM/SEL (CFCM including a selector reactor). All three configurations were operated as fully aerobic systems at 20°C with sludge ages of 20 to 30 d. These results are evaluated in some detail below because they have formed the framework for selector reactor design which is based on intracellular soluble substrate storage. Although this storage approach deviates in concept from the utilisation approach incorporated in activated sludge kinetic models, it will be demonstrated below that both approaches lead to similar end results.

Sludge settleability and filamentous organism identifications

From analysis of DSVI data and filamentous organism identifications from the three systems operated by Van Niekerk (1985), it was found that:

- The activated sludge in the CFCM system exhibited a pronounced tendency to bulk when compared to sludge from the CFCM/SEL or IFFD systems.
- Bacterial populations in activated sludge cultivated in CFCM/SEL and IFFD systems were characterised by the presence of distinct amorphous zoogleal colonies which were not observed in activated sludge from the CFCM system.
- In 12 out of 15 incidences in which the DSVI values were greater than 100 m*l*/g in the CFCM system, one of the filaments, *S. natans*, *Thiothrix sp*, or type 021N was dominant - in the other three cases, the dominant filaments were type 0961 or type 0803.
- Although filaments type 0041, type 0803 and type 0961 were frequently abundant in bulking sludges, they never produced

very high SVI values (<150 mℓ/g).
- The same filamentous organisms that caused bulking in the CFCM system were present in much smaller numbers in the sludges from the CFCM/SEL and IFFD systems.

Substrate uptake and respiration batch tests conducted by Van Niekerk (1985)

By mixing different proportions of soluble COD and VSS (called floc loading after Eikelboom, 1982) in a batch test, Van Niekerk (1985) measured soluble COD (<0.45 µm) concentrations and OUR with time. The typical pattern for the OUR response and change in soluble COD concentration in the batch tests is illustrated in Fig. 6 (from Van Niekerk, 1985). During the period of initial soluble COD uptake, an increasing OUR is observed; because log soluble COD concentration plotted against time yielded a straight line, the soluble COD uptake was modelled as a first-order rate with respect to the soluble COD concentration (and VSS concentration). The OUR continues at a constant high rate until about 60 % of the soluble COD is taken up. Thereafter the OUR declines rapidly, but levels off at a rate greater than the OUR at the start of the test, after which little more soluble COD is taken up. The OUR at the start of the test is that associated with endogenous respiration. The area under the elevated OUR curve is the concentration of oxygen utilised (mg O/ℓ) in association with the rapid uptake of soluble COD and according to Van Niekerk (1985), directly gives the concentration of soluble COD respired (utilised) during the rapid uptake phase. By comparing the concentration of oxygen utilised and soluble COD taken up, it was concluded that on average from

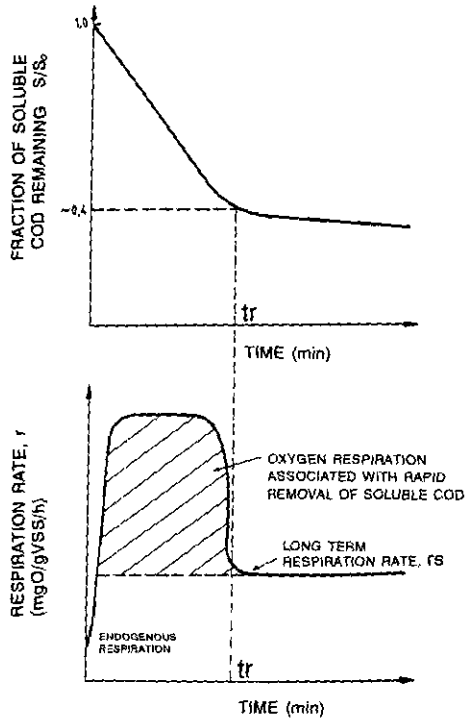


Figure 6

Typical soluble (<0.45 µm) COD concentration and OUR profiles observed by Van Niekerk (1985) under batch test conditions upon mixing influent waste water and activated sludge harvested from IFFD systems and continuously fed systems with selector reactors (CFM/SEL) (from Van Niekerk, 1985).

all their tests, only 38% of soluble COD taken up was utilised, the rest (62%) was stored internally.

Conclusions from continuous and batch test results

From their experimental work, Van Niekerk (1985) concluded the following regarding substrate uptake rates and bulking control in completely aerobic long sludge age CFCM, CFCM/SEL and IFFD activated sludge systems [loading rate <0.3 g COD removed/(g VSS·d)].

- The concentration of the soluble COD (<0.45 µm) fraction in waste water is very important in the stimulation of filamentous bacterial growth in CFCM systems.
- Activated sludges abstracted from CFCM/SEL and IFFD systems exhibit a different soluble COD uptake and OUR response to activated sludge abstracted from CFCM systems in the presence of excess soluble COD. Activated sludges abstracted from the CFCM/SEL and IFFD systems, which are subjected to alternating high and low soluble COD sewage concentrations, have the ability to rapidly remove soluble COD and store intracellularly a major fraction (62%) of the accumulated substrate. High respiration rates accompany the period of rapid soluble COD uptake. The soluble COD and OUR response patterns in the presence of high concentrations of soluble COD of activated sludges harvested from IFFD and CFCM/SEL systems are similar. In contrast, activated sludge abstracted from a CFCM system, responds to the presence of excess soluble COD with a relatively slow soluble COD uptake and a small respiration rate increase.
- Activated sludge from the three experimental systems did not exhibit significantly different rates of particulate COD (SBCOD) removal.

Comparison of Berkeley and UCT results

The above results of Van Niekerk (1985) (Berkeley) need to be compared with those from the writers (UCT) because of the possible differences these may have on low F/M filament bulking control and the design of selector reactors. The comparison therefore is made from two perspectives:

- sludge settleability and filamentous organism development
- substrate uptake and respiration rates.

With regard to the effect of system type on filament proliferation and sludge settleability, in both groups (UCT and Berkeley) the experimental results indicated that in general the IFFD and CFCM systems did not bulk with low F/M filaments. However, although for the UCT group the CFCM system had at no stage a DSVI > 60 mℓ/g, for the Berkeley group, the CFCM system often exhibited periods of very poor sludge settleability. The filaments which were dominant in the three systems of the Berkeley group i.e. type 02IN, *Thiothrix* sp., *S. natans*, type 0961 and type 0803, were at no stage dominant in either of the systems of the UCT group. Furthermore with the exception of type 0803, these dominant filaments were not present in the sludge of the full-scale system with which the UCT systems were started up.

With regard to the effect of system type on substrate uptake, both research groups found that the IFFD systems developed high initial soluble COD uptake rates whereas the CFCM systems did not. Although these experimental results did not differ in any substantial manner, their interpretation by the two groups differs

markedly. The Berkeley group interpret the low ratio of oxygen utilised (accepted to be equivalent to COD utilised or respired) to soluble COD taken up (0.38) to imply that internal storage of soluble COD (0.62) in the form of polyhydroxybutyrate (PHB) takes place. In the UCT batch tests in which soluble COD uptake was measured, the ratio of the oxygen utilised to soluble COD taken up was 0.35, a value similar to that of the Berkeley group. However, in conformity with activated sludge kinetic models, the UCT group interprets this as conventional heterotrophic metabolic behaviour, without significant intracellular soluble COD storage which can be explained as follows: Heterotrophic metabolism comprises anabolism in which a fraction of the organic substrate ($f_{cv} \cdot Y_H$ = 1.48 mg COD/mg VSS · 0.45 mg VSS/mg COD = 0.66 where Y_H = yield coefficient and f_{cv} = the COD/VSS ratio of the VSS mass formed) is converted to organism mass and catabolism, in which the remaining fraction ($1-f_{cv} Y_H$ = 0.34) of the taken-up substrate is degraded to generate energy to undertake the anabolic process. To enable the organism to generate the energy, the electrons of degraded organics need to be passed on to a terminal electron acceptor, i.e. oxygen for aerobic conditions. It is therefore not unexpected that the oxygen utilised is only one third of the COD taken up (utilised). Consequently, although different in interpretation, the experimental results are stoichiometrically virtually identical in that the oxygen utilised was around 35% and 38% of soluble COD taken up, indicating that similar yield coefficients (Y_H) and COD/VSS ratios (f_{cv}) would be obtained from both sets of results which are in conformity with accepted values in activated sludge kinetic models such as Henze et al. (1987) and Dold et al. (1991) i.e. Y_H = 0.45 mg VSS/mg COD and f_{cv} = 1.48 mg COD/mg VSS.

The adequacy of this anabolism-catabolism interpretation is illustrated by simulation using the UCT kinetic general activated sludge model (Dold et al., 1991) which incorporates uptake and direct synthesis of readily biodegradable COD rather than uptake and storage. The results of the simulations of the batch tests illustrated in Figs. 3a and b are illustrated in Fig. 7 which demonstrates that the general UCT kinetic model is able not only to reasonably accurately simulate the RBCOD uptake and utilisation under batch test conditions in which a selector effect has been stimulated, but also to simulate the other processes taking place simultaneously such as nitrification and utilisation of SBCOD derived from either the influent or from organism death and lysis (endogenous respiration). (The smoothed decreases in OUR at the end of the first and second plateaus for the CFCM sludge compared with the sharp decreases at the same periods for the IFFD sludge are a consequence of the lower VSS concentration at which the CFCM batch test was done - 690 mg VSS/ℓ compared with 1 342 mg VSS/ℓ for the IFFD sludge - resulting in the half saturation coefficients influencing the kinetic rates to a much greater extent in the CFCM simulation than in the IFFD simulation; the half saturation coefficients were kept the same at the standard values for both simulations). Therefore the phenomenon of the selector effect can be taken account of completely within the structure of the general kinetic model. The utilisation of RBCOD is modelled with the Monod formulation and the presence or absence of the selector effect is included by appropriate choice of the two Monod constants, i.e. μ_H and K_{si}; high values for both to include the selector effect (Ekama and Marais, 1986). The framework of Monod kinetics therefore adequately describes soluble (RBCOD) uptake under batch test conditions or in selector reactors, and therefore provides a rational basis for the design of aerobic selector reactors (see below). Indeed, recent activated sludge modelling techniques have become more sophisticated with the development of the structured

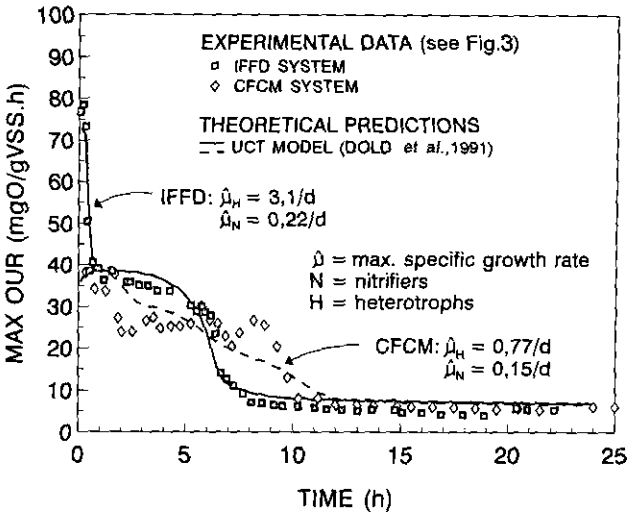


Figure 7

Experimental and simulated 24 h batch OUR profiles for sludges harvested from IFFD and CFCM systems. Kinetic constants for the simulated results calculated from the experimental data (see Figs. 3a and b) as set out in ***Appendix 1****. At low batch test VSS concentrations, the half saturation coefficient in the Monod function significantly influences the simulation results and is the reason for the smoothed decreases in OUR for the CFCM sludge (690 mg VSS/ℓ) compared with the precipitous decreases in OUR for the IFFD sludge (1 360 mg VSS/ℓ).*

biomass approach (Kappeler et al., 1993. Wild et al., 1994). With this approach, enzyme concentrations are modelled, as are organism and substrate concentrations, allowing a change in external substrate (RBCOD) concentration to stimulate a change in an internal enzyme concentration which in turn stimulates a change in organism maximum specific growth rate or half saturation coefficient. In this way the selector effect (increased μ_H and K_s) is automatically included without the necessity of manually changing the values of μ_H and K_s and will be manifested if the system configuration incorporates alternating feed-starve conditions (RBCOD concentration gradient).

Design of selector reactors

Part 3: Development of a design procedure for aerobic selector reactors

From the above it is clear that the design and efficacy of the selector reactor hinges around removal and utilisation of the influent soluble biodegradable COD concentration (RBCOD). In order to design a selector reactor, a knowledge of this concentration in the influent is therefore required.

Determination of the RBCOD fraction

The Berkeley group measured the RBCOD concentration by means of the 0.45 μm filtration method, taking due account of the non-degraded soluble component represented by the soluble COD remaining after the initial high OUR phase (Fig. 6). Mamais et al.

(1993) later refined the method by introducing a $Zn(OH)_2$ flocculation step after filtration to remove colloidal material that may pass through the 0.45 µm membrane and contribute to the soluble COD. The biodegradable component of this soluble COD is estimated by subtracting the unbiodegradable component which is obtained from the effluent soluble COD concentration of a long sludge age system treating the particular waste water.

The UCT group measured the influent biodegradable soluble COD, or equivalently the readily biodegradable COD, with bioassay methods. Although these methods are much more tedious in that they require operation of biological reactors, they have the advantage of giving directly the RBCOD. For further information on waste-water characterisation, in particular the measurement of the readily biodegradable COD fraction by physical and biological methods see WRC (1984); Ekama et al. (1986); Dold et al. (1986); Torrijos et al. (1994); Henze et al. (1994); and Wentzel et al. (1995). In the last mentioned (Wentzel et al., 1995) a method is presented for measuring the influent active heterotrophic organism concentration, and therefore also reactor active organism concentration. The measurement of the influent RBCOD concentration is important not only for the design of selector reactors but also for the design of biological N & P removal plants, in which the RBCOD fraction also plays a pivotal role. The function of the anaerobic reactor as a selector in these plants is discussed in Ekama et al. (1996b).

Sizing of the selector reactor

The design of the selector is examined by considering the kinetics of readily biodegradable COD utilisation. In the general activated sludge model (Dold et al., 1980; 1991; Dold and Marais, 1986; Henze et al., 1987), the utilisation of readily biodegradable COD is modelled in accordance with the Monod equation, i.e. :

$$\frac{dS_{bs}}{dt} = -\frac{(\mu_H/Y_H)\cdot S_{bs}}{(K_s+S_{bs})}\cdot X_H \quad (\text{mg COD}/\ell\cdot\text{d}) \qquad (1)$$

where:

S_{bs} = readily biodegradable COD concentration (mg COD/ℓ)
X_H = active organism concentration (mg AVSS/ℓ)
μ_H = maximum specific growth rate of the floc-formers (heterotrophs) (/d) $= Y_H \cdot K_{ms}$
Y_H = yield coefficient = 0.45 mg VSS/mg COD
K_{ms} = maximum specific readily biodegradable COD utilisation rate [mg COD/(mg AVSS·d)]
K_s = half saturation coefficient (mg COD/ℓ).

The K_s value for S_{bs} utilisation is usually less than 5 mg/ℓ, so that for S_{bs} utilisation down to 20 mg/ℓ, the term $S_{bs}/(K_s+S_{bs})$ in Eq. (1) is close to unity. Hence for most of the S_{bs} utilisation, Eq. (1) may be simplified to :

$$\frac{dS_{bs}}{dt} = -(\mu_H/Y_H)X_H = -K_{ms}X_H \qquad (2)$$

making the substrate utilisation reaction zero order with respect to S_{bs}.

Applying Eq. (2) to a S_{bs} mass balance around the selector reactor in a single-reactor aerobic activated sludge system gives:

$$\begin{pmatrix}\text{Mass change of}\\ S_{bs}\text{ in system}\end{pmatrix} = \begin{pmatrix}\text{Mass of}\\ S_{bs}\text{ in}\end{pmatrix} - \begin{pmatrix}\text{Mass of}\\ S_{bs}\text{ out}\end{pmatrix} - \begin{pmatrix}\text{Mass change of } S_{bs}\\ \text{through utlisation}\end{pmatrix}$$

$$V_s dS_{bs} = Q_i S_{bsi} dt - (1+s)\, Q_i S_{bs} dt - V_s dt\,(K_{ms})X_H \qquad (3)$$

$$\therefore \frac{dS_{bs}}{dt} = \frac{Qi}{V_s}[S_{bsi} - (1+s)\,S_{bs}] - K_{ms}X_H \qquad (4)$$

where :

Q_i = influent flow (ℓ/d)
V_s = volume of selector (ℓ)
s = underflow recycle ratio = Q_r/Q_i
S_{bsi} = readily biodegradable COD concentration in influent (mg COD/ℓ)

At steady state $dS_{bs}/dt = 0$ and hence :

$$K_{ms}X_H = \frac{Q_i}{V_s}[S_{bsi} - (1+s)\,S_{bs}] \qquad (5)$$

Now let the volume of the selector V_s be a fraction f_{vs} ($\approx f_{xs}$ for equal MLVSS concentrations in the selector and main aeration reactor) of the volume of the total biological reactor (including the selector) V_p i.e. $f_{vs} = f_{xs} = V_s/V_p$, also let the active fraction of the mixed liquor volatile settleable solids (MLVSS) be f_{av}, and the influent readily biodegradable COD concentration S_{bsi} a fraction f_{ts} of the total influent COD S_{ti}. Then, from Eq. (5) :

$$\therefore K_{ms} f_{av} X_v f_{xs} V_p = Q_i[f_{ts} S_{ti} - (1+S)\,S_{bs}] \qquad (6)$$

The objective of the selector is that most (>95%) of the readily biodegradable COD should be utilised in it so that the S_{bs} concentration leaving the selector is low. If most of the S_{bs} is utilised in the selector, then the term $(1+s)\,S_{bs}$ is negligible with respect to $f_{ts}S_{ti}$ and can be omitted without a significant error. Omitting the term and solving for the fractional volume of the selector f_{xs} yields :

$$f_{xs} = \frac{Q_i S_{ti}}{V_p X_v}\cdot\frac{1}{f_{av}}\cdot\frac{f_{ts}}{K_{ms}} = \frac{f_{ts}\,MS_{ti}}{f_{av}\,MX_v\,K_{ms}} \qquad (7)$$

Equation (7) shows that the relative size of the selector is directly proportional to the influent readily biodegradable COD fraction f_{ts} and inversely proportional to the readily biodegradable COD uptake rate K_{ms}. Note also that $X_v V_p$ is the mass of MLVSS in the system (which is denoted by MX_v, kg VSS) and $Q_i.S_{ti}$ (or equivalent $Q_{i\,ave}.S_{ti\,\text{weighted ave at ADWF}}$) is the total mass of COD applied to the system over the day (denoted by MS_{ti}, kg COD/d). The MX_v and its active fraction (f_{iv}) are related to the sludge age of the system, the average daily ADWF COD load (MS_{ti}) and the waste-water characteristics, i.e. from WRC (1984) :

$$MX_v = MS_{ti}\left\{\frac{(1-f_{up}-f_{us})\,Y_H R_s}{(1+b_H R_s)}(1+fb_H R_s) + \frac{f_{up}}{f_{cv}}R_s\right\} \qquad (8)$$

and

$$f_{av} = MS_{ti}(1-f_{up}-f_{us})\frac{Y_H R_s}{(1+b_H R_s)} / MX_v \qquad (9)$$

where:

f_{us}, f_{up} = unbiodegradable soluble and particulate COD fractions respectively
Y_H = yield coefficient = 0.45 mg VSS/mg COD
b_H = endogenous respiration rate = 0.24/d at 20°C
f = endogenous residue fraction = 0.20
f_{cv} = COD/VSS ratio of the sludge = 1.48 mg COD/mg VSS

An important outcome of Eq. (7) is that the selector reactor size in terms of the proportion of the VSS mass in the system it contains, is equal to the ratio of the influent RBCOD to active organism mass loading rate [$f_{ts} MS_{ti}/f_{av} MX_v$ - mg RBCOD/(mg AVSS.d)] and the RBCOD utilisation rate K_{ms}. Note that the selector reactor size is **not** a function of retention time. This does not mean that the selector reactor does not have a retention time; it does, but it is a proportion of the system retention time (nominal or actual). The system retention time (and thus the selector reactor retention time) depends on the system reactor volume, which in turn is dependent on the design VSS concentration (X_v) chosen for the section (i.e. $V_p = MX_v/X_v$, m^3).

Diurnal flow and load conditions need to be taken into account in sizing the selector. In the selector (in which the concentration of an appropriate electron acceptor is not limiting) the heterotrophic organisms are operating at their maximum RBCOD utilisation rate (K_{ms}) and the selector must be large enough so that RBCOD utilisation is virtually complete. The selector size is therefore proportional to the peak influent RBCOD loading rate to active organism mass ratio. This means that in Eq. (7), for diurnal flow conditions, Q_i and S_{ti} are the peak load values at dry weather flow (DWF) conditions i.e. Q_{iPDWF} and S_{tiPDWF}. However, because the mass of active organisms ($f_{av} MX_v$) is governed not by the peak DW COD load but by the daily average DW COD load, the mass of VSS and the active fraction given by Eqs. (8) and (9) are based on average DW flow and load. Hence for diurnal flow and load conditions, the selector mass fraction f_{xs} becomes

$$f_{xsPDWF} = f_{ts} MS_{ti} \cdot L_r/(f_{av} MX_v K_{ms}) = L_r f_{xsADWF} \qquad (10)$$

where:

f_{ts} = readily biodegradable fraction of the total influent COD (S_{bsi}/S_{ti})

L_r = peak to average COD load ratio under DW conditions

= MS_{tiPDWF}/MS_{tiADWF}

= $(Q_{iPDWF} S_{tiPDWF})/(Q_{iADWF} S_{tiADWF})$

S_{tiADWF} = flow weighted average total COD concentration under dry weather flow conditions (S_{ti} weighted ave.)

Under diurnal flow and load conditions, to maintain a high RBCOD loading rate at average and minimum load periods, the selector size required to utilise all the RBCOD at peak load is best compartmentalised into three or four selectors in series as originally conceived by Chudoba et al. (1973a;b).

The K_{ms} rate required to size the selector is calculated from the IFFD batch test data such as that in Fig. 3a (see **Appendix 1**). In terms of the UCT kinetic modelling approach (see **Appendix 1**), the K_{ms} rate calculated from Fig. 3a is 6.67 mg RBCOD/(mg AVSS·d) or 283 mg RBCOD/(g AVSS·h). For the CFCM system - Fig. 3b - it is 1.70 mg RBCOD/(g AVSS·h) or 71 mg RBCOD/(g AVSS·h). The IFFD system value appears to be a fairly consistent and reproducible rate for sludges with a selector effect, so for design of aerobic (or anoxic selectors - see Ekama et al., 1996a Paper 3) in the absence of batch test data, a K_{ms} rate between 240 and 300 mg RBCOD/(g AVSS·h) is recommended. Lower K_{ms} rates will result in larger selectors, so that if the actual rate is higher, the RBCOD will be utilised before the end of the selector zone. With compartmentalised selectors this should not be a problem because it results in the last selector compartment not having much RBCOD to remove. Consequently it is best to design with a lower K_{ms} rate which leads to larger selectors which then are able to absorb variations in RBCOD loading rate and the K_{ms}.

Calculation of oxygen demand in selector(s)

While the size of the selector is related to the RBCOD utilisation rate, the oxygen demand in the selector is the sum of the utilisation rates for RBCOD from the influent; SBCOD from the influent and self-generated through organism death and lysis; and nitrification[1]. From Fig. 3a, this can be seen to be as high as 75 mg O/(g VSS·h) so that at 3.5 g VSS/ℓ solids concentration, the volume-specific OUR would be 260 mg O/(ℓ·h). This is too high for surface aerators which are limited to a volumetric oxygen input of about 180 to 200 mg O/(ℓ·h) without severe floc disruption through excessive power input (>180 to 200 W/m^3). So to meet the high OUR, either fine bubble aeration with or without pure oxygen supplementation needs to be installed or the oxygen supply needs to be reduced. A lower oxygen input can be accommodated in a nitrifying plant because in the selector nitrification can be forfeited (but not in the main reactor) and nitrate can serve as an additional electron acceptor for the floc-former heterotrophs. From Fig. 3a (see **Appendix 1**) the nitrification OUR is 24.1 mg O/(g VSS·h) which, if ignored, reduces the total heterotrophic OUR (OUR_{Het}) to 52.1 mg O/(g VSS·h). This reduces the volume-specific OUR at 3.5 g VSS/ℓ to 182 mg O/(ℓ·h). In a non-nitrifying plant, the calculated heterotrophic OUR (OUR_{Het}) has to be met in all the compartments of the selector zone to avoid leakage of RBCOD through the selector into the main aeration reactor at peak flow and load. In a nitrifying plant, less than the OUR_{Het} can be supplied depending on the nitrate mass flow rate to the selector via the recycle flow(s) (mixed liquor and/or underflow - see design of anoxic selectors, Ekama et al. (1996a)). The design principle for this situation is that sufficient electron acceptors (oxygen and nitrate) must be supplied to all selector compartments of the series at the peak RBCOD loading rate to utilise all the influent RBCOD in the selector zone. At minimum or average flow and load, the RBCOD will be fully utilised in the first or second compartment (of a series of say 4) and so only the first one or two compartments will be operating at maximum OUR, the remainder at a much lower OUR. In the absence of batch test data, the selector zone OUR can be estimated with the IAWQ (Henze et al., 1987) or UCT (Dold et al., 1991) activated sludge kinetic models, provided the appropriate μ_H value is given as input (see **Appendix 1**) (unfortunately these models cannot deal with split underflow recycles to the selector and main reactor, see below).

Without these models, the OUR can be estimated by adding the specific OUR for RBCOD and SBCOD utilisation (as mentioned above, nitrification can be ignored) i.e.

$$OUR_{Het} = OUR_{RBCOD} + OUR_{SBCOD} \qquad [\text{mg O/(g AVSS·h)}]$$

$$= (1-f_{cv} Y_H) K_{ms} + (1-f_{cv} Y_H) K_{mp} \qquad (11)$$

where:

K_{mp} = maximum specific slowly biodegradable (particulate) COD utilisation rate [mg COD/(mg AVSS·h)]

[1] In terms of the IAWQ kinetic modelling approach, the oxygen demand in the selector is the sum of the utilisation rates for RBCOD in the selector and nitrification, where the RBCOD in the selector has two sources, that from the influent and that produced from the hydrolysis of SBCOD originating from the influent and from organism lysis and death (see footnote 2 p 109).

where K_{ms} is between 240 and 300 mg RBCOD/(g AVSS·h) [5.8 to 7.2 mg COD/(mg AVSS·d)] and K_{mp} is between 90 and 100 mg SBCOD/(g AVSS·h)[2.1 to 2.4 mg SBCOD/(mg AVSS·d)].

For example in Fig. 3a, the height of the initial high specific OUR rectangle is equal to 76.9 - 38.1 = 38.8 mg O/(g VSS·h) which for the particular IFFD system conditions (f_{av} = 0.41) gives a K_{ms} = 283 mg RBCOD/(g AVSS·h) or equivalently μ_H = 3.1/d. (see **Appendix 1**). The specific OUR for SBCOD utilisation is relatively constant for different activated sludges and does not change in response to the presence or absence of a selector effect so the range given above can be accepted with reasonable certainty. The K_{mp} rate in the UCT dynamic model (Dold et al., 1991) formed the basis for the range of the SBCOD utilisation rate given above and is midway within it. Hence an estimate for the design OUR_{Het} for the batch test of Fig. 3a from Eq. (14) would be 0.334 · 280 · 0.41 + 0.334 · 90 · 0.41 = 38.3 + 12.7 = 51 mg O/(g VSS·h). The actual value for the test is 52 mg O/(g VSS·h) (see Fig. 3a) indicating that an accurate OUR_{Het} estimate is obtained with this simplified approach. Note that with the IAWQ model (Henze et al., 1987), the SBCOD utilisation contribution to OUR_{Het} is not considered - in this model SBCOD is hydrolysed to RBCOD and only RBCOD is utilised. OUR_{Het} is therefore calculated from the μ_H (or K_{ms}) rate directly ignoring the K_{mp} term in Eq. (11) i.e.

$$OUR_{Het} = 0.334 \cdot (4.16/0.45) \cdot 0.41(1000/24)$$
$$= 52.7 \text{ mg O/(g VSS·h)}$$

(see Fig. 3a, **Appendix 1** and footnote 2).

A strategy to reduce the volume-specific OUR in the selector

If the volume-specific OUR_{Het} is too high because of high VSS concentrations (X_v) or active fractions (f_{av}), it can be reduced by recycling only a part of the underflow stream from the secondary settling tank to the head of the selector zone, the remainder is discharged directly to the main reactor. The effect of this strategy on the stimulation of the selector effect has not been tested experimentally, but it is expected that the acquisition of the selector effect by the sludge would still take place but probably at a slower rate, because on average the sludge is now less frequently exposed to the alternating feed starve conditions. (The selector effect has been very effectively stimulated in IFFD systems with an alternating feed-starve cycle of 1 d - see Part 2 above and Van Niekerk, 1985). This strategy has the effect of distributing sludge mass differently between the selector and main reactor; the lower the proportion (f_s) of the underflow recycled to the selector, the lower the VSS concentration and hence the lower the volume specific OUR_{Het}. However, in order to maintain the selector reactor mass fraction (f_{xs}) at the required value obtained from Eq. (10) above, the volume of the selector needs to be enlarged at the expense of the main reactor volume. The relationships relating to this strategy are as follows:

$$f_{vs}/f_{xs} = (1 + sf_s)/[f_s(1 + s) + f_{xs}(1 - f_s)] \quad (12)$$

$$X_s/X_v = [(1+s)f_s(1 - f_{xs})]/[(1+sf_s)(1 - f_{vs})] \quad (13)$$

$$X_m/X_v = (1 - f_{xs})/(1 - f_{vs}) \quad (14)$$

where :

f_s = fraction of underflow recycled to the selector zone

s = underflow recycle ratio with respect to the influent ADWF

f_{vs}/f_{xs} = selector volume fraction ($f_{vs} = V_s/V_p$) as a ratio of its mass fraction ($f_{xs} = X_sV_s/X_vV_p$)

X_s/X_v, X_m/X_v = selector (X_s) and main (X_m) reactor VSS concentrations as a ratio of the weighted mean concentration of VSS in the system (X_v)

V_s, V_m, V_p = volumes of the selector, main reactor and system respectively (i.e. $V_p = V_s + V_m$)

The product of the system weighted mean VSS concentration (X_v) and the system volume (V_p) gives the mass of sludge in the system as given by Eq. (8) above. From Eqs. (12) to (14) it will be found that X_m is 101 to 107% of X_v and X_s is 95 to 50% of X_v for f values between 1.0 and 0.3 respectively. Also, the selector volume fraction is 105 to 202% greater than the mass fraction for this same range of f from 1.0 to 0.3. So with a system of 100 m³ total reactor volume (V_p) and a weighted mean reactor VSS concentration (X_v) of 3.5 kg VSS/m³, requiring a selector mass fraction (f_{xs}) of 0.06 (i.e. containing 0.06 · 100 · 3.5 = 21 kg VSS), if only 30% (f = 0.3) of a 1:1 underflow recycle ratio (s) is discharged to the selector, then the selector volume fraction (f_{vs}) is 0.06 · 2.02 = 0.121 i.e. 12.1 m³ leaving 100 - 12.1 = 87.9 m³ for the main reactor. The X_s/X_v and X_m/X_v ratios are 0.493 and 1.07 making X_s = 0.493 · 3.5 = 1.73 kg VSS/m³ and X_m = 1.07 · 35= 3.74 kg VSS/m³. The selector mass fraction (f_{xs}) remains 0.06 (21 kg VSS) but the selector VSS concentration is now only about half of that when the full underflow recycle (f=1) at 1:1 is discharged to the selector. With X_s at about half of X_v, the volume specific OUR_{Het} also is halved i.e. 52 · 1.73 = 90 mg O/ℓ·h, which is more easily attainable with mechanical aeration systems without unduly high volume specific power inputs.

The above design approach for aerobic selectors was applied to calculate the selector size for the next series of experiments directed towards evaluating the efficacy of selectors in the control of low F/M filament bulking in fully aerobic systems.

Evaluation of selector reactors

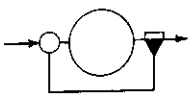
Part 4: Experimental evaluation of aerobic selectors in aerobic systems

System set-up

Two systems were operated, one a 15ℓ continuously fed, completely mixed aerated reactor (CFCM) which served as a control, the other a 14.7 ℓ continuously fed, completely mixed aerated reactor, with a preceding 0.3 ℓ aerobic selector reactor (CFCM/SEL) which served as the experimental system (see Table 2). For the particular conditions of the experiment (see Table 2 and Appendix 1), the selector fractional volume (f_{xs}) was calculated to be 0.020[2] i.e. 1/50th of the total system volume (0.30 ℓ in 15 ℓ). Because the system was operated under constant flow and load conditions, only a single selector was provided. In comparison to the selector reactor size found to control low F/M bulking by Lee et al. (1982) i.e. around 1/74th (0.014), a size of 1/50th (0.020) seemed reasonable.

As in the previous IFFD and CFCM experiments (Part 2 above), the two systems were started up with mixed liquor from the Mitchell's Plain activated sludge plant and fed Mitchell's Plain settled sewage. The starter sludge had a DSVI of about 250 mℓ/g and the dominant filamentous organisms (in descending order of dominance) were types 0581, 0092, 0675, *Nocardia* and type 0041. All of these filaments are classified as low F/M types. It was noted that *S. natans* was not observed in the starter sludge, nor had it been observed previously in the Mitchell's Plain plant.

TABLE 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 (CFCM)

SYSTEM	CFCM/SEL	CFCM
Operating conditions	Continuously fed completely mixed with selector	Continuously fed completely mixed without selector
Graphical representation		
Aeration	Fully aerobic	Fully aerobic
DO concentration; selector (mgO/ℓ) main reactor	2 - 4 2 - 3	2 - 3
Feed	Continuous (24h)	Continuous (24h)
Sludge source	Mitchell's Plain	
Sewage source	Mitchell's Plain settled	
Volume of feed (ℓ/d)	15	15
Concentration (mgCOD/ℓ)	350	350
TKN concentration (mgN/ℓ)	50 -70	50 -70
Sludge age (d)	20	20
Temperature (°C)	20	20
Volume of reactor (ℓ) main selector	 14.7 0.3	 15.0 -
MLVSS concentration (mg/ℓ)	1150	1150
MLSS concentration (mg/ℓ)	1400	1400
Load factor (F/M) [mgCOD/(gVSS.d)]	300	300
Nominal hydraulic retention time (h)	24	24
pH	7 - 8	7 - 8

[2] In Gabb et al. (1989b) f_{xs} was incorrectly calculated to be 0.015 i.e. 1/68th of the system volume; to accommodate possible variations in the influent RBCOD fraction and reduced RBCOD utilisation (K_{ms}) rates, the size of the selector was (fortuitously) increased to 0.020 i.e. 1/50th of the total system volume. The error arose because the IAWQ model K_{ms} (μ_H) rate i.e. 9.25 mg COD/(mg AVSS·d) (see **Appendix 1**) was used in Eq. (10) above (with L_r = 1.0) instead of the UCT model K_{ms} rate i.e. 6.8 mg RBCOD/(mg AVSS·d). Appreciating the significance of the difference is important. In Eq. (10) $f_{xs} MS_u L_r$ is the influent peak RBCOD mass flow rate and hence the RBCOD utilisation rate K_{ms} must relate to influent RBCOD only. This is the case in the UCT model where utilisation of RBCOD and SBCOD are considered separately via K_{ms} and K_{mp} rates (see Eq. 11). In contrast, in the IAWQ model, RBCOD to be utilised in the selector is derived from both the influent and from hydrolysis of the SBCOD (from the influent and self generated via organism death and lysis). To accommodate utilisation of this additional RBCOD, the K_{ms} (μ_H) rate in the IAWQ model is greater than that in the UCT model (see **Appendix 1**). In terms of the IAWQ model, the RBCOD load on the selector would need to include the RBCOD derived from SBCOD hydrolysis - if this additional RBCOD load is included in Eq. (10), then it would be correct to substitute the K_{ms} rate originating from the IAWQ approach (see **Appendix 1**). As it stands, Eq. (10) recognises only influent RBCOD and therefore a K_{ms} rate in terms of the UCT approach needs to be used in it.

Results and discussion

Criteria for identifying presence of selector effect

Jenkins et al. (1984) established three criteria whereby the presence of a selector effect in a sludge can be identified, viz.

- A high initial specific soluble COD (RBCOD) uptake rate (mg COD/mg VSS·d) with a concomitantly high specific OUR
- Virtually complete utilisation of the soluble biodegradable COD (RBCOD) in the selector reactor(s) (i.e. limited leakage to the main aeration reactor)
- The presence of significant numbers of *Zooglea* colonies.

During the experimental investigation, the CFCM/SEL system was checked for these three criteria by conducting at regular intervals: batch tests on sludge harvested from the system; soluble COD concentration profiles through the system; and microscopic examination of the sludge. From these tests it was observed that the three criteria were satisfied and therefore it was concluded that the selector reactor as designed had stimulated the selector effect.

Selector effect

The two systems were operated for 180 d from start-up. During this period, aerobic batch tests were conducted on sludge harvested from both systems, the initial OUR was measured and the RBCOD utilisation rate (K_{ms}) calculated (see **Appendix 1** or Still et al., 1985). In the starter sludge for both systems, the K_{ms} was 142 mg COD/(g AVSS·h). Figure 8 illustrates the change in K_{ms} with time for the two systems. In the CFCM system, the K_{ms} decreased to a value of 92 mg COD/(g AVSS·h) by day 54 and then to 67 mg COD/(g AVSS·h) by day 68. In the CFCM/SEL system the K_{ms} increased to 271 mg COD/(g AVSS·h) on day 54 and was 233 mg COD/(g AVSS·h) on day 67. Comparing these K_{ms} values with those measured in the IFFD and CFCM systems described in **Part 1**, it can be seen that:

- In the CFCM/SEL system the K_{ms} attained a similarly high value to that in the IFFD system [~ 250 mg COD/(g AVSS·h)].

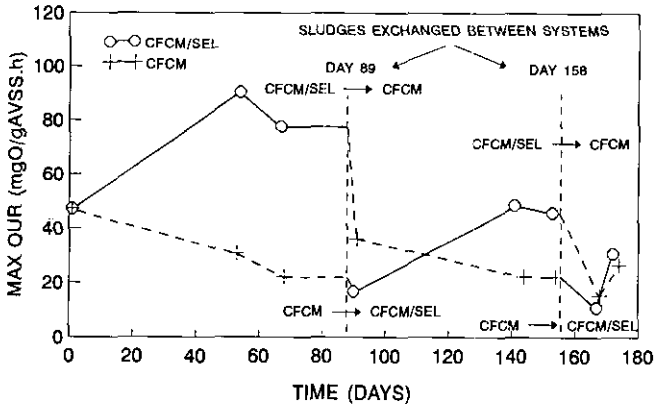


Figure 8

Maximum specific initial batch OUR in mg O/(g AVSS·h) on sludge harvested from two continuously fed completely mixed systems, one with (CFCM/SEL) and one without (CFCM) a selector reactor, from start up of the two systems (day 0) and after switching the sludges between the two systems on two occasions (days 89 and 158).

- In the CFCM system, the K_{ms} value was as low as that in the CFCM system described in Part 1 [~ 80 mg COD/(g AVSS·h)] i.e. about 1/3 of the IFFD and CFCM/SEL rates.

On day 89, the sludges in the CFCM and CFCM/SEL were interchanged between the two systems so that the CFCM sludge became exposed to CFCM/SEL conditions and the CFCM/SEL sludge became exposed to CFCM conditions. The objective of this was to determine how quickly the changes in K_{ms} develop under selector reactor conditions in comparison with IFFD conditions. Aerobic batch tests were conducted on the two systems on days 141 and 153; for the CFCM/SEL system the values of K_{ms} were 146 and 138 mg COD/(g AVSS·h) respectively and for the CFCM system, the values were 67 and 58 mg COD/(g AVSS·h) respectively. Although not as high as measured earlier in the CFCM/SEL system, these results confirmed that:

- the CFCM/SEL system stimulates a high K_{ms} rate (2½ times that of the CFCM system);
- when placed under CFCM conditions, a sludge with a selector effect progressively loses it, K_{ms} declining to a low value; and
- that these changes take place over a relatively short period of time (one sludge age)

Sludge settleability

The settleability of the sludge in both systems was monitored throughout the 180 d of operation and the results are illustrated in Fig. 9. The most obvious feature is that the CFCM/SEL system at no time developed a sludge with a DSVI > 200 m*l*/g, whereas the CFCM system had 2 incidents of filament proliferation (days 47 to 60 and days 97 to 112) in which the DSVI was greater than 600 m*l*/g. In both cases the dominant filaments causing bulking in the CFCM system were *S. natans* and/or *Thiothrix* and at all times in this system these were the dominant filaments. In contrast, in the CFCM/SEL system with the low DSVI, although these filaments were present, the dominant filament in two of the four identifications conducted between days 45 and 175 was *Haliscomenobacter hydrossis* (for details see Gabb et al., 1989b). *H. hydrossis* is listed as a low F/M filament but neither *S. natans* nor *Thiothrix* are classified as such; *S. natans* sorts in the low DO group and *Thiothrix* into the septic sewage or nutrient deficient group. Therefore when bulking did take place in the CFCM system it was not due to low F/M filaments.

During the two periods of very high DSVI (bulking) in the CFCM system, two techniques were tested to control the filament proliferation. In the first period (days 47 to 60) the dissolved oxygen DO concentration was increased from 2-3 to 7-8 mg O/*l* (day 57) because 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 m*l*/g. When the sludges were exchanged between the two systems on day 89, the DO of the CFCM system was reset to the earlier low concentration of 2-3 mg O/*l* i.e. the same as in the CFCM/SEL system. In the second bulking period (days 97 to 112) the same high DO control measure was applied to the CFCM system (i.e. increasing DO to 7-8 mg O/*l*) on day 98. However, this time it was unsuccessful and the DSVI continued to increase, from 500 m*l*/g on day 98 to approximately 1 100 m*l*/g on day 105. Clearly some cause other than low DO concentration was stimulating the growth of *S. natans*.

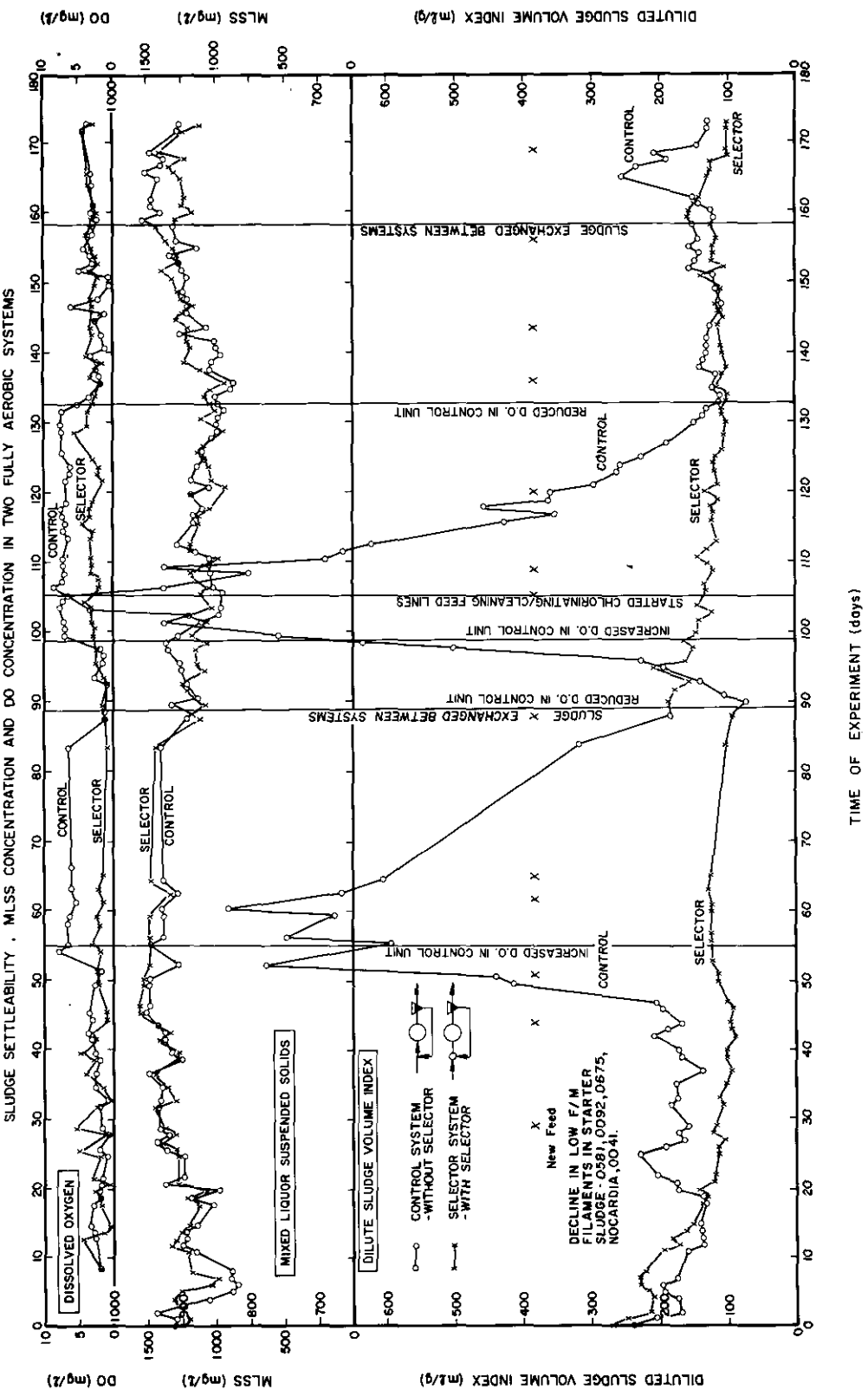


Figure 9

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 (x— x) and (2) without an aerobic selector (o— o), both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20 d) and temperature (20°C). Note that in the first 20 d, 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 in both systems. Thereafter the selector (CFCM/SEL) system DSVI remained relatively low (< 125 mℓ/g) but that in the control system (CFCM) increased dramatically (> 700 mℓ/g) from day 45 due to an explosive proliferation of S. natans *and* Thiothrix. *After the sludges were exchanged between the two systems on day 89, the CFCM system showed a second explosive proliferation of* S. natans; *the cause was found to be seeding from attached growth of* S. natans *on the influent feed line walls.*

Causes of Sphaerotilus natans *proliferation*

In many of the laboratory-scale investigations examining the effect of alternating feed-starve conditions (selector effect) on bulking in low F/M systems (see Part 1 above), *S. natans* was the dominant filament. In this respect, the CFCM system operated in this investigation was no different. However, *S. natans* bulking was regarded as an intrusion in the experimental programme because these filaments are not low F/M types and were not identified in the South African full-scale plants (Blackbeard et al., 1986; 1988); the principal objective was to verify that the selector effect could control low F/M filaments, filaments which up to this stage could not be sustained at bulking proportions in the laboratory systems operated as controls. Consequently methods were sought to eliminate the *S. natans* (and *Thiothrix*) filament intrusion so that the research programme could continue without restarting the experimental systems.

In seeking an explanation for the proliferation of *S. natans* in the CFCM system in particular, and in laboratory-scale systems in general (as opposed to the low incidence in full-scale plants) cognizance was taken of the findings of Gabb et al. (1985). In that work it was concluded that growth of *S. natans* in pilot plants was promoted by continuous seeding from attached growth of *S. natans* on the feed line walls. Consequently a routine for cleaning of the feed lines was instituted on day 105 (DSVI ~ 1100 mℓ/g) and thereafter the DSVI decreased to 100 mℓ/g by day 133. Proliferation of *S. natans* did not recur in the CFCM system over the following 42 d to the termination of the experiment on day 175 even after the DO concentration was reset to 2-3 mg O/ℓ on day 132. *S. natans* and *Thiothrix* were identified in the CFCM/SEL system but did not proliferate to excessive proportions (DSVI < 150 mℓ/g) indicating that even with seeding, the selector effect was able to control the proliferation of these filaments. This is in conformity with the literature cited in Part 1; in experiments in which selector reactors were reported to control bulking sludges, where the filaments were identified, invariably these were *S. natans* and *Thiothrix*. A more complete discussion of the role of *S. natans* seeding on its proliferation in laboratory and pilot-scale systems is given by Gabb et al. (1989a).

Summary

From the aerobic selector experimental results:

- In incidences in which bulking was noted in the control (CFCM) system, the problematic filaments were *S. natans* and *Thiothrix*; at no stage did filaments of the low F/M group proliferate.
- Inducement of the selector effect in the CFCM/SEL system appeared to control the growth of *S. natans* and *Thiothrix*.
- It was not possible to determine the role of the selector effect in the control of low F/M bulking since filaments of this group did not develop in the aerobic CFCM (control) systems.
- It can be concluded that the CFCM/SEL configuration developed a selector effect since the three criteria relating to selector reactor systems (Jenkins et al., 1984) were satisfied, i.e. the presence of *Zooglea*, a high initial OUR and RBCOD uptake rate measured in sludge from the system under batch test conditions, and virtually complete uptake of RBCOD in the selector reactor.

Conclusions

From the above experiments the following conclusions can be drawn:

- Soluble (<0.45 μm) COD (readily biodegradable COD, RBCOD) uptake rates (K_{ms}) stimulated under alternating feed-starve conditions, viz batch fed systems (IFFD); or continuously fed completely mixed systems including a selector reactor (CFCM/SEL), are 2 to 3 times higher [250 mg COD/(g AVSS·h)] than those measured in continuously fed completely mixed systems without selector reactors (CFCM) [80 mg COD/(g AVSS·h)]. For the IFFD and CFCM/SEL systems, the high soluble COD uptake (K_{ms}) rate has a concomitantly high initial OUR and similarly, for the CFCM systems, the low soluble COD uptake (K_{ms}) rate has a concomitantly low initial OUR. A sludge in which a high RBCOD and oxygen uptake rate has been stimulated is said to have acquired a selector effect.
- The selector effect can be stimulated in a sludge under alternating feed-starve conditions over a period (about half, 15 d) less than the system sludge age (30 d). Similarly, unless continuously subjected to alternating feed-starve conditions, the selector effect is lost over a similar period.
- Soluble biodegradable COD (RBCOD) and oxygen uptake rates in sludges with (or without) a selector effect observed in this investigation are similar to those observed by Van Niekerk (1985) because the oxygen utilised per COD taken up is in the approximate ratio 1:3. While Van Niekerk (1985) interprets this ratio in terms of an intracellular COD storage mechanism, it is demonstrated that this ratio conforms to the accepted heterotrophic organism catabolic-anabolic kinetic behaviour as embodied in the general activated sludge kinetic simulation models incorporating Monod kinetics such as those by Dold et al. (1980; 1991) and Henze et al. (1987). As a result it was found possible to accurately simulate batch test RBCOD and OUR behaviour of sludges with and without the selector effect by appropriately adjusting only the Monod constants μ_H (maximum specific growth rate of heterotrophs) and K_s (half saturation coefficient). Interestingly, the alternating feed-starve conditions were found also to increase the μ_N (maximum specific growth rate of nitrifiers).
- A selector reactor design procedure (size and oxygen demand) was developed. This procedure is shown to be consistent and fully integrated with current activated sludge simulation models, which therefore can be used to simulate selector reactor behaviour (RBCOD removal and OUR). A laboratory selector reactor sized in accordance with the procedure was found to satisfactorily stimulate a selector effect.
- Low F/M filament bulking sludges (DSVI > 250 mℓ/g) containing *M. parvicella* and types 0914, 0092, 0675, 0803 obtained from N removal full-scale plants and placed in fully aerobic laboratory-scale systems as starter sludge, invariably ceased bulking (DSVI < 80 mℓ/g) in 2 to 3 weeks irrespective of the presence or not of a selector effect.
- When the laboratory systems did bulk (DSVI > 200 mℓ/g), it was not due to low F/M filaments but due to *S. natans* and *Thiothrix* and then only in the systems which did not stimulate a selector effect, i.e. in the CFCM systems.
- It was established that *S. natans* bulking in the CFCM system took place as a result of seeding from attached *S. natans* growth on the influent feed line walls - regular cleaning of the feed lines eliminated the bulking problem.
- *S. natans* and *Thiothrix* did not proliferate in the CFCM/SEL system, indicating that the selector effect successfully suppressed *S. natans* and *Thiothrix* bulking (despite seeding from the influent feed line walls). This observation is in conformity with published literature in this area.

- The frequent incidence of *S. natans* proliferation in laboratory-scale systems in other investigations of this kind around the world suggests that seeding of these organisms may have been present also, as in this investigation. Indeed the success of aerobic selectors in controlling the bulking by *S. natans* in these systems which were generally low F/M systems, may have contributed to the notion that aerobic selectors are effective for controlling bulking by low F/M filaments.
- A disturbing feature of this investigation is that the low F/M filaments could not be sustained in the fully aerobic CFCM (control) systems. Consequently no definitive conclusion can be drawn regarding the efficacy of aerobic selectors for controlling these filaments.

The non-proliferation of the low F/M filaments in the fully aerobic systems could not have been a consequence of the influent wastewater characteristics; the same waste water fed to modified UCT biological N & P removal systems operated in the UCT laboratory under a different research programme **did** exhibit low F/M filament proliferation. As a result it was presumed that the fully aerobic systems had the propensity to sustain the presence of low F/M filaments but for some unknown reason did not manifest low F/M filament bulking. Because one of the main objectives of the research investigation was the control of low F/M filaments in N and N & P removal systems, the next stage was to investigate whether or not the selector effect could be stimulated under anoxic conditions. If so, and the selector effect is shown to control low F/M filament proliferation, then anoxic selectors can be implemented for bulking control without the loss of N removal. This aspect is investigated in Ekama et al. (1996a).

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APPENDIX 1
Calculation of maximum sipecific growth rate of heterotrodhs (μ_H) and nitrifiers (μ_N) from 24 h aerobic batch test data

List of symbols

Additional symbols used in **Appendix** only. Those not in the list below are defined in list below the **Abstract**.

f_{bs} = readily biodegradable COD fraction of the influent with respect to the biodegradable COD
f_n = fraction of the MLVSS which is organic N (usually = 0.10 mg TKN-N/mg VSS)
f_{us} = influent unbiodegradable soluble COD fraction
f_{up} = influent unbiodegradable particulate COD fraction
f_{nu} = influent unbiodegradable soluble TKN fraction
TSS = total suspended solids concentration (mg TSS/ℓ)
K_{mn} = maximum specific nitrate generation rate by nitrifiers (mg NO_3N^--N/(mg active nitrifier VSS·d)
Y_N = yield coefficient of nitrifiers (mg active nitrifier VSS generated/mg NO_3^--N generated)

The design procedure for aerobic (or anoxic, see Ekama et al. 1996a) selectors requires the maximum specific readily biodegradable COD utilisation rate K_{ms}, or, in terms of the kinetic activated sludge models (Henze et al., 1987; Dold et al., 1991), the maximum specific growth rate of heterotrophs (μ_H), to be known. Other important information required is the influent readily biodegradable COD fraction with respect to total COD f_{ts} ($= S_{bsi}/S_{ti}$) and active fraction of the VSS f_{av} (see Eq. 10). The former (f_{ts}) can be found from the same batch test results from which μ_H is calculated (see Ekama et al., 1986) and the latter (f_{av}) from operation of the parent system from which the sludge for the batch test is harvested (WRC, 1984; Ekama et al. 1986). If the parent system is operated on an intermittently fed fill and draw (IFFD) basis, then only one system is required and all the data are obtained from the same system. However, IFFD systems have the disadvantage that the OUR has to be measured continuously over the day to enable calculation of the daily mass of oxygen utilised so that COD mass balances over the system can be checked to evaluate the accuracy of the batch test data (Wentzel et al., 1995). Continuous OUR meters are available to do this (Randall et al. 1991; Spanjers and Olsson, 1992). Procedures for checking COD and N mass balances on CFCM systems, and for calculating the active fraction (f_{av}), the influent readily biodegradable COD fraction (f_{bs} - with respect to biodegradable COD or f_{ts} - with respect to total COD) and the other waste-water characteristics (f_{us} and f_{up} - unbiodegradable soluble and particulate COD fraction respectively and f_{nu} - unbiodegradable soluble TKN fraction) are given by Ekama et al. (1986). Also, the COD/VSS (f_{cv}) and TKN/VSS (f_n) ratios of the sludge will have been measured or assumed at the standard values (f_{cv} = 1.48 mgCOD/mgVSS, f_n = 0.10 mgN/mgVSS). By following the principles of the N and COD mass balance, these procedures are readily adapted to IFFD systems. If the COD and N mass balances are good (>95%) then the experimental systems will have been operated well and the waste-water characteristics (f_{us}, f_{up}, f_{nu}) and kinetic (b_H) and stoichiometric (f_{cv}, f_n, Y_H) constants for the heterotrophic organisms will have been established with sufficient accuracy. These values are therefore presumed known for the calculation of the K_{ms} (μ_H) rate from 24 h batch test data shown in Figs. 3a and b (see Table A1 below).

TABLE A1
CALCULATION OF (i) HETEROTROPHIC AND (ii) NITRIFICATION OXYGEN DEMAND, (iii) OXYGEN RECOVERY, (iv) NITRIFIER MAXIMUM SPECIFIC GROWTH RATE (μ_N) (v) HETEROTROPHIC MAXIMUM SPECIFIC RBCOD UTILISATION RATE (K_{ms}) AND ASSOCIATED MAXIMUM SPECIFIC GROWTH RATE (μ_H) IN TERMS OF UCT AND IAWQ KINETIC MODELS AND (vi) THE INFLUENT READILY BIODEGRADABLE COD FRACTION FROM THE BATCH TEST DATA SHOWN IN FIGS. 3A AND B FOR THE IFFD AND CFCM SYSTEMS RESPECTIVELY

Parameter	IFFD	CFCM
Mass of COD added per d	5.4 ℓ at 628 = 3 391 mg COD	0.91 ℓ at 624 = 568 mg COD
Mass of TKN added per d	5.4 ℓ at 99.4 = 537 mg N	0.91 ℓ at 99.4 = 90.5 mg N
Mass of VSS added per d	4.6 ℓ at 2917 = 13 418 mg VSS	2.39 ℓ at 938 = 2 242 mg VSS
Loading rate of batch test	3 391/13 418 = 0.253	568/2 242 = 0.253
Batch test volume	5.4 + 4.6 = 10 ℓ	0.91 + 2.39 = 3.3 ℓ
Measured VSS and TSS (mg/ℓ)		
Start	1 348 ; 1 537	690 ; 788
End	1 384 ; 1 571	690 ; 819
Mean	1 366 ; 1 554	690 ; 804

Parameter	IFFD	CFCM
Expected VSS from dilution[1] (mg/ℓ)	1 342	679
Sludge age of parent system (d)	30	30
Waste-water type	settled	settled
Waste-water characteristics		
Unbiodegradable particulate COD (f_{up})	0.00	0.00
Unbiodegradable soluble COD (f_{us})	0.08	0.08
Active fraction (f_{av}) (Eq. 9)	0.41	0.41
1. Calculate heterotrophic oxygen demand		
Active VSS added (mg AVSS)	0.41. 13 418 = 5501	0.41·2242 = 919
Biodegradable COD added ($1-f_{up}-f_{us}$) (mg COD/d)	0.92 · 3 391 3120	0.92 · 568 523
Mass active VSS generated in 1 d (mg AVSS)	0.45 · 3 120 = + 1 404	0.45·523 = + 235
Mass active VSS lost in 1 d via endogenous respiration (mg AVSS)	0.24 · 5 501 = - 1 320	0.24 · 919 = - 221
Net active VSS in test (mg AVSS)	5 501 + 1 404 - 1 320 = 5 585	919 + 235 - 221 = 933
Oxygen required for synthesis (mg O/d)	0.334 · 3120 = 1 042	0.334 · 523 = 175
Oxygen required for endogenous resp. (mg O/d)	1.48 · 0.8 · 0.24 · 5 585 = 1 587	1.48 · 0.8 · 0.24 · 933 = 265
Heterotrophic oxygen demand (mg O/d)	2 629	440
2. Calculate nitrification oxygen demand		
N required for synthesis (mg N/d)	0.10 · 1 404 = 140.4	0.10 · 235 = 23.5
N released due to endogenous resp. (mg N/d)	0.10 · 0.8 · 1 320 = 105.6	0.10 · 0.8 · 221 = 17.7
TKN conc. at end of test (mg N/ℓ)	4.2	3.3
Nitrate generated (mg N/d)	537 - 4.2 · 10 - 140.4 + 105.6 = 460	90.5 - 3.3 · 3.3 - 23.5 + 17.7 = 73.8
Nitrification oxygen demand	4.57 · 460 2103	4.57 · 73.8 = 337
3. Total oxygen demand (mg O/d)	2 629 + 2 103 = 4 732	440 + 337 = 777
per g VSS [mg O/g -VSS-d)	4 732/(1.342 x 10) = 353	777/(0.679 x 3.3) = 347

Parameter	IFFD	CFCM
4. Check oxygen recovery		
Area under OUR curve [mg O/(g VSS·d)] (see Figs. 3a & 3b)	16.1 + 178.4 + 138.4 = 332.9	17.2 + 195.3 + 142.3 = 355
% oxygen recovery	333/353 = 94%	355/347 = 102%
5. Calculate μ_N		
% nitrifiers in VSS mass of parent systems[2]	5.5%	5.5%
Nitrification stopped after	6.5 h	9.5 h
Nitrification rate (K_{mn})	460/(13 418 · 0.055)	73.8/(2 242 · 0.055)
(mg NO_3-N/(mg Nit VSS·d)	· 24/6.5 = 2.30	· 24/9.5 = 1.51
μ_N (= $K_{mn} \cdot Y_N$) (/d)	0.23	0.15
Nitrification oxygen demand [(mg O/(g VSS·h)]	2 102/(13.42 · 6.5) = 24.1	337/(2.24 · 9.5) = 15.8
6. Calculate heterotrophic K_{ms} (or μ_H)[3]		
5.1 IA WQ model (Henze et al., 1987)	(Fig. 3a)	(Fig. 3b)
Batch test initial max.sp. OUR	76.9	35.9
Heterotrophic max. OUR	76.9 - 24.1	35.9 - 15.8
(mg O/g VSS·h)	52.8	20.1
K_{ms} rate	52.8/(0.334 · 0.41)	20.1/(0.334 · 0.41)
- mg COD/(g AVSS·h)	= 386	= 147
- mg COD/(mg AVSS·d)	= 9.26	= 3.53
μ_H (= $Y_H K_{ms}$) (mg AVSS/mg AVSS·d)	= 4.17	= 1.59
5.2 UCT model (Dold et al., 1991)	Fig. 3a	Fig. 3b
Initial OUR for RBCOD utilisation	76.9 - 38.1 = 38.8	35.9 - 26.2 = 9.7
K_{ms} mg COD/(g AVSS·h)	38.8/(0.334 · 0.41) = 283	9.7/(0.334 · 0.41) = 71
mg COD/(mg AVSS·d)	= 6.79	= 1.70
μ_H (= $Y_H K_{ms}$)	0.45 · 6.80	0.45 · 1.70
(mg AVSS/(mg AVSS·d)	= 3.1	= 0.77
7. Readily biodegradable COD fraction		
Area under high initial OUR	Fig. 3a	Fig. 3b
(mg O/g VSS)	16.1	17.2
RBCOD mass utilised	16.1 · 13.42/(0.334)	17.2 · 2.24/(0.334)
(mg COD)	647	115
Mass bio.COD added (mg COD)	3 120	523
f_{bs} fraction	647/3 120 = 0.21	115/523 = 0.22
f_{ts} fraction	647/3 391 = 0.19	115/678 = 0.20

Notes

1 For this settled waste water with very little unbiodegradable particulate COD (f_{up} = 0.00 in this calculation, 0.04 in the simulations of Figs. 3a and b), all the particulate COD is biodegradable and utilised within the 24 h batch test duration. With the VSS generated (synthesis of active mass and accumulation of endogenous residue) and lost (endogenous respiration) being approximately equal for these particular parent systems and batch test conditions, it is reasonable to expect the VSS concentration in the batch test to be approximately equal to the mass of VSS added diluted into the batch test volume. For raw waste waters with appreciable unbiodegradable particulate COD (VSS) content and parent or batch test conditions that result in a significant difference between the VSS generated and lost, the VSS concentration at start and end of the batch test expected from dilution may be significantly different to that measured.

2 For the parent systems (IFFD and CFCM) the mass of COD fed (MS_{ti}) was 3 500 mg COD/d. The mass of VSS in the reactor (MX_v) generated from this with f_{up} = 0 and f_{us} = 0.08 and sludge age 30 d is MX_v = 3 500 (0.92 • 1.646 • 2.44+0) = 12 933 mg VSS. The nitrogen incorporated in wasted sludge therefore is 0.10 • 12933/30 = 43.1 mg N/d. The average influent and effluent TKN masses were measured to be 595 and 30.1 mg N/d respectively. Therefore the nitrate generated by nitrification was 595 - 43.1 - 30.1 = 522 mg N/d. Accepting the Y_N and b_N, values of nitrifiers to be 0.10 mgVSS/mgN and 0.04/d respectively, the nitrifier active VSS mass in the parent systems is MX_n = 0.10 • 522 • 30/(1+0.04 • 30) = 712 mg VSS. Hence the % VSS of the nitrifiers is 712/12935 • 100 = 5.5% or equivalently 55 mg nitrifier VSS/g heterotrophic VSS.

3 *The difference in the* K_{ms} (or μ_H) for the IAWQ and UCT kinetic models arises from a different conceptual approach to modelling utilisation of influent RBCOD and SBCOD (see Dold and Marais, 1986). In the former, only RBCOD is utilised and all SBCOD, whether from the influent or generated via organism death and lysis (cf. endogenous respiration) is first hydrolysed to RBCOD and then released to the bulk liquid to add to the RBCOD pool before utilisation. In the latter, the kinetic formulations of utilisation of RBCOD and hydrolysis of SBCOD are the same; but the hydrolysed SBCOD is not returned to the bulk liquid. Instead it is utilised directly by the active heterotrophic mass. Therefore in the IAWQ model all utilised COD passes through the RBCOD form whereas for the UCT model only the influent RBCOD fraction is utilised as RBCOD. For this reason the calculated K_{ms} (μ_H) for the IAWQ model is based on the total initial high heterotrophic OUR (total minus nitrification OUR), whereas for the UCT model it is based only on the height of the RBCOD component of the initial high OUR (area 1, Figs. 3a and b).