Filamentous organism bulking in nutrient removal activated sludge systems. Paper 3: Stimulation of the selector effect under anoxic conditions

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

Abstract

Intermittently fed, fill and draw (IFFD) systems and continuously fed completely mixed (CFCM) systems, both having anoxic/aerobic mass fractions of 25 and 76% respectively, did not develop low F/M filament bulking sludges. Although the IFFD conditions induced a selector effect it could not be concluded that the selector effect controlled low F/M filament bulking in the system because the CFCM system, which did not induce a selector effect, also did not bulk. The selector effect induced in the IFFD system controlled *Sphaerotilus natans* proliferation, but this filament is not found in South African full-scale activated sludge plants. From anoxic batch tests a design procedure for anoxic selectors, fully integrated into current activated kinetic models, is presented. Because the low F/M filaments prevalent in full-scale N and N & P removal plants did not develop in the laboratory-scale systems, no conclusion can be made regarding the role of selectors (anoxic or aerobic) in control of these filaments.

List of symbols

a	=	mixed liquor recycle ratio from the aerobic to the primary anoxic reactor with respect to Q_{iADWF}
a_{opt}	=	a-recycle ratio that loads the primary anoxic reactor to its denitrification potential
ADWF	=	average dry weather flow
AVSS	=	active heterotrophic organism VSS concentration (mg AVSS/ℓ)
b_H	=	heterotrophic organism endogenous respiration rate (/d)
	=	0.24/d at 20°C
BT	=	batch test
CFCM	=	continuously fed completely mixed
COD	=	chemical oxygen demand
d	=	day
DO	=	dissolved oxygen (mg O/ℓ)
D_p	=	denitrification potential - concentration of nitrate that can be biologically denitrified in an anoxic reactor (mg N/ℓ influent)
D_{ps}	=	denitrification potential of anoxic selector (mg N/ℓ influent)
DSVI	=	diluted sludge volume index
f_{av}	=	fraction of VSS mass that is active organisms
f_{bs}	=	influent RBCOD fraction with respect to the biodegradable COD
f_{x1}	=	primary anoxic sludge mass fraction
f_{x1min}	=	minimum f_{x1} to ensure that all the influent RBCOD is utilised
f_{cv}	=	COD/VSS ratio of the sludge mass synthesised
F/M	=	food to micro-organism ratio
f_{ts}	=	fraction of the total influent COD (S_{ti}) that is readily biodegradable (S_{bsi})
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_1	=	initial rapid rate of denitrification in the primary anoxic reactor utilising RBCOD in mg NO_3-N/(mg AVSS·d)
K_2	=	second slower rate of denitrification in the anoxic reactor utilising SBCOD in mg NO_3-N/(mg AVSS·d)
K_{ms}	=	maximum specific substrate utilisation rate [mg COD/(mg AVSS·d)]
L_r	=	peak to average COD load ratio under dry weather conditions
min	=	minute
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_pX_v
MLE	=	modified Ludzack-Ettinger N removal system
MLSS	=	mixed liquor suspended solids
MLVSS	=	mixed liquor volatile suspended solids
mV	=	millivolts
N	=	nitrogen
N_c	=	nitrification capacity - concentration nitrate generated by nitrification (mg N/ℓ influent)
NUR	=	nitrate utilisation rate as mg NO_3-N/(ℓ·h) or mg NO_3-N/(g AVSS·h)
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 (ℓ/d)
Q_r	=	underflow rate (ℓ/d)
RBCOD	=	readily biodegradable COD

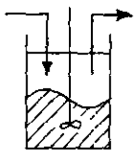
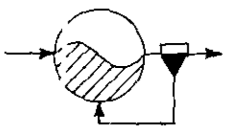
* To whom all correspondence should be addressed.
☎ (021) 650-2588; fax (021) 650-2603; e-mail ekama@engfac.uct.ac.za
Received 10 March 1995; accepted in revised form 1 December 1995.

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
SEL = selector
TKN = total Kjeldahl nitrogen
UCT = University of Cape Town
VSS = volatile suspended solids
X_H = active heterotrophic organism concentration
X_v = volatile suspended solids concentration (mg VSS/ℓ)
Y_H = sludge growth yield coefficient (mg VSS/mg COD)

Introduction

In Still et al. (1996) it was demonstrated that fully aerobic systems incorporating alternating feed-starve conditions, e.g. single-reactor IFFD systems and CFCM systems incorporating selectors (CFCM/SEL), induced in the sludge high initial uptake rates of RBCOD and OUR, i.e. the systems stimulated a selector effect. In comparison, fully aerobic single-reactor CFCM systems maintained low initial uptake rates of RBCOD and OUR, i.e. the system did not stimulate a selector effect. It was concluded that, in aerobic long sludge age systems, irrespective of whether or not a selector effect was induced, none of the aerobic systems supported low F/M filament growth in that when these systems were started up with low F/M filament bulking sludges (obtained from a full-scale N removal plant), they invariably ceased bulking. It was therefore not possible to determine whether or not the selector effect *per se* controlled low F/M filament proliferation.

TABLE 1
OPERATING PARAMETERS AND CONDITIONS OF IFFD AND CFCM SYSTEMS

SYSTEM	IFFD	CFCM
Operating conditions	Intermittently fed fill and draw	Continuously fed completely mixed
Graphical representation		
Aeration	Alternating: aeration(3h)/non-aeration (1h)	
DO concentration (mgO/ℓ)	0 during anoxic 2-4 during aerobic	
Feed	Intermittent (once daily)	Continuous (24h)
Sewage source	Mitchell's Plain settled	
Sludge source	Mitchell's Plain	
Mass of COD fed (mg/d)	5250	5250
Volume of feed (ℓ/d)	~6	15
Concentration (mgCOD/ℓ)	~875	350
Mass of TKN fed (mgN/d)	780	780
Sludge age (d)	20	20
Temperature (°C)	20	20
Volume of reactor (ℓ)	10	10
MLVSS concentration (mg/ℓ)	1700	1700
MLSS concentration (mg/ℓ)	2000	2000
Load Factor (F/M) [mgCOD/(gVSS.d)]	309	309
Nominal hydraulic retention time (h)	40	16
pH	7 - 8	7 - 8

The need for investigating whether or not a selector effect can be stimulated under anoxic conditions arises from the desirability for N removal by denitrification. If an aerobic selector receiving the influent and underflow recycle streams is placed ahead of a nitrification-denitrification system, most of the RBCOD will be utilised in the aerobic selector. This will result in a loss of denitrification in the subsequent anoxic zone by as much as 50% - the influent RBCOD will be utilised with oxygen as electron acceptor, not with nitrate. However, if the selector can be made anoxic rather than aerobic, the RBCOD will be utilised with nitrate as electron acceptor and no loss of denitrification will occur. If the selector effect should be found to satisfactorily control low F/M filament bulking, then anoxic selectors will provide low F/M filament control without the loss of N removal efficiency.

In this paper, the aerobic IFFD and CFCM experiments described in Still et al. (1996) are repeated, except that in this experiment alternating aeration/non-aeration periods were imposed on the IFFD and CFCM systems. The objective of imposing alternating aeration/non-aeration was to:

- observe the effect of alternating anoxic/aerobic periods on low F/M filament proliferation, and
- determine whether or not a high RBCOD uptake rate and a concomitantly high initial nitrate utilisation rate (NUR) could be induced in the sludge under anoxic conditions and to compare these rates with those observed under aerobic conditions.

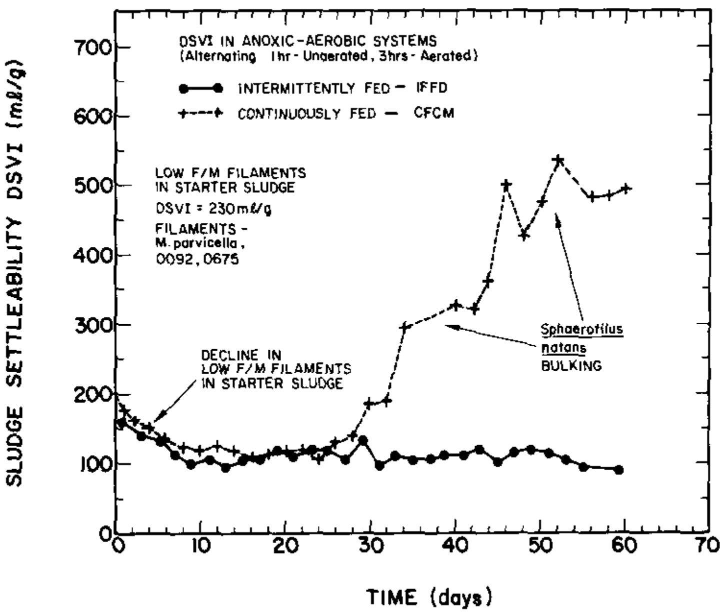


Figure 1

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

Experimental investigation

System set-up, operation and monitoring

Two single-reactor systems were set up, one IFFD, and one CFCM. For both systems all process parameters, such as sludge age (20 d), temperature (20°C), and mass of COD fed daily (5 250 mg COD/d), were the same (see Table 1). Both systems were fed Mitchell's Plain settled sewage and were started with Mitchell's Plain activated sludge. This starter sludge was a bulking one with a DSVI of 230 mℓ/g caused by the low F/M filaments *Microthrix parvicella*, and types 0092 and 0675.

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

The IFFD system was fed alternatingly under aerobic and anoxic conditions because this allowed the sludge to be exposed to high concentrations of RBCOD under both aerobic and anoxic conditions. If the IFFD system is fed under anoxic conditions only, then the sludge will not have been acclimatised to RBCOD uptake under aerobic conditions and the RBCOD utilisation rates with oxygen or nitrate would not be comparable. Conversely if the IFFD system is fed under aerobic conditions only, then the sludge will not have been acclimatised to RBCOD uptake under anoxic conditions and again the RBCOD utilisation rates with nitrate and oxygen would not be comparable. With a "balanced" exposure to RBCOD by feeding alternatingly, the RBCOD utilisation rate with oxygen is directly comparable with that with nitrate because the sludge has been equally acclimatised to RBCOD utilisation under aerobic and anoxic conditions.

The two systems were operated continuously for approximately 70 d. During this time the DSVI was measured every second day in both systems (Fig. 1). Also, in the IFFD system, the OUR was measured before feeding (on the days the system was aerobic after feeding) (Fig. 2). In the CFCM system the OUR was measured during two of the aerobic periods (Fig.2). Test methods were as described in Still et al. (1996) except that additionally nitrate concentrations were measured at less than 5 minute intervals with an Orion nitrate sensitive electrode as mV and calibrated against the nitrate samples taken every 20 minutes and analysed with the Auto Analyser Industrial Method 33.69W.

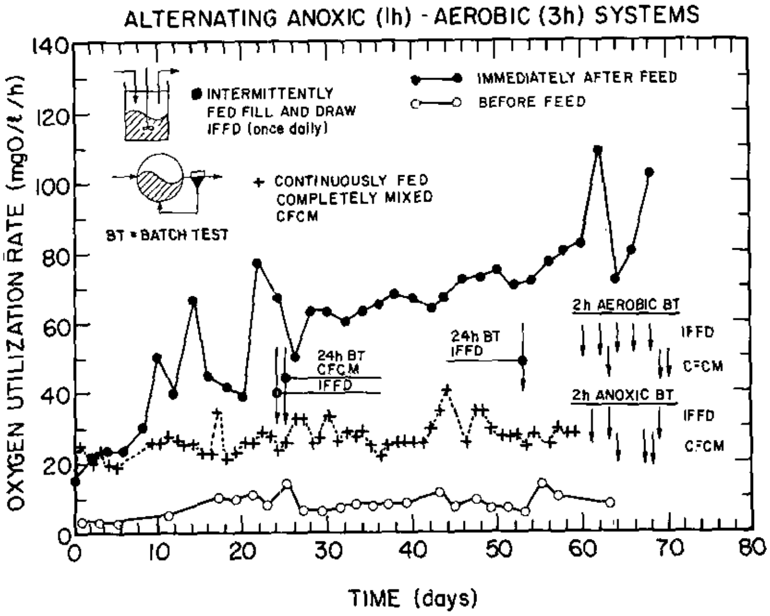


Figure 2

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

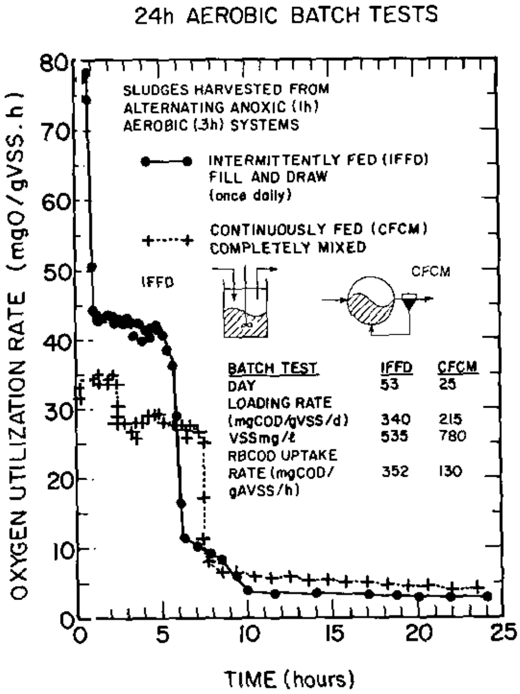


Figure 3

Oxygen utilisation rate [in mg O/(g VSS·h)] in 24 h aerobic batch tests (with nitrification) on sludges harvested from intermittently fed (•—•) and continuously fed (+-----+) alternating anoxic (1 h) - aerobic (3 h) systems both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20 d) and temperature (20°C). Note that the initial OUR in the intermittently fed system is much higher than that in the continuously fed system. (Visual best line fit)

Results

Selector effect

Between days 20 and 60 (see Fig. 2), aerobic batch tests of 24 h duration were conducted on sludge harvested from the two systems to check whether the OUR responses follow the same respective patterns as were induced in the sludges harvested from the fully aerobic IFFD and CFCM systems described by Still et al. (1996). Two such batch tests were conducted on the IFFD and one on the CFCM system and showed a high initial OUR for the IFFD system and a low initial OUR for the CFCM system confirming that a selector effect was induced in the IFFD, but not in the CFCM system. The results of these tests from days 53 and 25 for the IFFD and CFCM systems are shown in Fig. 3. In particular, in the CFCM system the initial RBCOD uptake rate associated with the low initial OUR was low [130 mg COD/g AVSS·h] whereas in the IFFD system, the initial RBCOD uptake rate associated with the high initial OUR was high [352 mg COD/(mg AVSS·d)].

Having established the similarity of the RBCOD uptake and associated initial OUR response under aerobic batch test conditions between the fully aerobic and anoxic-aerobic (CFCM and IFFD) systems, experiments were conducted to determine whether or not the OUR associated with the RBCOD uptake rate under aerobic conditions reflects as an equivalent NUR under anoxic conditions, i.e. does the high initial OUR under aerobic conditions in the IFFD system have a correspondingly high initial NUR under anoxic conditions and similarly for the low OUR in the CFCM system. To determine this, two types of batch test were conducted on sludge harvested from the two (anoxic-aerobic) systems between days 59 and 70: a 2 h aerobic batch test during which the OUR was measured; and a 2 h anoxic batch test during which the nitrate concentration was measured. Altogether, 8 aerobic batch tests were conducted, 5 on the IFFD system and 3 on the CFCM system, and 6 anoxic batch tests were conducted, 3 on each system (Fig. 2). The results of two aerobic batch tests on both systems are shown in Fig. 4 and of one anoxic batch test on both systems in Fig. 5. From Figs. 4 and 5 it can be seen that the anoxic/aerobic IFFD sludge had much higher initial OUR and NUR values than the anoxic/aerobic CFCM sludge. From the initial OUR and NUR of all the batch tests, the readily biodegradable COD (RBCOD) utilisation rate was calculated assuming no intracellular RBCOD storage takes place (see Still et al., 1996 or Ekama et al., 1986). The average RBCOD utilisation rates calculated for each of the 3 types of batch test conducted on the IFFD and CFCM systems (i.e. 24 h aerobic, 2 h aerobic, 2 h anoxic) are shown in Table 2, together with the average value for aerobic batch tests on the fully aerobic IFFD, CFCM/SEL and CFCM systems described in Still et al. (1996). From Table 2, it can be seen that the RBCOD utilisation rate under both aerobic and anoxic batch conditions is much greater in the IFFD system than in the CFCM system. These results are in agreement with those of Shao (1986), or Shao and Jenkins (1989).

The ability of the IFFD system sludge to take up RBCOD

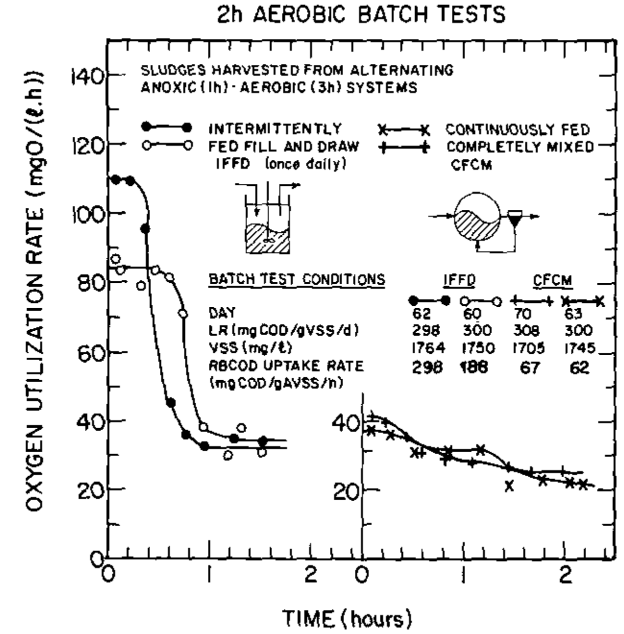


Figure 4

Oxygen utilisation rate [in mg O/(gVSS·h)] in 2 h aerobic batch tests (with nitrification) on sludges harvested from intermittently fed (●—●, o—o) and continuously fed (x—x, +—+) alternating anoxic (1 h) - aerobic (3 h) systems both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20 d) and temperature (20°C). Note that the initial OUR in the intermittently fed system is much higher than that in the continuously fed system (visual best line fit).

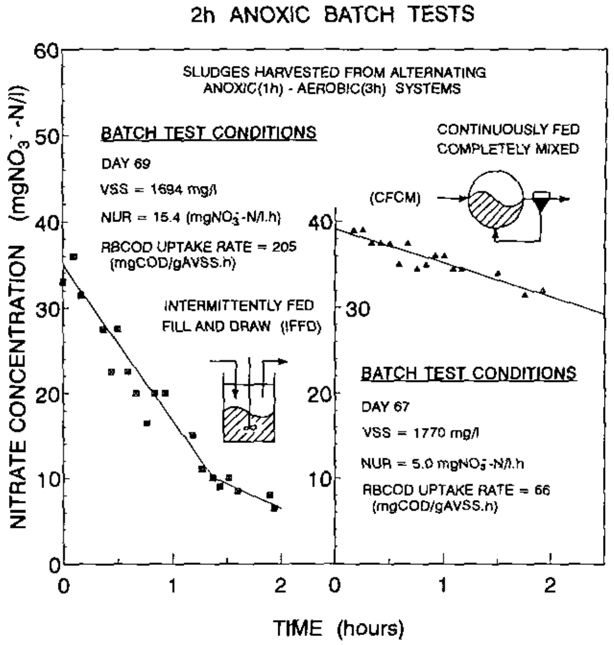


Figure 5

Nitrate concentration versus time response observed in 2 h anoxic batch tests at the same COD load per g VSS and the same VSS concentration (~1 700 mg VSS/ℓ) for sludges harvested from alternating anoxic-aerobic (3 h) single reactor systems fed (1) intermittently (batch) once daily (□—□) and continuously (△—△) both receiving the same sewage (Mitchell's Plain settled) and operated at the same sludge age (20 d) and temperature (20°C). Note that the NUR in the sludge from the intermittently fed system is more than 2 times higher than that in the sludge from the continuously fed system (visual best line fit).

rapidly indicates that the selector effect was present in the sludge under anoxic conditions. However, because the IFFD system was fed alternatingly under anoxic and aerobic conditions, it is not possible to state categorically from these experiments that the selector effect was induced by the anoxic conditions *per se* because the aerobic conditions may have contributed to the stimulation of the selector effect. Nevertheless it can be stated that the selector effect would have been induced under anoxic conditions only had the IFFD system been fed under anoxic conditions only. This conclusion is supported by the work of Shao (1986) and Stern and Marais (1974). The latter measured the first rapid rate of denitrification in plug-flow primary anoxic reactors to be 0.72 mg NO_3-N/(mg AVSS·d) which translates to an RBCOD utilisation rate of 258 mg COD/(g AVSS·h)[1]. This rate is as high as that observed in the IFFD system, i.e. 267 mg COD/(g AVSS·h) (Table 2) indicating that a selector effect was present in the sludge of Stern and Marais (1974). Unfortunately these rates cannot be compared with those of Shao and Jenkins (1989) because their rates are given as 10 to 12 mg NO_3-N/(g VSS·h) (not AVSS) and no information to estimate the active fraction is given. However, their value of 7.1 mg COD utilised per mg NO_3-N denitrified compares favourably with our value of 8.6. The similarity in K_{ms} and K_1 rates obtained in this investigation and that 10 years earlier by Stern and Marais (1974) with a different waste water, demonstrates not only that a selector effect was stimulated by the plug-flow primary anoxic reactors of Stern and Marais (1974) but also the reproducibility of this rate and hence its reliability for design of anoxic selectors (see below). Because in primary anoxic reactor systems the sludge is exposed to RBCOD under anoxic conditions only, the results demonstrate that the selector effect can be induced under anoxic conditions. Consequently, should the selector effect prove applicable for controlling bulking by low F/M filaments, then one may expect that anoxic selectors will be as effective as aerobic selectors, for the reason that similarly high RBCOD utilisation rates are stimulated under anoxic conditions (when nitrate serves as the electron acceptor) as under aerobic conditions (when oxygen serves as the electron acceptor).

[1] K_1 = 0.72 mgNO_3-N/(mg AVSS·d) · 1000 mg/g/24h/d = 30 mg NO_3-N/(g AVSS·h). The oxygen equivalent of nitrate on an electron acceptor basis is 2.86 mg O/mg NO_3-N and for every 1 mg O utilised $1/(1-f_{cv} Y_H)$ = 1/0.334 = 3.0 mg COD are degraded. Hence for 1 mg NO_3-N utilised 2.86 · 3.0 = 8.6 mg COD are degraded making the RBCOD utilisation rate equivalent to 30 mg NO_3-N/(g AVSS·h) = 30 · 8.6 = 258 mg RBCOD/(g AVSS·h)

Sludge settleability

The sludge settleability measurements for the anoxic-aerobic IFFD and CFCM systems are shown in Fig. 1. The starter sludge for both systems had a DSVI of 230 mℓ/g and contained filaments *M. parvicella*, 0092 and 0675. By the time routine analysis

TABLE 2
AVERAGE MAXIMUM SPECIFIC READILY BIODEGRADABLE COD UTILISATION RATE [mg RBCOD/(g AVSS·h)] UNDER ANOXIC AND UNDER AEROBIC CONDITIONS FOR SLUDGES HARVESTED FROM AN ALTERNATING ANOXIC/AEROBIC (IFFD) SYSTEM AND AN ALTERNATING ANOXIC/AEROBIC (CFCM) SYSTEM. ALSO LISTED ARE AVERAGES OBTAINED FROM AEROBIC BATCH TESTS ON SLUDGES HARVESTED FROM THE SAME TYPES OF SYSTEMS OPERATED FULLY AEROBICALLY (STILL ET AL., 1996).

READILY BIODEGRADABLE SUBSTRATE (RBCOD) UPTAKE RATE (Kms) (mgCOD/gAVSS.h)			
Batch Test Conditions	Parent System (anoxic/aerobic)		
	IFFD		CFCM
24h aerobic	310 (2)*		130 (1)
2h aerobic	307** (5)		85 (3)
2h anoxic	267*** (3)		70 (3)
Results from Paper 2	Parent System (aerobic)		
	IFFD	CFCM/SEL	CFCM
24h aerobic	320 (>20)	197 (4)	96 (24)

* Figure in brackets denotes number of tests.
** Calculated from OUR in mgO/(g AVSS·h) by multiplying by 3 mg COD per mg O utilised (Ekama et al., 1986).
*** Calculated from NUR in mg NO_3-N/(g AVSS·h) by multiplying by 8.6 mg COD per mg NO_3-N utilised (Ekama et al., 1986).

commenced a few days after the systems were started, the DSVI had already dropped to below 200 mℓ/g. By day 10 both systems had a DSVI around 110 mℓ/g. From day 25, the DSVI in the CFCM system began to increase rapidly, to 500 mℓ/g over about 20 d. The poor settleability was caused by a proliferation of the filament *Sphaerotilus natans* which is not a low F/M type, but a low DO type (Jenkins et al., 1984) and consequently of no particular relevance in this experiment. [The problem of *S. natans* bulking in laboratory systems was discussed in detail in Still et al. (1996) - for further information see Gabb et al. (1989)]. No control strategy against *S. natans* was taken such as imposing high DO concentration because of the disruption this may have had on the denitrification during the anoxic period. Also the influent feed lines were not chlorinated because these experiments were conducted during the time of the selector reactor experiments discussed in Still et al. (1996) and were terminated before it was confirmed that chlorinating the feed lines eliminated *S. natans* bulking. Consequently, the DSVI remained high (>500 mℓ/g) for the remainder of the experiment. In contrast, the DSVI in the IFFD system remained at around 100 mℓ/g; even though *S. natans* was identified in the sludge, it did not proliferate and cause poor sludge settleability. This observation is the same as that noted in Still et al. (1996) for fully aerobic conditions where *S. natans* (and *Thiothrix*) was controlled in the system with the selector effect but not in the system without the selector effect. This indicates that proliferation of *S. natans* is controlled by the selector effect irrespective of whether this is induced under anoxic or aerobic conditions.

Design of anoxic selectors

The most important criterion the selector needs to meet in order to be effective for controlling bulking (by certain filaments) is that all the influent RBCOD should be utilised in it (Shao and Jenkins, 1989). This means that not only must the selector be correctly sized, but also the supply of electron acceptors oxygen and/or nitrate must be sufficient to allow the heterotrophic active mass in the selector to utilise all the influent RBCOD at the peak flow and load period of the day. If sufficient electron acceptors are not supplied then RBCOD will not all be utilised by the heterotrophic organism mass and RBCOD will leak out of the selector and enter the main reactor, thereby defeating the principal requirement of the selector. (The question of the anaerobic reactor acting as a selector is discussed in Ekama et al., 1996). Insofar as sizing of anoxic selectors for diurnal flow and load conditions is concerned, the same calculation procedure and formulae for aerobic selectors [Eq. (10), Still et al. (1996)] apply. The only difference is in the RBCOD uptake rate (K_{ms}), which is slightly lower under anoxic conditions compared with aerobic conditions (85%, Table 2 above). Therefore for the same design situation the size of the anoxic selector is 10% larger than its aerobic counterpart. This difference is small and smaller than the differences in selector (anoxic or aerobic) sizes resulting from the range of K_{ms} rates given in Still et al. (1996). Consequently, there is little practical difference in aerobic and anoxic selector sizes because the range in K_{ms} rate is bigger than the difference between anoxic and aerobic values of this rate. Still et al. (1996) suggest that variation in K_{ms} can be taken into account by accepting K_{ms} rates near the lower end of the range and compartmentalising the selector.

For constant flow and load conditions the anoxic selector sludge mass fraction (f_{xs}) is identical to the minimum primary anoxic sludge mass fraction (f_{x1min}) for the modified Ludzack Ettinger (MLE) or 4 stage Bardenpho denitrification systems (see Eq. (6.20) in WRC, 1984)[2]. This is because both are concerned with the complete removal of the influent RBCOD in the 1st reactor receiving the influent and underflow recycle. This similarity allows the concepts of denitrification potential (D_p) and nitrification capacity (N_c) in the design of N removal systems (WRC, 1984) to be used to calculate the required recycle ratios - mixed liquor (a) and underflow (s) - to supply sufficient nitrate to the anoxic selector so that all the influent RBCOD is utilised at the peak flow and load time of the day.

For ADWF conditions the anoxic selector mass fraction (f_{xsADWF}) is given by Eq. (7) in Still et al. (1996) and is equal to f_{x1min}

---

[2] For constant flow and load conditions, f_{xs} and f_{x1min} are equal because:

$$f_{x1min} = \frac{f_{bs}(1-f_{cv}Y_H)(1+b_HR_s)}{2.86\,K_1\,Y_H\,R_s} \qquad \text{[Eq. 6.21 in WRC, 1984]}$$

$$= \frac{f_{bs}(1-f_{cv}Y_H)\,MS_{bi}}{2.86\,MX_H} \qquad \text{[from } MX_H = MS_{bi}\frac{Y_HR_s}{1+b_HR_s}\text{]}$$

$$= \frac{f_{ts}\,MS_{ti}\,(1-f_{cv}Y_H)}{f_{av}\,MX_v\,2.86\cdot K_1} \qquad \left[\begin{array}{l}\text{from } f_{bs}\,MS_{bi} = f_{ts}\,MS_{ti}\\ \text{and } MX_H = f_{av}\,MX_v\end{array}\right]$$

$$= \frac{f_{ts}\,MS_{ti}}{f_{av}\,MX_v\,K_{ms}} \qquad \text{[from } K_{ms} = 2.86\,K_1(1-f_{cv}Y_H)\text{]}$$

$$= f_{xs} \qquad \text{[Eq. (7) in Still et al., 1996]}$$

given by Eq. (6.21) in WRC (1984). In order to take account of peak dry weather flow (PDWF) conditions, the selector size for constant flow and load is increased by the factor L_r so that:

$$f_{xsPDWF} = f_{xsADWF} \cdot L_r \quad (1)$$

where L_r = the ratio of the peak to average RBCOD load [see Eq. (10) in Still et al., 1996, and f_{xsPDWF} is the selector mass fraction that would be obtained from Eq. (10) in Still et al., 1996].

The denitrification potential (D_{ps}) of the anoxic selector at size f_{xsADWF} at ADWF is given by Eq. (6.20) in WRC (1984) with $f_{xl} = f_{xsADWF}$, viz.:

$$D_{psADWF} = S_{bi} [f_{bs}/8.6 + K_2 f_{xsADWF} Y_H R_s/(1+b_H R_s)] \quad (mg\ N/\ell) (2)$$

where the symbols have their usual meaning (WRC, 1984) viz.

S_{bi} = flow weighted average biodegradable COD concentration (mg COD/ℓ)
f_{bs} = influent RBCOD fraction with respect to biodegradable COD
8.6 = mg COD utilised/mg NO_3-N denitrified
K_2 = K_2 denitrification rate - that by utilisation of SBCOD from the influent and organism death and lysis
= 0.101 mg NO_3-N/(mg AVSS·d) at 20°C
Y_H, B_H = heterotrophic organism constants; yield coefficient (0.45 mg VSS/mg COD) and endogenous respiration rate (0.24/d at 20°C)
R_s = system sludge age (d)

To take account of PDWF conditions, the selector size for ADWF is increased by L_r and at PDWF conditions the RBCOD load on the selector is L_r times the average RBCOD load; hence the denitrification potential of the anoxic selector of size f_{xsPDWF} at PDWF is:

$$\begin{aligned} D_{psPDWF} &= S_{biPDWF} [f_{bs}/8.6 + K_2 f_{xsPDWF} Y_H R_s/(1+b_H R_s)] \\ &= S_{bi} [(L_r f_{bs})/8.6 + K_2 (L_r f_{xsADWF}) Y_H R_s/(1+b_H R_s)] \\ &= L_r D_{psADWF} \end{aligned}$$

From the above, it can be seen that to take account of PDWF conditions, not only is the selector L_r times larger than that for ADWF conditions but also the denitrification potential of this PDWF sized selector (f_{xsPDWF}) at PDWF is L_r times the denitrification potential of the ADWF sized selector (f_{xsADWF}) at ADWF conditions. In other words D_{psPDWF} can be calculated using the flow weighted average influent biodegradable COD concentration S_{bi} but with both the RBCOD fraction (f_{bs}) and the anoxic selector mass fraction (f_{xsADWF}) scaled up by L_r, the former to take account of the increased RBCOD load at PDWF and the latter to take account of the larger selector mass fraction required to remove this larger RBCOD load at PDWF compared with ADWF.

Knowing D_{psPDWF}, the required a-recycle ratio (a_{opt} with respect to ADWF), to recycle sufficient nitrate to the anoxic selector (at f_{xsPDWF} size) for PDWF conditions at a specified underflow recycle ratio (s with respect to ADWF also) follows the same procedure and equations for calculating the optimum a-recycle ratio for the MLE system (Eq. (6.30) in WRC, 1984). While not analytically exact, this procedure gives a close approximation of the required a-recycle ratio because generally for long sludge age and hence long nominal hydraulic retention time systems (>15h), even with significant diurnal variations in flow and load, the nitrate concentration in the main aeration reactor is fairly constant over the day. As a consequence, variation in the main reactor nitrate concentration does not need to be taken into account to calculate the nitrate load on the anoxic selector at PDWF conditions - the nitrification capacity (N_c) at ADWF (as given by Eq. (5.29) in WRC, 1984) is a sufficiently close approximation of the nitrate concentration generated in the main reactor over the day. In designing a-recycle ratios (a_{opt}) for selectors it will be found that generally at low influent TKN/COD ratios, the a-recycle ratios will be high, and at high influent TKN/COD ratios the a-recycle ratio will be low. For the settled waste water defined in **Appendix 1** of Still et al., 1996, at 20°C, s = 1, f_{bs} = 0.22 and L_r = 2.67 (obtained from sinusoidally varying flow and COD concentration each with an amplitude of 1.0) for TKN/COD ratios >0.090, the required a-recycle ratio with respect to ADWF a_{opt} is <5.0:1). With anoxic selectors it is undesirable to have a split underflow recycle discharge to the selector and main reactor; all the underflow recycle is required in order to recycle as much nitrate to the anoxic selector as possible to keep the a-recycle ratio low. Because anoxic selectors are generally small (f_{xs}< 0.12), leakage of nitrate and nitrite out of the selector into the main aeration reactor would not ordinarily stimulate bulking by low F/M filaments provided the main aeration reactor is not under aerated (Casey et al., 1994). The same applies to primary anoxic reactors provided they are small (f_{xl} < 0.20). The presence of nitrate and nitrite at the transition from anoxic to aerobic conditions as a stimulus for low F/M bulking is discussed in the subsequent papers in this series.

The performance of anoxic selectors designed with the above procedure can be readily evaluated for diurnal flow and load performance with the UCT (Dold et al., 1991) or IAWQ (Henze et al., 1987) general kinetic simulation models. Anoxic selectors sized by the above procedure were not tested in this investigation.

Conclusions

From operating long sludge age (20 d) IFFD (fed once daily) and CFCM systems both of which incorporated sequential unaerated (1 h) and aerated (3 h) periods, it was found that:

- The IFFD system stimulated in the sludge, oxygen and nitrate utilisation rates around 3½ times higher than those in the sludge of the CFCM system, indicating that the IFFD sludge had acquired a selector effect.
- The RBCOD utilisation rates in the sludges of both systems associated with nitrate utilisation were about 85% of those associated with oxygen utilisation. In the IFFD and CFCM system sludges, the RBCOD utilisation rates associated with oxygen utilisation were 307 and 85 mg RBCOD/(g AVSS·d).
- Although it is not possible from the experimental evidence of this investigation to state categorically that a selector effect would be induced in a sludge under anoxic selector conditions only, results from Stern and Marais (1974) and Shao (1986) indicated that this is so.
- It was concluded in Still et al. (1996) that the kinetics of RBCOD uptake and utilisation under aerobic batch conditions and in aerobic selector reactors can be adequately simulated by the general activated sludge kinetic models incorporating Monod kinetics for the utilisation of RBCOD (e.g. Dold et al.,

1991 and Henze et al., 1987). The close correlation of the RBCOD utilisation rates under anoxic and aerobic conditions with nitrate and oxygen utilisation rates found in this investigation indicated that the kinetics of RBCOD uptake and utilisation under anoxic batch conditions and in anoxic selector reactors can also be adequately simulated with these models.

- A design procedure for anoxic selectors is presented. In the design of anoxic selectors the supply of nitrate into the selector needs to be balanced with the load of influent RBCOD at peak flow and load in order to avoid leakage of RBCOD to the main reactor. Depending on the influent TKN/COD ratio, this may require high mixed liquor a-recycle ratios. The procedure was not tested experimentally.
- Both the IFFD and CFCM systems appeared to ameliorate equally effectively, the low F/M filament (type 0092, *M. parvicella* and type 0675) bulking condition in the starter sludge. When bulking did occur, it occurred only in the CFCM system and then by the low DO filament *S. natans* - confirming that the selector effect controls this filament (see Still et al., 1996).
- From the above, provided the sludge is suitably acclimatised to anoxic conditions, a selector effect can be stimulated under anoxic conditions. Consequently, it is expected that if aerobic selectors are effective for controlling bulking by low F/M filaments, then anoxic selectors will be equally effective.

Closure

In this investigation with anoxic (25%) - aerobic (75%) systems, as in the earlier one with fully aerobic systems, it was found that low F/M filaments could not be sustained in the laboratory-scale systems, despite the fact that the full-scale plant from which the starter sludge was obtained, and laboratory modified UCT N & P removal systems receiving the same waste water, all manifested low F/M filament proliferation. Therefore, before proceeding with any further experiments into the role of the selector effect in controlling low F/M filaments, it is imperative that a laboratory-scale system configuration be found that develops low F/M filaments other than an N & P removal one; because N & P removal systems do not allow incorporation of an aerobic or an anoxic selector without disrupting the biological excess P removal. This aspect is considered in the next paper of this series (Gabb et al., 1996).

Acknowledgements

This research was financially supported by the Water Research Commission, Foundation for Research Development and University of Cape Town and is published with their permission.

References

CASEY TG, WENTZEL MC, LOEWENTHAL RE, EKAMA GA and MARAIS GvR (1994) A hypothesis for the causes and control of anoxic-aerobic (AA) filament bulking in nutrient removal activated sludge systems. *Water Sci. Technol.* **29** (7) 203-212.

DOLD PL, WENTZEL MC, BILLING AE, EKAMA GA and MARAIS GvR (1991) Activated sludge system simulation programs (Version 1.0). Water Research Commission, PO Box 824, Pretoria 0001, RSA.

EKAMA GA, DOLD PL and MARAIS GvR (1986) Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. *Water Sci. Technol.* (Copenhagen) **18** 91-114.

EKAMA GA, WENTZEL MC, CASEY TG and MARAIS GvR (1996) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 6: Review, evaluation and consolidation of results. *Water SA* **22** (2) 147-152.

GABB DMD, EKAMA GA, JENKINS D and MARAIS GvR (1989) The incidence of *Sphaerotilus natans* in laboratory-scale activated sludge systems. *Water Sci. Technol.* (Brighton) **21** 29-41.

GABB DMD, EKAMA GA, JENKINS D, WENTZEL MC, CASEY TG and MARAIS GvR (1996) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 4: System configurations and operating conditions to develop low F/M filament bulking sludges at laboratory-scale. *Water SA* **22** (2) 127-138.

HENZE M, GRADY CPL (Jr), GUJER W, MARAIS GvR and MATSUO T (1987) Activated Sludge Model No. 1. IAWQ STR No. 1, IAWQ, London.

JENKINS D, RICHARD MG and DAIGGER GT (1984) Manual on the Causes and Control of Activated Sludge Bulking and Foaming. Published by Water Research Commission, PO Box 824, Pretoria 0001.

SHAO YJ (1986) The Mechanism and Design of Anoxic Selectors for the Control of Low F/M Filamentous Bulking. Ph.D. Thesis, Univ. of California, Berkeley, CA.

SHAO YJ and JENKINS D (1989) The use of anoxic selectors for the control of low F/M activated sludge bulking. *Water Sci. Technol.* (Brighton) *21* (6/7) 606-619.

STERN LB and MARAIS GvR (1974) Sewage as the Electron Donor in Biological Denitrification. Research Report W7, Dept. of Civil Eng., Univ. of Cape Town.

STILL DA, EKAMA GA, WENTZEL MC, CASEY TG and MARAIS GvR (1996) Filamentous organism bulking in nutrient removal activated sludge systems. Paper 2: Stimulation of the selector effect under aerobic conditions. *Water SA* **22** (2) 97-118.

WRC (1984) Theory, Design and Operation of Nutrient Removal Activated Sludge Processes. Water Research Commission, PO Box 824, Pretoria 0001, RSA.