Filamentous organism bulking in nutrient removal activated sludge systems

Paper 1: A historical overview of causes and control

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Abstract

The presence of filamentous organisms in the activated sludge system has been problematic since early this century and has been noted in systems operating as aerobic or incorporating anoxic or anaerobic zones. Early attempts to control bulking in overtly aerobic systems were at best *ad hoc* measures, often based on anecdotal evidence and usually were unsuccessful. Non-specific control methods such as chlorination have been found successful but these do not remove the causes for bulking. Identification of problematic filament types and association of these with specific operating conditions and influent characteristics were the first important steps taken toward establishing specific methods of control. The kinetic selection approach, first proposed by Chudoba et al. (1973a; b) has provided a basis for developing strategies for specific bulking control in aerobic systems, most notably the selector reactor for control of bulking in low food to micro-organism (low F/M) systems. The development of systems for the removal of nitrogen (N) and phosphorus (P) resulted in an increase in the occurrence of filament types not associated with bulking sludges in aerobic systems. The majority of these filaments have been categorised as low F/M types and therefore the kinetic selection approach was adopted as the starting point for developing specific control procedures for bulking in nutrient removal plants.

Introduction

This paper is the first in a series of 12 papers that summarise the work conducted by the Water Research Group at the University of Cape Town (UCT) over the past decade into the problem of low F/M (food/micro-organism ratio) filamentous organism bulking in nutrient removal activated sludge sewage treatment plants. A brief description of the 12 papers including this one is as follows:

Paper 1: A historical overview of causes and control.

Paper 2: Experimental examination of the role of the "selector effect" in controlling low F/M filament bulking in aerobic systems and comparison with experimental work conducted by other research groups.

Paper 3: Experimental examination of the role of the anoxic zone in controlling low F/M filament bulking.

Paper 4: Determination of experimental conditions necessary for the development of low F/M filament bulking in laboratory-scale systems.

Paper 5: Experimental examination of aerobic selectors in anoxic-aerobic (N removal) systems.

Paper 6: Review, evaluation and consolidation of research into specific control of low F/M filaments to establish directions for further research.

Paper 7: Exploratory experimental investigation into the effect of various influent characteristics and operating parameters on low F/M filament proliferation.

Paper 8: An experimental programme to examine the role of nitrate and nitrite as electron acceptors in proliferation of low F/M filaments.

Paper 9: A review of the biochemistry and microbiology of facultative heterotrophic organisms.

Paper 10: A conceptual model for the microbiological and biochemical processes mediated by facultative heterotrophic organisms in activated sludge systems.

Paper 11: A conceptual model for the proliferation of low F/M filaments in systems incorporating sequential anoxic and aerobic conditions.

Paper 12: A review of international experience in application of selectors, and upgrading from aerobic to nutrient removal activated sludge systems.

Background

Since its development by Ardern and Lockett in 1914, the activated sludge system has gained increasing importance in the treatment of municipal waste waters. This is a consequence of its adaptability to variation in waste-water composition, high rates of removal of organic material and ability to remove the nutrients nitrogen (N) and phosphorus (P) to low levels without chemical addition.

Its initial development as an aerobic process was a consequence of its greater economy and surety of effluent quality than the trickling filter, especially with regard to nitrification. Significant developments in the activated sludge system were introduced by Barnard in 1973 and 1975. By incorporating anoxic and anaerobic zones he demonstrated that a high percentage of the influent N and P could be removed by biological mechanisms in the system without the aid of chemical addition. It was later demonstrated that through the imposition of specific environmental conditions and substrate supply, the growth of certain species can be promoted so as to fulfil some desired function. Examples are:

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- With a sufficiently long aerobic sludge age, nitrifying organisms develop and produce an effluent low in ammonia.
- With an appropriate sludge age, and a sequence of in-series reactors operating in anaerobic, anoxic and aerobic states, with inter-reactor recycles, different species of micro-organisms develop that
  - nitrify;
  - denitrify; and
  - store phosphorus in excess of their metabolic requirements.

By these means the eutrophic elements, N and P, are removed from the waste water biologically. Indeed, much of the later research into the activated sludge system (1980 to 1990) has been concerned with finding the environmental conditions and substrate components that promote the growth of such organisms. However, imposing these conditions may also stimulate the growth of other organisms which may, in some situations, act adversely on the operation of the system. In particular, an important group of organisms which develops in the sludge biomass and can adversely affect plant performance is the filamentous microorganisms. The debilitating effect on plant performance of significant proportions of these organisms in the sludge mass has prompted a large number of studies internationally into the problem. The research described in this series of Papers was initiated by the severity of the bulking problem in South African activated sludge plants, which are principally N, and N and P ones.

Quantities of filamentous organisms are found in most activated sludge systems; indeed their presence is essential for effective operation of the plant (Sezgin et al., 1978; Jenkins et al., 1984). The final stage in activated sludge systems is the separation of the organism mass from the treated waste water in the secondary settling tank, and return of the separated sludge mass to the reactor basin. For efficient solid/liquid separation the organisms must aggregate in compact flocs which settle readily. This aggregation is promoted if filamentous organisms are present in a "reasonable" concentration. During settling, sludge containing flocs with some filaments extending into the bulk liquid acts as a net, entraining small floc material to produce a clear effluent. If filaments are absent, pin-point flocs form, which may lead to inefficient solid-liquid separation with flocs escaping with the effluent. If filaments are present in excess, they bind separate flocs in a web-like structure which impedes solid-liquid separation and gives rise to the phenomenon known as bulking sludge. The term "bulking" seeks to describe the increase in settled sludge volume per unit dry mass which may develop in the activated sludge mass of a treatment plant manifesting in high sludge volume index (SVI) values.

The bulking phenomenon was reported in the 1920s and early 1930s in countries where the aerobic activated sludge system was becoming the established treatment method. Notably these reports were by Scott (1928) in England, Ruchoft and Watkins (1928) in the United States, and Smit (1934) in Holland.

According to the ATV Working Report (1989), until the 1950s bulking was not a serious problem in municipal plants; it was encountered mainly in plants treating a high proportion of industrial wastes. However, from 1950, bulking was becoming increasingly problematic in municipal activated sludge plants. In the 1970s and early 1980s, surveys of several hundred waste-water treatment plants in Europe showed that bulking occurred in about 50% of the plants (Hünerberg et al., 1970; Eikelboom, 1975; Matsché 1977; Wagner, 1982). In England, Tomlinson (1976) in a survey of 65 plants found that 41 (63%) "either experienced serious loss of solids due to bulking or had SVI values greater than 200 mℓ/g". One important point to note is that these plants were overtly aerobic systems, mainly designed not to nitrify, that is, the plants were operated at relatively short sludge ages (high food to micro-organism ratio, F/M).

In the earliest applications of the activated sludge system in South Africa in the late 1950s, high effluent quality standards were demanded from the system. Indeed, the activated sludge system became the preferred treatment process because it could meet the required standards more reliably than the trickling filter. The need for N and P removal from municipal waste waters to limit eutrophication and mineralisation (salt accumulation) of surface waters has resulted in even the early application of the activated sludge system being designed for biological N removal and later for biological N and P removal. The environmental conditions encountered by the organism mass in the N and P removal system are very different to those in conventional fully aerobic systems. Nevertheless, the N and P systems did not appear to be exempt from filamentous bulking problems - indeed it appeared that these systems had a propensity to produce generally poorer settling sludge than their more conventional short sludge age fully aerobic counterparts.

Biological N and P removal plants have in-series configurations of anaerobic, anoxic and aerobic reactors, with inter-reactor recycles and are operated at sludge ages ranging from 15 to 30 d, which from a high-rate perspective, would be considered to be very long. Basically, there are two types of biological N and P removal system, viz. nitrification-denitrification (ND) for N removal only and nitrification-denitrification biological-excess-phosphorus removal (NDBEPR) for both N and P removal, the latter also called a biological nutrient removal (BNR) system. In a survey of 111 waste-water treatment plants in South Africa, Blackbeard et al. (1986) found that 56 plants, which jointly treated 68% of the 1 515 Mℓ/d total design flow, produced bulking sludges (diluted SVI > 150 mℓ/g). Of the 111 plants surveyed, 26 were nutrient removal and the balance, N removal, either intentionally or inadvertently. In a subsequent survey, Blackbeard et al. (1988) focused attention on N and P removal plants and found that of 33 nutrient removal plants investigated, 27 produced bulking sludges. Recent surveys in other countries have identified similar results as biological N and P removal systems have been implemented (Pujol et al., 1991; Seviour et al., 1990; Andreasen and Sigvardsen, 1993; Rosetti et al., 1993; Eikelboom, 1993; Kunst and Riens, 1993; Foot et al., 1993; Seviour et al., 1993- see **Paper 12**).

From the above, bulking due to filamentous organisms has a long history of occurrence and at present constitutes a major problem in activated sludge systems. Bulking is encountered over virtually the entire spectrum of systems, from short and long sludge age aerobic systems operating in plug-flow, in-series and completely mixed regimes, to long sludge age anoxic-aerobic N removal and anaerobic-anoxic-aerobic N and P removal systems.

Quantifying bulking behaviour

The term bulking has come to be associated with the loss of mixed liquor solids with the effluent. However, the loss of solids in the effluent can stem from one of two causes: treatment capacity overload (hydraulic and/or organic load) or deterioration of sludge settleability due to proliferation of filaments. It is necessary to distinguish between these causes. Consequently bulking is defined in terms of the settleability of the sludge, not in terms of the effluent quality from the settlers. Widely used sludge settleability parameters are the SVI and the improved measures based on it, i.e. the diluted sludge volume index (DSVI) or the stirred specific volume index at 3.5 g/ℓ ($SSVI_{3.5}$). Of these parameters, the DSVI and $SSVI_{3.5}$ give improved correlation with the settling behaviour in the secondary settling tank over that provided by the SVI (Ekama and Marais, 1986). Strong motivation for adopting the DSVI is given by Lee et al. (1983). They evaluated various sludge settleability indices (SVI, DSVI and SVI at standard concentrations of 1.5, 2.5 and 3.5 g/ℓ) against the total extended filament length (TEFL, in km/gMLSS), i.e. the content of filamentous organisms in the activated sludge expressed as a measured length per unit sludge mass. They found the DSVI gave the best correlation with TEFL, and notably, for TEFL > 30 km/g the DSVI increases sharply above 150 mℓ/g. In conformity with these findings, the DSVI is used in all experimental work associated with this series of papers and it is accepted that bulking sludges have a value of DSVI > 150 mℓ/g and non-bulking sludges a value of DSVI < 150 mℓ/g.

Defining bulking in terms of the settling properties of the sludge is necessary in order to exclude situations where sludge loss with the effluent is due to inadequate hydraulic design of the secondary settling tank or due to pin-point floc formation (good settling but poor flocculation). With some influents (usually industrial), at relatively short sludge ages bulking may occur due to massive development of zoogloea. Consequently, microscopic examination of sludge is an essential requirement, along with the settleability test, to establish whether or not the sludge loss incident is a filamentous bulking problem.

Consequences of filamentous bulking

In designing the secondary settling tank, the requirement to accommodate bulking sludges has significant technical and economic consequences. Sludge settleability governs not only the daily flow and load that can be treated in an activated sludge plant but also the sludge treatment facilities such as dewatering. For a particular plant the influent peak wet weather flow (PWWF) sets the overflow rate (m/h) in the secondary settling tank, and the daily mass of COD treated and sludge age determines the sludge mass in the biological reactor. Ekama and Marais (1986) showed that a sludge with a DSVI of 150 mℓ/g can be handled satisfactorily in the settling tank up to a maximum overflow rate at PWWF (3 x ADWF) of 1 m/h at a mixed liquor suspended solids (MLSS) concentration of 3.5 g/ℓ. Should the DSVI deteriorate to 200 mℓ/g the maximum overflow rate reduces to 0.6 m/h at 3.5 g/ℓ, or to maintain the same overflow rate (at 1 m/h), the reactor MLSS concentration must be reduced to 2.4 g/ℓ - with a DSVI increase from 150 to 200 mℓ/g, about 33% less flow and load can be treated in the plant. In contrast, if the DSVI is reduced from 150 to 100 mℓ/g the overflow rate can be increased to 1.8 m/h at 3.5 g/ℓ, or, the reactor concentration can be increased to 5.4 g/ℓ at an overflow rate of 1 m/h - a 54% increase in flow and load can be treated.

Clearly the settling tank and sludge settleability are the bottleneck in plant treatment capacity. Should a plant be designed for a specific load and DSVI and during operation the DSVI is found to be higher, the settling tank will limit the attainable load to less than the design load, or to accommodate the design load, augmentation of the settling tank capacity will be needed. In contrast, if the sludge settles better than the design DSVI, then a flow and load greater than the design values can be treated allowing future extensions to be postponed. Controlling, or preferably eliminating bulking therefore holds promise of major financial savings which is the driving force behind finding solutions for this problem.

Causes of filamentous bulking

Early observations

In the 1920s and 1930s bulking was widely imputed to be due to *Sphaerotilus natans*. According to Smit (1934), Ruchhoft and Watkins (1928) were the first to succeed in " .... cultivating an organism (*S. natans*) which in pure culture closely resembled the threads present in bulking sludge". It is apparent that a common misconception at the time was that all incidences of bulking at full-scale were due to *S. natans*. This emphasis has to some degree continued to present times because *S. natans* so readily develops inadvertently on laboratory systems as a consequence of it being an attached (wall growing) filamentous organism (Gabb et al., 1989) and possibly accounts for the large quantity of laboratory research aimed at reducing the growth of *S. natans* in laboratory-scale systems (see **Papers 2** and **6**). Smit (1934) appears to have been the first to show that filamentous organism types other than *S. natans* could be present in a bulking sludge.

Efforts at identifying the causes of bulking and its possible amelioration have in most instances followed a practical route by attempting to link bulking to some factor(s) in the influent, or the operation of the plant. Examples are:

Scott (1928) implicated carbohydrate in the influent, but Smit (1934) showed that this would apply only in influents high in carbohydrate and could not explain bulking with a normal sewage influent which usually has a low carbohydrate content.

Donaldson (1932) attributed the cause of bulking to the mixing regime in aeration tanks. He suspected that filamentous organism growth in the rectangular diffused-air aerated tanks was due to back mixing, thereby changing the intended plug-flow regime towards a completely mixed one. As a solution he proposed that the aeration tanks be baffled.

Later observations

Tomlinson (1976), from an extensive survey of occurrence of bulking in England, on 65 plants, attempted to identify some of the causes of bulking, *inter alia*, by statistically based analysis. From questionnaires to operators of these plants he could identify no "... overall correlation between the occurrence of bulking and any of the parameters which are normally measured, or specified in design, for example sludge loading, sludge age, retention time, power input, dissolved oxygen concentration, temperature, proportion of industrial waste waters, sewage septicity." He did, however, establish that the mixing régime influenced bulking - plants employing plug-flow configurations were less prone to bulking than plants employing complete mixing, an aspect already noted by Donaldson (1932). Tomlinson concluded that the survey could not produce more specific information because it dealt with long-term behaviour and bulking often occurred over relatively short periods, and, the range of plants in size and design was very large so that specific causes could not be identified reliably in the statistical analysis.

As to the methods employed by operators to overcome bulking, Tomlinson lists 18 procedures including amongst others: increase/decrease of MLSS concentration (i.e. increasing/decreasing F/M ratio), hydraulic retention time, sludge recycle ratio, aeration, sludge wasting rate; re-seeding with fresh sludge; control of industrial discharge; ceasing aeration for short periods; aeration of the recycle; and others. Some of these procedures showed success but the *ad hoc* nature in application made it difficult to identify viable procedures for general application.

The ATV Working Report (1989) listed the main factors that gave rise to bulking in German activated sludge systems in the 1950s:

- Increased proportion of industrial waste water in municipal plants
- Increased demands on efficiency and as a result, a tendency to increase the loading rates
- Operating with completely mixed tanks
- Distributed waste-water feed.

Filament identification

In the 1960s, identification and classification of filamentous organisms gained increasing attention as a consequence of the major cost implications associated with bulking. Association was sought between the specific filament types and the operational/environmental conditions and influent characteristics which give rise to its proliferation. Isolation and identification of the different filament types proved a difficult task; many types were not taxonomically recognised micro-organisms and therefore were not documented in standard microbiological identification references such as Bergey's Manual (1974; 1984). Farquhar and Boyle (1971) based identification on morphology and staining and compared the results to a key derived from a number of microbiological references. However, as many of the filaments in activated sludge were not listed in these references, this approach was still inadequate because it attributed bulking to the few filaments that were taxonomically recognised. Eikelboom (1975; 1977), by microscopically characterising filamentous organisms in activated sludge, established an identification key which has become the international basis for filament identification in activated sludge over the past 20 years. The key recognises 29 different kinds of filament types which greatly expanded and refined the filament identification process. The procedures and techniques have been compiled by Eikelboom and Van Buijsen (1981) in the form of a microscopic sludge examination manual which has been adopted world-wide as a standard reference. Eikelboom and Van Buijsen (1981) recognised that many of the filaments were not yet described taxonomically and that this was unlikely to be done expeditiously. Consequently, for unidentified filaments they allocated type numbers until such time as the characteristics of the filament were adequately described for inclusion in the standard keys. Their approach was eminently practical, consisting of quick and simple techniques whereby reasonably reliable identification of filaments could be attained from microscope studies with and without staining. The role of Eikelboom's pioneering work in the proliferation of filamentous organism research through the removal of the formal taxonomic constraints should not be underestimated. It has provided a fundamental basis and structure for all subsequent research in the field, allowing workers to have confidence when comparing filament types responsible for different bulking incidences. Widespread use of the method has led to improvements and refinements such as that by Jenkins et al. (1984) who produced a filament identification and bulking control manual. Both Eikelboom's and Jenkins' manuals have proved of great value in bulking research in general, and that reported in this series of 12 papers in particular.

Filament identification and causes of bulking

Jenkins et al. (1984) attempted to define the waste-water characteristics, system design parameters and operating conditions conducive to proliferation of different filamentous organism types with the aid of the identification manuals, and surveys of filamentous organisms in activated sludge plants viz.:

- 525 samples from 270 plants in the USA (Richard et al., 1982; Strom and Jenkins, 1984)
- 356 samples from 139 plants in Germany (Wagner, 1982)
- 1 100 samples from 200 plants in Holland (Eikelboom, 1977).

The outcome of this work is set out in Table 1. Of the 29 filament types recognised by the identification manuals and therefore observed to have been present in some activated sludge systems, only 11 are of major importance as a result of their widespread occurrence and dominance. Ten of the 15 filament types listed in Table 1 account for about 90% of the bulking incidents in the surveyed plants and five broad categories of causes were identified, i.e. low DO, low F/M, septic waste water/sulphide, nutrient deficiency and low pH. Ranking in order of frequency of occurrence of the different filaments in the different countries is given in Table 2 including the South African survey of 96 plants by Blackbeard et al (1986). The lists for the United States and Europe are not dissimilar in that the top 6 to 8 most frequently occurring filaments are from 4 of the 5 causative categories, but both differ substantially from that for South Africa where 6 of the top 8 are all low F/M ones with the other two not categorised. At the time of the surveys, plants in Europe and in the United States were principally aerobic with relatively high loading factors (high F/M) or equivalently short sludge ages. Plants in South Africa have sludge ages that can be up to an order of magnitude longer than some plants in the United States and in Europe (i.e. very low F/M) and always incorporate anoxic-aerobic or anaerobic-anoxic-aerobic zones. Whereas the filament populations that develop in the United States and European plants could be expected to not differ too greatly from one another, the significant differences in environmental factors imposed on the organisms in biological N, and N and P removal plants in South Africa clearly give rise to filament populations that differ considerably from those in European and USA plants.

While the grouping of filaments into apparently causative categories was a significant advance towards understanding the causes and control of filamentous bulking, Strom and Jenkins (1984) cautioned against rigorous application of the approach in

TABLE 1
DOMINANT FILAMENT TYPES AS INDICATORS OF CONDITIONS CAUSING ACTIVATED SLUDGE BULKING (FROM JENKINS ET AL., 1984)

Suggested causative conditions	Indicative filament types
Low DO	type 1701, *S. natans*. *H. hydrossis*
Low F/M	*M. parvicella*, *H. hydrossis*, *Nocardia* sp., types 021N, 0041, 0675, 0092, 0581, 0961, 0803, 0914, 1851
Septic waste water/sulphide	*Thiothrix* sp., *Beggiatoa* and type 021N
Nutrient deficiency	*Thiothrix* sp., *S natans*, type 021N, and possibly *H. hydrossis* and types 0041 and 0675
Low pH	Fungi

TABLE 2
COMPARISON OF DOMINANT FILAMENTOUS ORGANISMS IN BULKING SLUDGES FROM ACTIVATED SLUDGE PLANTS IN DIFFERENT COUNTRIES OBSERVED IN SURVEYS UP TO 1986

Filamentous organism	Ranking in order of prevalence			
	USA[1]	The Netherlands[2]	West Germany[3]	South Africa[4]
Nocardia sp.	1	-	-	7
Type 1701	2	5	8	9
Type 021N	3	2	1	13
Type 0041	4	6	3	6
Thiothrix sp.	5	19	-	15
Sphaerotilus natans	6	7	4	-
Microthrix parvicella	7	1	2	2
Type 0092	8	4	-	1
Haliscomenobacter hydrossis	9	3	6	12
Type 0675	10	-	-	4
Type 0803	11	9	10	8
Nostocoida limicola	12	11	7	10
Type 1851	13	12	-	3
Type 0961	14	10	9	14
Type 0581	15	8	-	16
Beggiatoa sp.	16	18	-	-
fungi	17	15	-	-
Type 0914	18	-	-	5

1. Richard et al. (1982) and Strom and Jenkins (1984): 525 samples from 270 treatment plants.
2. Eikelboom (1977): 1 100 samples from 200 treatment plants.
3. Wagner (1982): 3 500 samples from 315 treatment plants.
4. Blackbeard et al. (1986): 96 samples from 96 treatment plants.

that "at present most of the filament types can only be categorised to a few broad groupings of associated conditions", implying that at a specific treatment plant, conditions may be present other than those listed in Table 1, which can change the filament types. Nevertheless, this association between filament type and causative condition has found considerable practical application and identification of these indicators has come to be regarded as the first step in ameliorating sludge bulking problems.

One category of conditions in Table 1 apparently causing bulking is designated by the term "low F/M", implying a low loading rate of substrate to sludge mass (low load factor, LF) or alternatively long sludge age. This series of papers makes continual reference to this category because 6 of the 8 most commonly occurring filaments in South African plants are listed in this category i.e. types 0092, 0675, 0041, *M. parvicella*, *Nocardia* sp. and type 0803. The other 2 of the top 8 (types 0914 and 1851) are not listed in any of the categories and it has been suggested that they be included in the low F/M category as a consequence of their frequent association with the other 6 filaments (Blackbeard et al. 1986, 1988).

The low F/M category contains the longest list of filaments and unfortunately is rather vaguely defined. No explicit definition for low F/M (or equivalently load factor) is specified so presumably it arose mainly to distinguish between high and low F/M plants. The difficulty in clearly defining this category lies in there being:

- no threshold value separating low from high F/M;
- various definitions and measures whereby it can be expressed (COD, BOD5, VSS, MLSS); and
- in its dependence on waste-water characteristics (i.e. raw or settled waste water).

This makes comparison of information presented in the literature in terms of F/M extremely difficult. A more consistent and fundamental parameter, and therefore a more preferable one, would be the sludge age (Marais and Ekama, 1976). However, even linking the low F/M filament category to sludge age only may be inadequate as this categorisation is unduly broad; at long sludge ages (low F/M) a wide range of different operating conditions and configurations is possible, each of which may stimulate proliferation of different filaments within the low F/M category (Chudoba et al., 1974; Chudoba, 1985). With the introduction of N, and N and P removal plants, the plant configurations and operational conditions have changed drastically compared with the conventional high-rate fully aerobic systems prevalent in Europe and the USA. In such systems other factors such as unaerated mass fraction, frequency of alternation between anoxic and aerobic conditions, low DO conditions at anoxic-aerobic transitions, etc. may become more important than the F/M (sludge age) in causing bulking. If indeed this should be found to be so, there would be a case for renaming the low F/M category with a name more descriptive of the conditions that lead to their proliferation. This is in fact what has happened as will be outlined in this series of papers.

Approaches to control of filamentous bulking

There are two approaches to bulking control: non-specific and specific. With non-specific control some toxicant, usually chlorine, although ozone and hydrogen peroxide also can be used, is dosed into the activated sludge system. Because the filamentous organisms causing the bulking extend beyond the flocs into the bulk liquid, they are more exposed to the toxicant and therefore are selectively killed; in contrast the floc-formers are not seriously affected by the toxicant because they find protection inside the sludge flocs. Due to the selective killing of the filaments, their numbers and lengths are reduced and the bulking problem is ameliorated. The toxicant affects all filaments irrespective of type and for this reason this method of bulking control is termed non-specific.

The procedures for implementation of chlorination are well documented in the literature such as in the bulking control manual of Jenkins et al. (1984). The method has been tested at laboratory-scale for biological N and P removal systems (Lakay et al., 1988) and found to be satisfactory, provided the guidelines set down by Jenkins et al. (1984) are followed. However, chlorination has a rather serious shortcoming in that undesirable compounds such as trihalomethanes and chlorinated hydrocarbons tend to form, which poses a potential health risk in the event the treated effluents are reclaimed for potable water supplies. To avoid this problem Van Leeuwen (1988) and Van Leeuwen and Pretorius (1988) investigated the use of ozone for bulking control in an N and P removal pilot plant. They concluded that ozonation successfully controls filamentous bulking and imparts additional benefits i.e.:

- improves the removal of organic substances;
- aids nitrification and to some degree biological excess P removal (BEPR); and
- produces an effluent that is more suitable for reuse than effluent from activated sludge treatment plants without ozonation.

However, ozonation use is limited by financial costs, especially in large plants with severe bulking problems.

Generally the problem with all non-specific bulking control measures is that as soon as toxicant dosing is terminated, the filaments regrow and, inexorably, bulking conditions return. This is because non-specific bulking control deals with the symptoms of bulking, i.e. reduces the filaments, but does not remove the causes of the filament proliferation on a permanent basis.

Specific control of bulking focuses on identifying and eliminating the conditions that promote the proliferation of the specific nuisance filaments causing the bulking problem. Once these conditions are identified, it may be possible to create environmental conditions in the activated sludge plant which would inhibit or suppress the growth of the filamentous organisms. If successful, the method would provide a permanent solution to the particular bulking situation. For this reason, this overview has focused and all subsequent papers in this series will focus on the more desirable specific control of bulking. With regard to specific bulking control, control of the filaments in the low F/M category is of major importance - this is the largest filamentous organism group and not only do these filaments cause practically all of the bulking problems in South African N, and N and P removal plants but also cause considerable bulking problems in the USA and in European plants (Table 2).

Specific control

The first attempt to provide a fundamental explanation for the occurrence or non-occurrence of filamentous bulking was made by Chudoba et al. (1973a; b). They proposed a filamentous or floc-forming organism selection criterion based on competition between filaments and floc-formers for a mutually limiting soluble substrate. The rates of soluble substrate utilisation by the filaments and floc-formers were defined in terms of Monod kinetics and by assigning different values to the kinetic constants μ (maximum specific growth rate,/d) and K_S (half-saturation coefficient, mg/ℓ) for the filamentous and floc-forming organisms, bulking conditions in completely mixed and non-bulking conditions in plug-flow laboratory activated sludge systems could be explained. This kinetic explanation for filamentous bulking led to the development of the selector reactor - a small reactor ahead of the main aeration reactor receiving the influent and sludge return flows for bulking control in low F/M (long sludge age) systems (Chudoba et al., 1973b). This approach was accepted to provide the basis for control of bulking by the troublesome and ubiquitous low F/M filaments and has influenced bulking research at laboratory-scale and control in full-scale plants for the past two decades. The bulking research programme described in this series of papers therefore commenced with an evaluation of this specific bulking control method which is considered in detail in the next paper (**No. 2**) of this series.

Closure

In the work reviewed so far four developments and findings of major significance were noted for specific bulking control, viz:

- Eikelboom's (1975, 1977) microscopic filament identification keys which released filament identification from the constraints of attributing filamentous bulking to only the bacteriologically recognised filamentous species and provided for the first time a comprehensive common filament identification technique.
- Empirical classification of filament types into categories based on waste-water characteristics and plant design and operating conditions observed to promote their proliferation (Jenkins et al., 1984).
- Filamentous organisms in the low F/M category i.e. *M. parvicella*, 0092, 0675, 0041, 0803, *Nocardia* sp., cause all of the filamentous bulking problems in South African N, and N and P removal plants as well as in many USA and European activated sludge plants.
- Kinetic selection criterion for control of filament proliferation in low F/M systems from which the selector reactor for control of filamentous bulking was developed (Chudoba et al., 1973a; b).

Chudoba's kinetic selection approach and the selector reactor principle he developed has had (and still has) a definitive influence on European and USA perceptions of the causes and control of low F/M bulking and has influenced both design and operation of the plants over the past decade. It is therefore important that the relevance of Chudoba's selection criterion on low F/M filament bulking be examined critically and this task is undertaken in the next paper in this series, **Paper 2**.

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