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ACTIVATED SLUDGE MICROBIOLOGY PROBLEMS AND THEIR CONTROL

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CONTENTS

INTRODUCTION

Many problems can develop in activated sludge operation that adversely affect effluent quality with origins in the engineering, hydraulic and microbiological components of the process. The real "heart" of the activated sludge system is the development and maintenance of a mixed microbial culture (activated sludge) that treats wastewater and which can be managed. One definition of a wastewater treatment plant operator is a "bug farmer", one who controls the aeration basin environment to favor good microbiology.

This paper will discuss the types of microbiological problems that can occur in activated sludge operation. These include dispersed (non-settleable) growth, pin floc problems, zoogloeal bulking and foaming, polysaccharide ("slime") bulking and foaming, nitrification and denitrification problems, toxicity, and filamentous bulking and foaming. The best approach to troubleshooting the activated sludge process is based on microscopic examination and oxygen uptake rate (OUR) testing to determine the basic cause of the problem or upset and whether it is microbiological in nature. These methods are easy, fast and inexpensive compared to other approaches, and are generally understandable and accepted.

MICROBIOLOGY PROBLEMS AND THEIR CAUSES

Poor Floc Formation, Pin Floc and Dispersed Growth Problems

Basic floc formation, required for activated sludge operation due to the use of gravity clarifiers, is due to a growth form of many species of natural bacteria. Floc-forming species share the characteristic of the formation of an extracellular polysaccharide ("slime") layer, also termed a glycocalyx. This material, which consists of polysaccharide, protein and sometimes cellulose fibrils, "cements" the bacteria together to form a floc. Floc formation occurs at lower growth rates and at lower nutrient levels, essentially starvation or stationary growth conditions.

Floc-forming species may grow in a dispersed and non-settleable form if the growth rate is too fast. This latter condition, termed dispersed growth, occurs rarely in domestic waste activated sludge operation but occurs often in industrial waste treatment, generally due to high organic loading (high food to microorganism ratio (F/M) conditions). Here, no flocs develop and biomass settling does not occur, resulting in a very turbid effluent. The correct remedial action for a dispersed growth problem is a reduction in the F/M of the system, usually done by raising the MLSS concentration. Dispersed growth problems often occur after a toxicity or hydraulic washout event when the activated sludge biomass is low and high F/M conditions prevail.

Small, weak flocs can be formed in activated sludge that are easily sheared and subject to hydraulic surge flotation in the final clarifier leading to a turbid effluent. These small flocs, termed pin floc, consist only of floc-forming bacteria without a filament backbone and usually

are <50um in diameter. Pin floc occurs most commonly at starvation conditions -- a very low F/M and long sludge age. Chronic toxicity can also cause a pin floc condition.

Free floating filaments can, at times, cause a dispersed growth problem. Here, the cause is filament-specific and is the same as for filamentous bulking (discussed below).

Toxicity

Toxic shocks can be a severe problem in activated sludge operation. In a recent study, toxicity upset was experienced by approximately 10% of 25 Colorado activated sludge plants examined during one year. Toxicity problems were found to be a larger problem in small communities compared to larger cities, due to the lack of dilution of toxic releases in small systems. Examples of toxicity events were the washing of cement or lime trucks to a manhole, dumping of congealed diesel fuel to the sewer system, and overload of small systems with septage (which contains a high amount of organic acids and sulfides which can be toxic).

Sulfide toxicity to activated sludge is more common than currently recognized. Sulfide may originate from outside the activated sludge system, from septic influent wastewater or from septage disposal, or it may originate "in-house", from anaerobic digester flows or from aeration basins or primary or final clarifiers with sludge build-up and anaerobic conditions. Hydrogen sulfide toxicity is highly pH dependent, due to the H2S form being the toxic agent and not HS-. The pKa for H2S is 7.0, indicating higher toxicity at a pH of 7 or less when H2S is predominant, and less toxicity as the pH increases above pH 7 and H2S dissociates. One mg/L of H2S reduces the activated sludge OUR by 50% at pH 7, and the H2S dose to give a 50% OUR reduction increases to 100 mg/L at pH values above pH 8. It is advised to add lime or other alkaline agent to the aeration basin to raise the pH to 7.5 or above if sulfide toxicity is occurring.

Toxicity can be diagnosed microscopically, often in the following sequence:

1. an initial flagellate "bloom";
2. subsequent complete die-off of protozoa and other higher life forms;
3. biomass deflocculation, often accompanied by foaming;
4. loss of BOD removal; and
5. filamentous bulking upon process recovery.

Toxic wastes generally do not favor filaments directly (except in the case of H2S); rather, upset conditions allow filaments to proliferate. For example, bulking by *Sphaerotilus natans* frequently follows a toxic upset due to a high F/M condition. Here the "true" F/M value may be many-fold that calculated based on total biomass present, due to low viability of the biomass.

While microscopic observations can diagnose toxicity after the fact, a better method is use of the OUR test to detect toxicity early.

The OUR of an activated sludge fed increasing amounts of a nontoxic waste will initially rise with increasing waste additions to the test bottle, followed by no further increase in OUR with even higher waste additions. In contrast, the OUR of an activated sludge fed a toxic waste may increase initially with increasing waste strength, but will decrease rather dramatically at waste additions above a toxicity threshold value. A useful definition of microbial "death" is when the fed OUR is less than the basal endogenous OUR.

The OUR test is simple (all that is required is as a BOD bottle and a dissolved oxygen probe) and usually takes less than two hours to perform. The normal OUR of the activated sludge must be known before hand, so run this test periodically to know what is normal for your plant.

Nitrification and Denitrification Problems

Nitrification can create problems in activated sludge operation. Many plants experience an upset condition with dispersed growth and filamentous bulking every spring when warmer temperatures induce nitrification. Some plants experience a loss of chlorine disinfection during nitrification onset, due to a transient period (weeks) of nitrite build-up. Nitrite has a significant chlorine demand (one part nitrite consumes one part chlorine) while ammonia and nitrate do not.

A large problem in some plants is a low pH (to as low as pH = 6) caused by extensive nitrification and low wastewater alkalinity. This often causes pin floc and high effluent turbidity. Some plants reduce aeration to reduce nitrification or add soda ash, lime or magnesium hydroxide as a source of alkalinity if this becomes a problem. The use of lower dissolved oxygen concentration (1.0 mg/L or less) to control nitrification is not without the risk of inducing filamentous bulking by low dissolved oxygen filaments.

Another problem caused by nitrification is denitrification. Here, bacteria common in the activated sludge floc respire using nitrate in place of free oxygen when it is lacking and release nitrogen gas as a by-product. This gas is only slightly soluble in water and small nitrogen gas bubbles form in the activated sludge and cause sludge blanket flotation in the final clarifier. An indication of the occurrence of denitrification can be obtained by holding the sludge in the settling test jar for several hours. If the sludge rises ("pops") within 2 hours or less, denitrification problems may be occurring. Denitrification problems are more prevalent during the warmer times of the year and can be more severe if a filamentous sludge is present, due to more extensive entrapment of the nitrogen gas bubbles by a filamentous sludge.

Control of denitrification is either by control of nitrification (reduced sludge age or reduced aeration); or by reducing denitrification by removing the sludge faster from the final clarifier (increased RAS rates) or by increasing the dissolved oxygen concentration in the final clarifier. This can be done by increasing the aeration basin dissolved oxygen concentration especially at the clarifier end of the aeration basin. One method useful in severe cases is the addition of hydrogen peroxide as an oxygen source directly to the center well of the final clarifier.

Nitrification and denitrification problems can be particularly troublesome in industrial waste systems where ammonia is supplemented. Here, inorganic nitrogen (ammonia or nitrate) must be

present in the aeration basin at all times to allow proper treatment and to avoid filamentous or slime bulking but must be kept below approximately 5 mg/L to avoid nitrification-denitrification problems (low pH and floating sludge). The common practice of batch addition of nutrients to the aeration basin often leads to denitrification problems due to periods of high nitrate concentration (above 5 mg/L).

A number of industries, particularly papermills, have experienced a frothy, floating sludge in the aeration basin. This can lead to a significant amount of the sludge inventory in the foam, compromising process control. This problem occurs in systems with a high front-end organic loading and a long hydraulic detention time (2 days or more). Nitrification and denitrification occur at the back end of the system due to endogenous conditions there and the release of ammonia from the biomass. Nitrification and denitrification often occur together within the floc, with no finding of free nitrate when examined.

Nutrient Deficiency and Polysaccharide Bulking and Foaming

Nitrogen and phosphorus can be growth limiting if not present in sufficient amounts in the influent wastewater, a problem with industrial wastes and not domestic wastes. In general, a BOD5:N:P weight ratio in the wastewater of 100:5:1 is needed for complete BOD removal. Other nutrients such as iron or sulfur have been reported as limiting to activated sludge, but this is not common.

Extracellular polysaccharide is produced by all activated sludge bacteria and is, in part, responsible for floc formation. Overproduction of this polysaccharide can occur at nutrient deficiency (and also oxygen deficiency or high F/M) which builds up in the sludge (it is poorly degraded) and leads to poor sludge settling, termed "slime bulking", and to problems in sludge dewatering. Normal activated sludge contains from 10 to 20% polysaccharide on a dry weight basis with the higher polysaccharide content occurring at younger sludge ages. Sludges with polysaccharide content above 20% may have settling and dewatering problems (values to 90% have been observed with some nutrient deficient industrial waste sludges).

Signs of nutrient deficiency include: filamentous bulking; a viscous activated sludge that exhibits significant exopolysaccharide ("slime") when "stained" with India ink; and foam on the aeration basin that contains polysaccharide (which has surface active properties). One check for nutrient deficiency is to be sure that some ammonia or nitrate and ortho-phosphate remain in the effluent at all times. The recommended effluent total inorganic nitrogen (ammonia plus nitrate) and ortho-phosphorus concentrations are 1-2 mg/L to ensure sufficient nutrients. Note that total Kjeldahl nitrogen and total phosphorus are not used, as these may contain organically-bound nutrients, not rapidly biologically available ("bug bodies").

Zoogloea Bulking and Foaming

A special case related to slime bulking is zoogleal bulking. Here, fingered zoogloea proliferate in activated sludge to the extent that sludge settling is hindered. Zoogloea overgrowth also causes reduced sludge dewatering. The responsible organism is *Zoogloea ramigera*, the "classical" floc-former. Here, large masses of this dendritic floc-former may physically interfere in sludge settling and compaction similar to filamentous bulking.

Zoogloea occur at high F/M conditions and when specific organic acids and alcohols are high in amount due to septicity or low oxygen conditions. Note that the sludge polysaccharide values as measured by the anthrone test are normal (10-20%) even when zoogloea are high in amount, due to the particular types of biopolymers formed by these bacteria (amino-sugars that don't react in the anthrone polysaccharide test). The anthrone test is a good way to separate a zoogloea overgrowth problem from a low nutrient polysaccharide problem.

Filamentous Bulking

Filamentous bulking and foaming are common and serious problems in activated sludge operation, affecting most activated sludge plants at one time or another. Filamentous bulking is the number one cause of effluent noncompliance today in the U.S.

An understanding of filamentous bulking and foaming, the causative filaments and their causes and control, has steadily increased over the past 20 years since Eikelboom and van Buijsen published their filament identification system in 1981 (Eikelboom and van Buijsen, 1981). This approach to filament identification has been updated and modified by Jenkins et al. (1993, 2003) and has become used worldwide. Once the causative filaments could be identified, at least to a recognized type, their causes could be determined and control measures appropriate to each filament found.

A bulking sludge is defined as one that settles and compacts slowly. An operational definition often used is a sludge with a sludge volume index (SVI) of >150 ml/g. However, each plant has a specific SVI value where sludge builds up in the final clarifier and is lost to the final effluent, which can vary from a SVI <100 ml/g to >300 ml/g, depending on the size and performance of the final clarifier(s) and hydraulic considerations. Thus, a bulking sludge may or may not lead to a bulking problem, depending on the specific treatment plant's ability to contain the sludge within the clarifier.

A certain amount of filamentous bacteria can be beneficial to the activated sludge process. A lack of filamentous bacteria can lead to small, easily sheared flocs (pin-floc) that settle well but leave behind a turbid effluent. Filaments serve as a "backbone" to floc structure, allowing the formation of larger, stronger flocs. The presence of some filaments also serves to catch and hold small particles during sludge settling, yielding a lower turbidity effluent. It is only when filaments grow in large amounts (approximately 10^7 um filaments per gram of activated sludge) that hindrance in sludge settling and compaction occurs. In concept, bulking can be envisioned as

the physical effects of the filaments on the close approach and compaction of the activated sludge flocs. Depending on the type of filament involved, two forms of interference in sludge settling occur: (1) interfloc-bridging - where the filaments extend from the floc surface and physically hold the floc particles apart; and (2) open-floc structure - where the filaments grow mostly within the floc and the floc grows around and attached to the filaments. Here, the floc becomes large, irregularly-shaped, and contains substantial internal voids. The untrained observer often overlooks this latter type of bulking.

A bulking sludge can result in the loss of sludge inventory to the effluent, causing environmental damage and effluent violations. In severe cases, loss of the sludge inventory can lead to a loss of the plant's treatment capacity and failure of the process. Additionally, disinfection of the treated wastewater can become compromised by the excess solids present during bulking. In less severe cases, bulking leads to excessive return sludge recycle rates and problems in waste activated sludge disposal. Many problems in waste sludge thickening are really filamentous bulking problems.

The true incidence of bulking in the U.S. is unknown but has been estimated to affect at least 60% of plants, either continuously or intermittently. Recent work in Colorado suggests that at least 90% of activated sludge plants experience a bulking episode at least once during the year. Bulking may be one of the main reasons why approximately 50% of U.S. activated sludge plants don't consistently meet their effluent discharge standards.

Early microbiological investigations into filamentous organisms found in activated sludge were hampered by a lack of knowledge concerning the types of filaments that may occur. Usually, *Sphaerotilus natans* was diagnosed, often without adequate identification. However, it is now known that approximately 25 different filamentous bacteria commonly occur in activated sludge and each may lead to operational problems. D.H. Eikelboom in Holland (*Water Research* 9:365, 1975) provided a rational basis to "identify" the different filamentous bacteria found in activated sludge. This identification system is based on filament characteristics as viewed under phase contrast microscopy for live samples (*in situ*) and two simple staining reactions: the Gram and Neisser stain. Each filament can be "classified" using a four-digit code, avoiding the earlier problems of lack of specific scientific names. This is important as many of the filaments found in activated sludge have not been isolated in pure culture and hence their identity remains unknown. As these filaments are isolated and properly named (a current research thrust), generic names replace the four digit number code. Hence, the current list of filaments is a hybrid between numbers and genus names. Currently there are 24 recognized filaments (or groups of related filaments in some cases) that cause activated sludge bulking or foaming. These are given in Table 1.

Table 1. Recognized Filaments That Cause Activated Sludge Bulking or Foaming

Sphaerotilus natans	*Microthrix parvicella**
type 1701	*Nocardia* spp.**
Haliscomenobacter hydrossis	*Nostocoida limcola* I, II & III
type 021N	type 0961
Thiothrix I and II	type 0581
Beggiatoa spp.	type 0092
type 0914	type 0411
type 0041	type 1863**
type 0675	fungi
type 1851	actinomycetes
type 0803	

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* this filament causes both bulking and foaming.
** these filaments cause foaming only.

Causes for almost all of the different filaments are now known (there is always a need to improve this information). Filament causes have been determined using three separate approaches. First, a number of filaments have been isolated in pure culture and their competitive growth abilities examined in laboratory studies. Many of these studies are summarized by Jenkins et al. (1993; 2003). This approach has been successful for *S. natans*, type 1701, *Haliscomenobacter hydrossis*, type 021N, *Thiothrix* I and II, and *Microthrix parvicella*.

Second, the author has microscopically examined and identified the filaments in over 10,000 activated sludge samples over the past 20 years. This extensive database has been analyzed for positive and negative statistical associations between the different filaments. This has resulted in a number of positive associations between filaments of known and unknown causes, establishing a probable cause for the filament of unknown cause. Alternately, a filament of unknown cause may be negatively associated with a filament of known cause, indicating that these filaments do not share a common cause.

Third, practical experience at trial and error successful control methods in plants with a bulking or foaming problem has shown the cause for some filaments not found in the above approaches.

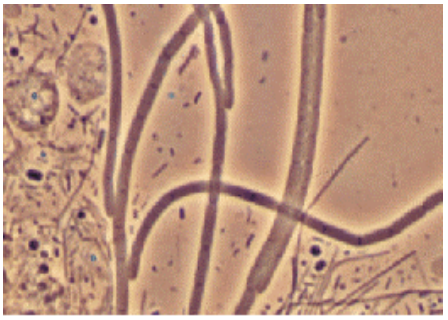
CAUSES OF FILAMENTS

A summary of the conditions that cause filament growth and the filaments associated with each of these conditions is given in Table 2. There are six environments or growth conditions that cause the overgrowth of filaments in activated sludge. Four of these occur in municipal wastewater systems while all six occur in industrial wastewater systems, with two specific only

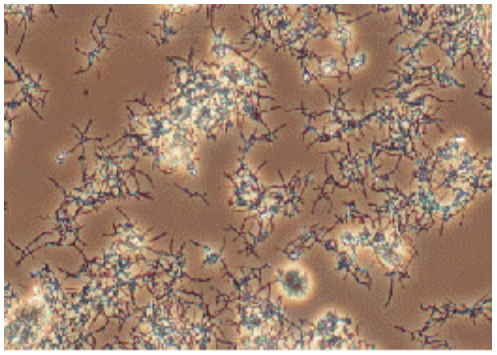
to industrial systems (low nutrients and low pH). Many of the filaments have been associated with other causes in the past, but recent work has indicated the causes given in Table 2 as the primary reason for their growth. Other modifying conditions may apply to some filaments, and these are discussed below.

Table 2. Causes of Filament Growth in Activated Sludge

Cause	Filaments
1. Low Dissolved Oxygen Concentration	*Sphaerotilus natans* type 1701 *Haliscomenobacter hydrossis*
2. Low F/M	type 0041 type 0675 type 1851 type 0803
3. Septicity	type 021N *Thiothrix* I and II *Nostocoida limicola* I,II,III type 0914 type 0411 type 0961 type 0581 type 0092
4. Grease and Oil	*Nocardia* spp. *Microthrix parvicella* type 1863
5. Nutrient Deficiency	
Nitrogen:	type 021N *Thiothrix* I and II
Phosphorus:	*Nostocoida limicola* III *Haliscomenobacter hydrossis* *Sphaerotilus natans*
6. Low pH	fungi



S. natans (1000X)



Nocardia Foam (200X)

Note that *H. hydrossis* was previously listed as a low F/M filament. This filament is caused by low DO, but grows relatively slowly and only occurs at lower F/M and a longer sludge age. Lower F/M is not its cause, only where it occurs.

Six specific causes of filament growth and bulking are currently recognized (see Table 2). The information in Table 2 is now used in reverse to the way that it was developed -- from the identification of the most significant filaments present in a bulking sludge, the "cause" for such growth can be determined. Note that some filaments have more than one cause as shown in Table 2. The combination of conditions listed may favor bulking by a particular filament more so than any single condition. It is important to perform filament identification early in a bulking episode to identify the causative filament. Once bulking continues for some time, process upset can lead to the proliferation of other filament types (secondary filaments) which can confuse diagnosis of the real cause.

Today, many activated sludge plants regularly monitor the occurrence and abundance of filaments in their sludge, which has become an important process control tool. This often leads to "heading off" a bulking episode before it becomes serious. Since the microbial population in activated sludge changes slowly in most cases, generally requiring 2-3 sludge ages to radically change, this microscopic observation needs to be performed only at weekly intervals. However, during a period of bulking onset or during application of remedial actions such as chlorination, daily observation of the activated sludge is warranted.

Filamentous Foaming

A brief review of activated sludge foams and their causes is given in Table 3. Use of microscopic examination can readily diagnose most of these, particularly when filaments are involved.

Table 3. Description and Causes of Activated Sludge Foams

Foam Description	Cause(s)
thin, white to grey foam	low cell residence time or "young" sludge (startup foam)
white, frothy, billowing foam	once common due to nonbiodegradable detergents (now uncommon)
pumice-like, grey foam (ashing)	excessive fines recycle from other processes (e.g. anaerobic digesters)
thick sludge blanket on the final clarifier(s)	denitrification
thick, pasty or slimy, greyish foam (industrial systems only)	nutrient-deficient foam; foam consists of polysaccharide material released from the floc
thick, brown, stable foam enriched in filaments	filament-induced foaming, caused by *Nocardia*, *Microthrix* or type 1863

Three filamentous organisms can cause activated sludge foaming: *Nocardia* and *Microthrix parvicella* (commonly), and type 1863 (rarely). Nocardial foaming appears to be the most common and occurs at approximately 40% of activated sludge plants in the U.S.

Nocardial foam occurs as a thick, stable, brown foam or "scum" inches to many feet thick on aeration basin and final clarifier surfaces. Normal scum traps (too small) and water sprays (too weak) may be useless to control this type of foam. This foam consists of activated sludge solids (flocs) containing large amounts of *Nocardia* filaments growing from their surface and is quite stable, compared to most other foams, due to the physical "interlocking" of the *Nocardia* filaments. These foams are easy to diagnose microscopically - they are dominated by branched, Gram positive filaments and a simple Gram stain of the foam is all that is needed. The analysis should include comparison to the underlying MLSS (prepare both samples for Gram staining on the same slide). A true Nocardial foam will contain 10-100 fold more *Nocardia* than the underlying MLSS. Nocardial foams also contain substantial lipid concentrations (hexane extractable), up to 40% of dry weight versus 5-10% for Nocardia-free activated sludge solids (whether this lipid content of foams is due to the *Nocardia* themselves or to entrapped grease and fat is not clear). In addition, these foams contain significant entrapped air, with a bulk density of approximately 7 g/cc.

Nocardial foams occur in all types of plants, with no particular association with specific modes of operation or aeration. These foams may be more severe in plants with fine bubble or jet aeration and in oxygen activated sludge plants. These foams also occur equally in plants treating domestic, industrial and mixed wastes. Industrial wastes promoting *Nocardia* growth (and foaming) include dairy, meat and slaughterhouse, food processing, pharmaceutical, and any others that contain a significant amount of grease, oil or fat. Nocardial foaming is also associated with high-density restaurant operation in recreational areas (e.g. ski resorts and summer camps). Nocardial foaming has been observed to be caused by treatment of locomotive and truck washing wastes.

Severe Nocardial foams cause a number of operational problems. These include aesthetics, odors, and safety hazards if they overflow basins to cover walkways and handrails. In cold weather these foams can freeze, necessitating "pick and shovel" removal. Foam may escape to the effluent, increasing effluent suspended solids and compromising disinfection. In covered aeration basins, foam can accumulate to exceed the available hydraulic head for gravity flow of wastewater through the basin. Process control can be compromised if a significant fraction of a plant's solids inventory is present in the non-circulating foam (e.g. up to 40% of the total solids inventory can be present in such foams and process control calculations may not be correct).

There should be some concern expressed for the handling of Nocardial foams. The most common *Nocardia* species found in such foams, such as *N. amarae*, are not pathogenic to laboratory animals; however, other less frequently isolated actinomycete strains are known opportunistic human pathogens (e.g. *N. caviae*, *N. brasiliensis*, *N. asteroides* and strains of *Mycobacterium*). No actual infection has been documented, however, treatment plant workers and nearby residents may be at risk.

PRACTICAL CONTROL METHODS FOR FILAMENTOUS BULKING AND FOAMING

The start of any problem solving has to involve microscopic examination of the activated sludge. This reveals whether the problem is, or is not, caused by filaments. If caused by filaments, and most are, identification of the causative filament(s) yields a direction or approach to take for the remedy, as shown in Table 2.

Although a myriad of solutions to bulking have been used (some involving witchcraft), several methods are most practical and proven. These include both short term (treating the symptoms) and long term (treating the cause) changes in operation.

Short Term Control Methods

Short term measures include: "sludge juggling" - changes in return activated sludge (RAS) rates and in waste feeding points; polymer and coagulant addition to aid sludge settling; and chlorination.

Sludge Juggling

Several methods useful for intermittent bulking problems, but which will not solve a chronic problem, are manipulation of RAS flow rate and manipulation of waste feed points to the aeration basin to minimize the adverse effects of a bulking sludge.

It should be obvious that one must remove solids from the final clarifier faster than they are added. Therefore, the RAS flowrate must be increased in a bulking situation to prevent loss of solids to the effluent. There is a limit to the increase in RAS flowrate as the increased return flow to the system hydraulically pushes more sludge from the clarifier, making effluent TSS losses worse. Some operators report success in bulking control by holding sludge in the clarifier for lengthy time periods. This may work for some filaments (probably by creating septic and toxic conditions), however, in other cases it may worsen the problem (for example, by encouraging sulfide-oxidizing filaments).

A reduction in solids loading to the clarifier can be achieved by a reduction in the system's sludge inventory (a reduction in the aeration basin MLSS concentration). However, this may be detrimental by actually encouraging filament growth (discussed later). A change to step feeding of wastes, where possible, can reduce the MLSS concentration in the clarifier feed without reducing the system's sludge inventory. Here, the MLSS concentration is highest at the head end of the aeration basin (a form of sludge storage) and is decreased in the clarifier feed, thus reducing clarifier loading due to MLSS dilution with wastes. This redistribution of solids in the system usually takes less than one day.

Polymer and Coagulant Addition

There exist several methods of chemical addition to enhance activated sludge settling. Most used are synthetic, high molecular weight, anionic polymers alone or in combination with cationic polymers that serve to overcome the physical effects of filaments on sludge settling. These are usually added to the MLSS as it leaves the aeration basin or to the secondary clarifier center well. Use of polymer does not significantly increase waste sludge production but can be quite expensive, up to $450. per million gallons treated (obviously this is only used if absolutely necessary). A polymer supply company should be consulted for advice on selection of a polymer and its dosage (the chemical composition of most polymers is a trade secret). Jar testing should be performed to determine the type of polymer needed and its dosage, which is quite plant specific. Further, this jar testing needs to be repeated often, as the needed polymer and its dosage can change, particularly if the filament type(s) change.

In some instances, inorganic coagulants/precipitants such as lime or ferric chloride can be beneficial. These produce a voluminous precipitate that sweeps down the activated sludge, improving settling. Sludge production may be significantly increased if these are used. The weighting action of inert biological solids has also been used to aid sludge settling in activated sludge modifications such as the Hatfield or Kraus processes that recirculate anaerobic digester contents through the aeration basin. Some papermills intentionally release fiber or clay to the wastewater system to help sludge settling during a bulking episode.

Chlorination

Two toxicants, chlorine and hydrogen peroxide, have been used successfully to control filamentous organisms and stop a bulking episode. Chlorine is most widely used as it is inexpensive and available on-site at most plants, and only this will be discussed here. Chlorination for bulking control is widespread, used by more than 50% of plants.

The goal of chlorination is to expose the activated sludge to sufficient chlorine to damage filaments extending from the floc surface while leaving organisms within the floc largely untouched. Filamentous and floc-forming bacteria do not appear to significantly differ in their chlorine susceptibility. Chlorine dosage is adjusted such that its concentration is lethal at the floc surface but is sublethal within the floc, due to chlorine consumption as it penetrates into the floc. This is analogous to "peeling an orange" and removing the filaments attached to its surface. It should be pointed out that chlorination is not a cure-all for all activated sludge microbiological problems. Chlorination will actually make problems worse if the problem is non-filamentous, e.g. slime bulking or poor floc development.

Chlorine can be applied from a chlorinator using chlorine gas feed or as a liquid hypochlorite. A separate chlorinator should be dedicated to bulking control and an independent rotameter and sampling point in this chlorine line is needed. The chlorine addition point is of most importance and should be at a point where the sludge is concentrated, raw wastes are at a minimum, and at

a point of good mixing. Poor initial mixing results in the consumption of large amounts of chlorine without bulking control. Three common chlorine addition points are: (1) into the RAS stream at a point of turbulence (elbows in pipes; into the volute or discharge of RAS pumps; and into and below the liquid level in a riser tube of an airlift RAS pump); (2) directly into the final clarifier center well or feed channel; and (3) in an installed sidestream where the MLSS is pumped from and returned to the aeration basin.

Chlorine addition to the RAS line(s) is the method of choice and most generally successful. Chlorine addition to the aeration basin usually does not work and often causes floc dispersion and system damage.

The two most important parameters are chlorine dosage and frequency of exposure of the activated sludge to chlorine. Chlorine dose is measured conveniently on the basis of sludge inventory in the plant – termed the overall chlorine mass dose. Effective chlorine dosages usually are in the range 1-10 pounds chlorine/1000 pounds MLVSS inventory/day (2-4 should work). Chlorine dosage should be started low and increased until effective. Sludge settleability usually improves within 1-3 days if the correct chlorine dosage is applied.

Most domestic waste plants can achieve a frequency of exposure of the activated sludge inventory to chlorine of three or greater per day (the optimum) in the RAS line. The needed frequency is a function of the relative growth rates and efficiencies of kill of filamentous and floc-forming organisms. Success has been achieved at frequencies as low as one per day but not less, however, this is plant specific.

In plants with long aeration basin hydraulic residence times (industrial waste plants), the daily solids flux in the RAS line is generally too low for successful bulking control using chlorine at this point alone. Here, most success has been achieved using multiple chlorine addition points such as the RAS line(s) and the final clarifier(s) in combination.

A target SVI value (or other sludge settling measure) must be set and chlorine applied only when this value is exceeded. This is determined by trial-and-error at each plant. It should be remembered that chlorination controls filament extension from the floc surface and merely reduces the symptoms of bulking. Filaments will regroup rapidly, often with a vengeance, after termination of chlorination since the cause of the bulking has not been addressed.

Signs of over chlorination are a turbid (milky) effluent, a significant increase in effluent TSS, a loss of the higher life forms (protozoa), and a reduction in BOD removal. It is normal to see a small increase in effluent suspended solids and BOD5 when using chlorine for bulking control.

Microscopic examination of the activated sludge during chlorination is recommended to control chlorine application. Chlorine effects on filaments include, in order: a loss of intracellular sulfur granules (in those filaments that have these); cell deformity and cytoplasm shrinkage; and finally filament breakup. For sheathed filaments, the sheath is not destroyed by chlorine. Here, sludge settle ability remains poor until the sheaths are washed out of the system by sludge wasting, which can take 1-2 sludge ages. Chlorine use should be stopped when only empty sheaths remain and not continued until the SVI falls, which can result in over chlorination. As a general

observation, chlorination should be stopped when about 70% of the cells are damaged or missing in a filament.

One argument to chlorine use in bulking control is the possibility of the production of chlorination by-products. This is unlikely since the chlorine is short-lived in activated sludge (minutes) and applied at a low dosage (lower than used in effluent disinfection). Chlorine cannot be used if waste constituents react with chlorine to form by-products such as petrol-chemical or phenol wastes.

Long Term Control Methods

Long term measures include activities such as: control of influent waste septicity (organic acids and H2S); nutrient additions (industrial waste systems only); changes in aeration; and changes in biomass concentration or changes in waste feeding pattern.

These control measures will be expanded upon below. In addition, control of foaming problems will be addressed at the end of this paper.

Low Dissolved Oxygen Problems

In general, the rate of BOD removal is near maximum at 1.0 mg/L dissolved oxygen (DO) concentration, while the rate of nitrification is near maximum at 2.0 mg/L DO. However, the actual DO concentration within the biological flocs is less than that measured in the bulk solution around the flocs, due to oxygen use as it penetrates into the flocs.

Low aeration basin DO leads to bulking by several filaments: *S. natans*, type 1701 and *H. hydrossis*. The DO concentration needed to control these filaments is not a constant, rather, is a function of the organic loading rate (F/M) of the system (Palm et al., 1980). At F/M values of about 0.5 or less, a DO concentration of 2.0 mg/L usually controls these filaments. However, at higher F/M values a DO value of greater than 2.0 mg/L may be needed. This is due to the need to keep the floc interiors aerobic, and this is more difficult at higher F/M values where the OUR of the sludge is high. The DO concentration in the bulk solution around the flocs has to be high enough to maintain an aerobic floc interior. Since oxygen moves into the floc by diffusion, its bulk concentration needs to be high enough to reach the floc centers before becoming depleted. A bulk solution DO concentration of 4.0 mg/L or more has been needed to prevent these filaments in some industrial wastewater systems operated at high F/M values of >0.5. Note that raising the MLSS concentration causes a reduction in the system F/M and OUR, and this change can alleviate oxygen limitation within the flocs and control the low DO filaments. Low DO filaments have been eliminated from many systems by an increase in the MLSS concentration.

Control of low DO bulking is by raising the aeration basin DO concentration, if possible, or by raising the aeration basin MLSS concentration to decrease the F/M (both should be done concurrently). Note that this action is opposite to what intuition directs -- to reduce the MLSS concentration, since less biomass needs less oxygen (wrong! - the F/M is actually increased at lower MLSS concentration). An increase in the RAS rate may also be beneficial, as this brings biomass back to the aeration basin where it helps lower the F/M.

A common experience is that it takes a higher aeration basin DO concentration to "cure" low DO bulking than to prevent it in the first place. Often, a short term bulking control option is used, most often chlorination, to control this bulking problem.

Wastewater Septicity and Organic Acids

Septicity is the term used to describe the condition where the wastewater becomes anaerobic and anaerobic bacteria ferment organic materials to organic acids such as acetic, propionic, butyric and valeric acids. Sulfate reducing bacteria also convert sulfate to hydrogen sulfide at this condition. A septic wastewater thus contains a relatively high amount of organic acids and hydrogen sulfide.

A number of filaments grow on organic acids and some hydrogen sulfide (type 021N, *Thiothrix* I and II, type 0914 and *Beggiatoa*). Observation of these filaments with intracellular sulfur granules is a tip-off of a septicity problem and high hydrogen sulfide concentration. An organic acid concentration of >100 mg/L and a sulfide concentration of >1-2 mg/L usually causes an overgrowth of these bacteria.

Septicity can occur ahead of the plant, in the collection system, or can occur in the treatment plant. Common locations of septicity in a collection system include lift stations, force mains and long, stagnant lines. Influent septicity is usually indicated by odors (sulfide or "rotten egg" smell), a dark color to the wastewater, and corrosion.

High amounts of organic acids and sulfides also occur in septage. These filaments may occur due to a high loading of septage. Some industrial wastewaters also contain a high amount of organic acids, such as wastewater from pickling and textile dyeing operations.

Septicity can also occur in the treatment plant. Common locations of septicity include poorly aerated or poorly mixed equalization basins; septic primary clarifiers; poorly mixed aeration basins; septic final clarifiers; and septic sludge processing side-stream returns. A common cause of septicity is the use of a primary clarifier as a sludge thickening tank or return of waste activated sludge to a primary clarifier.

Septicity can be tested for by analyzing the various basin influents and effluents for their organic acid content, using the distillation and pH titration method in *Standard Methods* (the same test as used for anaerobic digester operation). An organic acid concentration >100 mg/L is high and would account for the growth of these filaments. Hydrogen sulfide can also be tested for

using one of the readily available HACH Chemical Co. test kits. A hydrogen sulfide concentration >1-2 mg/L causes the growth of type 021N and *Thiothrix* I and II.

Note that some of the filaments now listed as septicity filaments (i.e. type 0961, type 0581 and type 0092) were previously listed as low F/M filaments. It has been learned that these filaments are actually caused by septicity and organic acids, but these grow slowly and only occur at a lower F/M. Low F/M is not their cause, only where they occur.

There is some selection of these filaments according to the type of organic acids present. Type 021N and *Thiothrix* I and II prefer simple organic acids such as acetic, propionic and butyric acids. Type 0581 and type 0092 appear to prefer higher carbon number and more complex organic acids. For example, type 0092 is a particular problem when the wastewater contains citric acid from industry.

Influent wastewater septicity can be treated by pre-aeration (which releases odors), chemical oxidation (chlorine, hydrogen peroxide, or potassium permanganate), or chemical precipitation (ferric chloride). Septicity in the collection system can be prevented by addition of sodium nitrate as an "oxygen source" (commercially available as Bioxide).

If the influent wastewater septicity cannot be reduced, then the aeration basin can be configured to allow better treatment of organic acids and sulfides. The organic acid concentration and sulfide concentration in contact with the biomass can be reduced by using completely-mixed or step-fed aeration basin conditions. A plug flow aeration basin configuration or a sequencing batch reactor is the worse case for this condition.

Low F/M Problems and Selectors

Four filaments -- type 0041, type 0675, type 1851 and type 0803 -- are specifically caused by low F/M conditions, usually below an F/M of 0.15, and corresponding longer sludge age. Their specific mechanism of successful competition is not known. These may simply be slow growing and occur only at longer sludge age associated with lower F/M. These may also grow on particulate BOD, which would be used after the more readily degradable soluble BOD is exhausted. It has also been suggested that these filaments compete successfully due to a low endogenous maintenance energy requirement.

Control of low F/M bulking can be achieved by reducing the aeration basin MLSS concentration and increasing the F/M (manipulating the "M" component). Lowering the MLSS concentration may not be suitable for many plants as this may cause the loss of nitrification and increase waste sludge production. Any change in operation that effectively increases the substrate concentration available to the activated sludge and introduces batch or plug-flow characteristics to the aeration basin, even on a short-term basis, will help combat low F/M bulking. These include: compartmentalization of aeration basins; fed-batch operation; intermittent feeding of wastes; and use of a selector. These latter methods do not reduce the MLSS concentration in the system. Incidentally, step feeding of wastes, recommended for low DO bulking, can lead to low F/M bulking, so this may need to be changed.

Filamentous bulking by the low F/M filaments is most common in completely-mixed aeration basin systems at low aeration basin substrate (BOD) concentration. Intermittently-fed and plug-flow systems are more resistant to this type of bulking. This observation has lead to the use of selectors where the RAS and the influent wastewater mix for a short time prior to the main aeration basin.

A selector is a mixing basin or channel where RAS and influent wastes mix prior to the aeration basin. Selector design is empirical at this time. Successful examples involve a 15-30 minute contact time of the RAS and influent waste; are aerated; and achieve at least an 80% removal of soluble BOD5 through the selector. Several newer designs are either operated anoxic (no free oxygen but nitrate present) or anaerobic, however, these are too new to state their general usefulness. Design and operation of selectors for filament control is beyond the scope of this paper, and the interested reader is directed to Jenkins et al. (1993, 2003) for further information.

A selector can be too large or too small in size to properly function. The goal is to provide a short term, high substrate condition which favors certain floc-formers but which discourages filaments. These floc-formers appear to rapidly store BOD as cellular storage products in the selector, which they use later for growth in the main aeration basin (they pack their own "lunch bags" in the selector). If the selector is too large, the substrate concentration achieved may not be high enough to encourage these special floc-formers and discourage filaments. If too small, insufficient time may be available for substrate uptake and storage. Also, a selector that is too small may cause the floc-formers to shunt carbonaceous substrate to exocellular polymer that can increase the SVI of the sludge ("slime bulking") and pose problems in waste sludge dewatering. The best approach is to try several selector sizes, using a larger basin or channel with movable baffles or exit gates.

Selectors are specific tools to combat low F/M filaments and are not needed by all plants. There have been many instances of inappropriate selector use where they actually made the problem worse, for example, where bulking was caused by low DO, nutrient deficiency or septicity.

Nutrient Deficiency

Nitrogen and phosphorus can be growth limiting if not present in sufficient amounts in influent wastewater, a problem with industrial wastes and not domestic wastes. In general, a BOD5:N:P weight ratio in the wastewater of 100:5:1 is needed for complete BOD removal. Other nutrients such as iron or sulfur have been reported as limiting to activated sludge, but this is not common.

Signs of nutrient deficiency include: filamentous bulking by several specific filaments (see Table 2); a viscous activated sludge which exhibits significant polysaccharide ("slime") when "stained" with India ink; and foam on the aeration basin which contains a high amount of polysaccharide (which has surface active properties). One check for nutrient deficiency is to be sure that at

least 1.0 mg/L total inorganic nitrogen (TIN = ammonia plus nitrite plus nitrate) and 0.5 - 1.0 mg/L ortho-phosphorus (soluble phosphorus) remain in the effluent at all times. The best location to test for nutrient residuals is the feed from the aeration basin to the final clarifier(s). Sometimes nutrients are released from the sludge at endogenous conditions in the final clarifier(s), falsely elevating the effluent nutrient concentrations.

If needed, nutrients should be dosed to the incoming wastewater or the aeration basin. Nitrogen sources include: anhydrous ammonia, urea, and ammonium salts ((NH4)2SO4, NH4Cl or NH4NO3). Both ammonia and nitrate are nitrogen sources for growth. Phosphorus sources include: H3PO4, Na2PO4 and (NH4)2PO4 (among others).

In systems treating mixed domestic and industrial wastes, only total inorganic nitrogen (TIN) and soluble ortho-phosphorus should be used to calculate nutrient availability. Organically combined nitrogen and phosphorus (Kjeldahl nitrogen and total phosphorus) may not be hydrolyzed fast enough by the microorganisms in the activated sludge to keep pace with BOD use. Also, the nutrient addition rate should match the influent BOD strength as much as possible, as short term BOD spikes can cause an aeration basin to become nutrient limited for short time periods (which can cause bulking) even though the 24-hour average BOD:N:P ratio is satisfactory.

Foaming Control

Three filaments cause foaming: *Nocardia*, *M. parvicella* and type 1863. All of these filaments grow on grease and oil, and these can become a problem when grease and oil are high in amount in the influent wastewater. Systems that lack primary clarification (the main grease and oil removal mechanism) appear to suffer more foaming problems. Communities with enforced grease and fat ordinances appear to suffer less from foaming problems. Also, disposal of septage, which contains substantial grease and oil content, to small activated sludge systems has been associated with foaming problems.

Note that *Nocardia* here is used as a group name rather than a specific species. Recent work has shown that a number of actinomycetes can cause foaming and include *Nocardia amarae*, *N. pinensis*, *N. rhodochrus* and other Nocardia-like species. These are often collectively referred to as the Nocardioforms, or the foam-causing actinomycetes.

Nocardia and *M. parvicella* also occur at a longer sludge age. The sludge age at which these filaments can be controlled is a function of the wastewater temperature, being lower at higher temperature. *Nocardia* appears to be favored at higher aeration basin temperatures and *M. parvicella* at lower aeration basin temperatures. *Nocardia* can usually be controlled by a sludge age below 6-8 days and *M. parvicella* at a sludge age below 8-10 days at moderate wastewater temperatures. However, many plants have had to reduce the sludge age to less than 2 days for *Nocardia* control, and this may be inconsistent with other process goals, such as nitrification or sludge handling capability.

A third factor in the growth of *Nocardia* and *M. parvicella* is septicity or low oxygen conditions. Note that the combination of grease and oil, longer sludge age, and septicity or low oxygen conditions is needed for these filaments to overgrow the system and cause foaming. In this regard, *Nocardia* and *M. parvicella* can be considered "low DO filaments", although low DO per sec doesn't cause them without the other two factors.

Nocardia and *M. parvicella* appear to grow better on unsaturated fatty acids in comparison to saturated fatty acids. A change in the US diet from saturated to unsaturated fatty acids is one reason why foaming by these bacteria is more prevalent today than it was 20-30 years ago. Also, anaerobic bacteria break down fatty acids by first modifying them to an unsaturated form. This may be why septicity is one of the causes for these bacteria, providing them with a source of unsaturated fatty acids.

Type 1863 differs in growing at a low sludge age, usually less than 3-4 days. It indicates a high amount of grease and oil and a young sludge condition. Many type 1863 foaming episodes have been caused by a reduction in primary clarification when units were removed from service for repair or cleaning and grease and oil concentration increased in the aeration system.

Control of *Nocardia* and *M. parvicvella* foaming is difficult. Chemical antifoam agents have not proven generally effective, probably because these act on chemical surfactants and not on a solids-stabilized foam. Many plants reduce aeration to control foaming, but process performance may suffer if oxygen becomes limiting. Further, low oxygen-induced bulking may occur when this is done.

Physical control of foams is most widely practiced using enlarged surface scum traps and forceful water sprays (often containing 50 mg/L chlorine). Many foams reach problem levels because they build up on these surfaces and are not removed. Foam should be removed entirely from the system and not recycled back into the plant, for example, into the headworks. Foam disposal into aerobic or anaerobic digesters can result in foaming there, so this should be avoided.

Return sludge chlorination has not eliminated *Nocardia*, although it often helps, due to *Nocardia's* growth mostly within the activated sludge flocs where it isn't readily contacted by chlorine. Also, much of the *Nocardia* may be present on the aeration basin surface and this doesn't go through the RAS line to see chlorine. RAS chlorination is more useful for foams caused by *M. parvicella*.

Many anaerobic digester foaming incidents may be attributed to treatment of *Nocardia*-containing waste activated sludge. A nationwide survey in 1981 by the American Society of Civil Engineers revealed that as many as half of the anaerobic digesters in use had experienced foaming at one time or another. It was recently reported that 54% of 26 California activated sludge plants surveyed had recently experienced anaerobic digester foaming (Van Niekerk et al.,JWPCF 59:249, 1987). Here, it is important to remember that *Nocardia* cells float, dead or alive, due to their hydrophobic cell surface. Even though *Nocardia* are strict aerobes, their cells are readily floated and cause foaming even under anaerobic conditions.

Nocardia and *M. parvicella* are controlled by addressing all three causative factors above. A reduction in the grease and oil content of the wastewater is needed, either through source control or improved operation of the primary clarifier (if present) to better remove grease and oil. These filaments are usually controlled by a reduction in the system sludge age as given above. Septicity, if present, needs to be controlled, and the aeration basin DO concentration should be raised. Note that higher aeration causes more foam formation, due to the physical action of more air present. Many operators reduce aeration when foaming occurs to reduce the foam, but this only causes more filament growth in the long term.

SUMMARY

Most activated sludge upsets and loss of process control are caused by one of several microbiological problems which include poor floc formation, pin floc, dispersed growth, filamentous and slime bulking, filamentous foaming, zoogloeal bulking, nitrification and denitrification problems and toxicity. Use of the microscopic examination and the OUR test are invaluable tools in troubleshooting the activated sludge process. Once the cause of the problem or upset is known, specific remedies appropriate for the problem can be used. Short term control methods such as chlorination are often used to quickly stop a bulking problem. However, the best approach is to investigate the long-term control methods suitable for the problem that is occurring to achieve trouble free operation.

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