OPERATOR'S GUIDE TO ACTIVATED SLUDGE BULKING

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ABSTRACT

A range of factors have been suggested to explain the causes of filamentous bulking. Unfortunately they are often opposites. Different theories have been developed based on dissolved oxygen, substrate diffusion within the floc, bacterial growth kinetics and food storage properties. These concepts have been combined with new analysis of anoxic bulking to produce a consistent unified theory. Full scale plant examples are used for illustration.

1.0 INTRODUCTION

Sludge bulking affects 60% of activated sludge plants. It is caused by growth of floc-bridging filamentous bacteria which results in poor sludge compaction and settling (SVI > 150 ml/g) and potential solids wash-out from the final clarifiers. A critical mass of filamentous bacteria can develop within a week but it may take 2 to 3 sludge ages for effective biological control. This paper utilises the Monad equation and competitive growth factors associated with bacteria shape and floc size together with selection strategies based on food storage and substrate preference to explain SVI values at different BOD: MLSS (F/M) loadings.

Good floc-forming bacteria have a spherical shape that facilitates growth in three dimensions and a large, rapid food storage capability (80% uptake in 15 minutes). This enables competitive growth when food and dissolved oxygen are not limited. Filamentous bacteria are cylindrical can only grow in either one or two directions but have higher surface/volume ratio. They can also grow outside the floc. This provides a competitive 'scavenger' advantage when growth essentials are scarce.

In 1965, the UK Water Pollution Research Laboratory suggested optimum settleabilities corresponded to conventional plant loadings (carbonaceous oxidation) and extended aeration plant loadings (full nitrification). Case studies use high F/M, BNR and low F/M plants and the corresponding bacterial morphology, physiology and floc size to explain the selection of either floc forming or filamentous bacteria which then results in better or worse SVI values.

2.0 KINETIC SELECTION

This theory (Chudoba 1973) is based on the Monad bacterial growth equation. It predicts that with unlimited substrate present, floc formers are selected because they have a high maximum growth rate (μ max).

Table 1: ***Indicative parameters from the literature (pure cultures in water)***

Organism	μmax	Ks	K_{DO}	Decay rate
Good floc-former	6	4	0.20	0.08
Type 1701	3	2	0.015	0.06
Microthrix	1	0.5	0.030	0.03

At low substrate concentration or low DO, filamentous organisms are selected because they have low half saturation or affinity constants (K_S or K_{DO}). See Fig 1.

Bacterial growth rate $= \frac{\mu \max [S]}{K + [S]}$ μ max = maximum growth rate
S = Substrate concentration
K = half saturation constant

In practice, kinetic factors are sub-optimal (dotted lines) due to substrate diffusion limitations within the floc, competition from other organisms and fluctuating sewage concentrations.

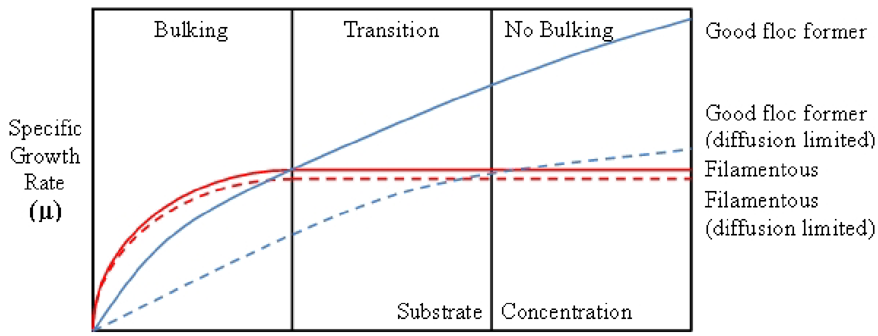
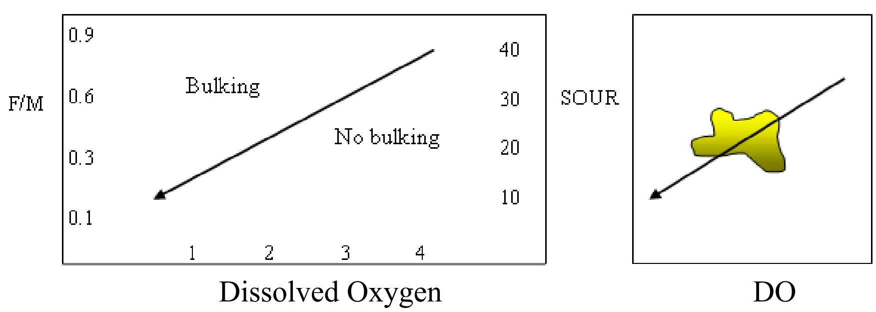


Figure 1: ***Theory of Kinetic selection***

3.0 CONVENTIONAL ACTIVATED SLUDGE PLANTS (HIGH LOADING)

First generation Australian activated sludge plants typically comprised primary settling tanks followed by surface aeration in 1 to 5 compartmental cells. Aeration times were 5 to 6 hours (carbonaceous oxidation only) with F/M ratios of 0.4 and sludge ages of 4 to 6 days. With lots of food available to support growth (demonstrated by a high oxygen utilization rate), fast growing floc-forming bacteria should be preferentially selected – provided that there is adequate time for all stored food to be utilized - otherwise the storage capacity will be lost. The plug flow configuration provided a high substrate at the inlet with the oxygen demand reducing at the outlet. Non-filamentous sludges were predicted, but bulking was common. Bulking can occur if the DO in the mixed liquor is low (or septic). Refer Jonathon Palm,1980.



25 years ago, plants in Brisbane typically had bulking problems caused by Thiothrix, Type 0411, Type 1701 and H hydrossis. In Sydney, the main filamentous organisms were S natans, Type 0961 and M parvicella. The filamentous bacteria S natans, Type 1701, H hydrossis and M parvicella are low K_{DO} strategists. The aerobic filaments Thiothrix, Type 0411 and Type 0961 can utilise sulphide caused by septicity for metabolism as an alternative to oxygen.

The high specific oxygen uptake rate (SOUR) associated with a high F/M ratio results in a low DO concentration in the bulk MLSS and within the floc. This promotes low K_{DO}

filamentous bacteria.
In addition, the surface aerators in these early plants were often not fitted with uptake draft tubes resulting in long turn-over times and poor tank mixing which with the high OUR caused a vertical dissolved oxygen gradient. DO levels measured at the liquid surface may have been 2.0 mg/L but DO levels at the bottom of the tank were < 0.2 mg/L. An oxygen gradient would also have existed within the floc due to DO diffusion resistance. At an F/M ratio > 0.4, an average DO concentration of 1.0 mg/L would have zero oxygen at the floc centre and no oxygen in 20% to 80% of the floc, subject to size and OUR.

3.1 Case Study

A 6500 EP overloaded conventional surface aeration plant was augmented by a 2000 EP package plant. Both plants had bulking sludge and a healthy foam presence. To resolve the bulking problem the flow configuration was changed so the main activated sludge plant treated all flows and the package plant operated as a 30d aerobic digestion plant.

Bulking caused by low DO filamentous bacteria was controlled on the main plant as follows. An air diffuser manifold was installed on the tank floor below the surface aerator using air from the package plant to minimise the vertical DO gradient. The MLSS was reduced to 1200 mg/L to provide a sludge loading of 0.8, a corresponding sludge age of 2 days and SOUR of 40 mg/L/g.h. These changes resulted in a smaller floc size and a uniform DO in the MLSS which provided an aerobic floc with no bulking or foaming. The high food absorption rate required 50% of MLSS to be wasted to the digester, replaced by new, hungry bacteria.

Foam was confined to dead spots at the surface of the aerobic digester. ***Note:*** At a very high sludge age (eg plant overloaded at commissioning or after a solids washout or toxic discharge) dispersed floc can occur. This is not bulking. Flocs simply do not form. Even if particles settle, the effluent is turbid with a high BOD.

4.0 CONVENTIONAL ACTIVATED SLUDGE (LOW LOADING)

Most of Australia's largest activated sludge plants were built in the 1970's incorporating diffused air aeration. They were often designed in accordance the UK aeration equipment supplier's recommended F/M ratio of 0.2 for producing an effluent BOD of 10 mg/L.

The mean sewage temperature in the UK is 14°C compared to 24°C in Australia. A 10°C temperature increase doubles the bacterial reaction rate. As a result, at this F/M and sludge ages of 6 to 9 days, partial nitrification can occur in plants designed with only enough air capacity for carbonaceous oxidation. As there was insufficient air to meet the high combined oxygen demand for both BOD and NH_3 oxidation, simultaneous nitrification and de-nitrification occurred. Typical effluent concentrations were NH_3 10 mg/L and NO_3 10 mg/L. ***Note:*** with an effluent nitrate > 15 mg/L, rising sludge or de-nitrification in the clarifier occurs. This is also observed after completing the SVI test, but it is not bulking.

In partial nitrification plants, in addition to the common low DO and Sulphide using organisms, in Brisbane filament Types 0803 and Type 914 were now also detected. In Melbourne, the low DO organisms Type 0411 and Type 021 N were commonly found. Foam producing actinomycete nocardioforms and M parvicella were also often present. The diffused aeration process produces larger flocs than surface aeration plants as there is no mechanical floc shearing. Larger flocs have also been correlated with a high sludge age. Flocs experience DO and substrate concentration gradients but are not NH_3 limited. This dis-functional NO_3/NH_3 regime typically has a SOUR of 20 mg/L/g.h. These micro-climate conditions often support growth of resourceful lower F/M organisms such as, Type 021 N, Type 0803, Type 0092 and Nostocoida limicola. Growing outside the floc in the bulk liquid, utilizing soluble substrates, their higher surface area, low K_S and low K_{DO} values makes them good scavengers out-competing the good floc forming bacteria.

4.1 Case Study

A large diffused air activated sludge plant with a design F/M ratio of 0.22 and 7 to 8 day sludge age, experienced chronic bulking problems resulting in a risk of solids washout from the clarifiers. Raw sewage pumps needed to be operated in accordance with sludge blanket levels in the clarifier using the sewer capacity for storage. The sewage backlog would be cleared by about 1.00am - 4.00am, in time for the next day's peak sewage flow.

The plant loadings were re-configured to control the bulking problem. Stage I was operated at a sludge age of 3 days with half the aeration tanks decommissioned and MLSS reduced from 2500 mg/L to 1500 mg/L. Stage Π was operated in a full nitrification mode with a 12 day sludge age. This required installation of two new blowers to increase air supply by an additional 30%. Bulking and foaming were essentially eliminated (some Type 1701 present).

5.0 BIOLOGICAL NUTRIENT REMOVAL

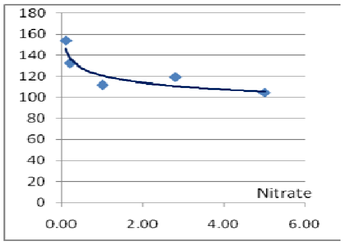
Biological nutrient removal plants appeared in the 1980's. Compartmental BNR plants with feed/starve conditions, a high aerobic fraction and a DO of 2 mg/L often have good settling sludge because the fast growing, "μ" strategy floc formers are not constrained by either substrate or dissolved oxygen deficiencies or floc diffusion limitations.

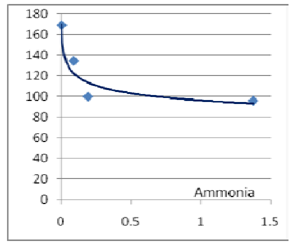
Floc formers also have a "metabolic" selection advantage since phosphate accumulating and de-nitrifying bacteria rapidly take up soluble readily biodegradable substrates (RBCOD) in the anaerobic and anoxic zones. Filamentous organisms are left with the slowly biodegradable food (SBCOD) in the aeration phase. Floc formers can also use this particulate food entrapped within the floc, but have the advantage of stored energy when all the SBCOD has run out.

However, Dick Eikelboom and others reported an increase in sludge bulking when BNR operation was introduced in Europe; 80% of plants also reported foaming. Bulking occurred equally on either N & P removal plants or N removal only, and at compartmentalised UCT systems, oxidation ditches and SBR/intermittent aeration plants. However, plants operated with an aerobic fraction greater than 55% (full nitrification) maintained low SVI values.

- Bulking and foaming are more severe in spring and autumn in many countries, including Australia. It is likely that seasonal temperature changes impact on the growth of nitrifying bacteria. Partial nitrification produces high ammonia concentrations which can be preferentially taken up by filamentous bacteria – particularly Microthrix parvicella.
- In complete mixed aeration tanks and intermittent aeration systems, a long and continuous influent feed time resulted in a low soluble RBCOD concentration in the aeration zone which provided the filamentous "K_S" strategists with a competitive selection advantage.

Bulking occasionally occurs at well designed plant producing low effluent NH_3 and NOx. If SVIs were sorted in groups from low to high SVI and corresponding effluent results plotted, a correlation with low Ammonia and Nitrate concentration (< 0.5mg/L) was found. ***Note:*** Too much aeration at a very long sludge age can cause pin-point flocs (over-aeration). These small flocs < 25 µm, settle well but produce a turbid effluent. This is not bulking.





These conditions indicate extremely low carbon and nutrient levels in the bulk liquid. Bacteria are dependent on stored substrate (endogenous respiration). However, in the final clarifiers, which used to be designed with a DWF detention time of 6 hours but now have 18 hours, any DO and NO_3 in the MLSS will be quickly reduced to zero. After about 8 hours, extreme starvation conditions develop (particularly within the flocs) resulting in death and cell lysis. However, two very resilient filamentous organisms with low cell maintenance requirements are able to utilise the nutrients released from the dead cells and store it as high energy food.

- Microthrix parvicella is spaghetti like and likes fatty and oily food and ammonia.
- Particulates are always attached to Type 0041, it likes carbohydrates and protein.

When MLSS is returned to the bioreactors with fresh sewage and NO_3 in the "a" recycle or DO in the aerobic reactor, these organisms with their stored energy can be dominant.

5.1 Case Study

Population growth required an oxidation ditch operating at a sludge age of 20 days with full nitrification and SVI < 100 g/L to be upgraded. Mechanical aerators were replaced with a diffused aeration system and consultants advised that if the plant was operated in a BNR mode with a sludge age of 12 days, it could now treat 50% more flow (SOUR 12 mg/L/g.h).

Changing to nitrification/denitrification resulted in sludge bulking. Operators trialled different mixing speeds of 0.2 and 0.4 m/s to improve settleability in the oxidation ditch; RAS rates of 50-150%; aerobic fractions of 55-70%, and tapered/fixed DO control (2 mg/L). DSVI was reduced to <140g/ml - but still too high for the hydraulically overloaded clarifiers. RAS chlorination was installed at a Cl_2 dose rate of 2 kg/kg MLSS. Settleability improved within 9 days (DSVI<100 g/ml). ***Note:*** Filamentous bacteria with a higher surface area/volume ratio are more susceptible to Cl_2 than the floc forming organisms which also have floc diffusion protection. Cl_2 didn't impact on effluent quality.

6.0 EXTENDED AERATION PLANTS

Extended aeration systems include package sewage treatment plants, oxidation ditches and continuous flow, intermittent aeration plants. They date from the 1960s and were designed with an F/M ratio of 0.05, operating at a sludge age 25 to 30 days with higher MLSS – usually > 3000 mg/L. They have the largest floc size but the lowest oxygen uptake rates.

A Queensland survey (Debbie Bradford) found occasional bulking at 4 out of 15 oxidation ditch plants (27%). With no limitation on substrate or dissolved oxygen and a low particulate F/M ratio, floc forming bacteria were dominant but foaming was reported at 11 plants (73%). Bulking occurred at 50% of package plants with 95% reporting Nocardia foaming. Coarse bubble aeration used in package plants results in poor mixing and dead spots with pockets of low dissolved oxygen causing simultaneous nitrification/denitrification bulking and foam. Three out of four intermittent aeration plants had both bulking and foaming. A UK survey reported that M parvicella was a particular problem at SBR plants in North England and Scotland causing bulking and foaming but not in the warmer Southern England, indicating that bulking was related to the lower sewage temperatures impacting on nitrification ie NH_3. Foaming requires:

- a critical mass of Gram+ filamentous organisms (5-10% of the MLSS is enough)
- the presence of hydrophobic surfactants (bubble stabilisers)
- a bubble release mechanism

Foaming is associated with either Nocardioforms or M parvicella. These have a hydrophobic cell wall and can attract hydrophobic long chain fatty acid compounds.

De-nitrification within the floc generates intra-cellular nitrous and nitric oxides and inter-cellular nitrogen gas bubbles trapped within the filamentous hydrophobic network.

6.1 Case Study

A large activated sludge plant had primary settling and four aeration basins incorporating a tapered aeration pattern. The plant was 100 % aerobic, but operated at a sludge age of 8 days with an effluent NH_3 2 mg/L and NO_3 10 mg/L indicating a high degree of denitrification at the RAS and sewage interface. Stirred SVI was 125 ml/g and foam was not a major issue.

Plant configuration was changed from plug flow to a contact stabilisation mode. This caused major de-nitrification in the bulk liquid and floc. Overnight, the patchy foam depth of 40 mm increased to about 1 m, covered the entire tank surface and took 10 days to clean up. Foaming ceased after restoring plug flow and fully aerobic conditions.

7.0 CONCLUSIONS

Bulking occurs when the micro-environment has a nutrient or DO deficiency or if Sulphides are present, promoting selection of filamentous organisms. Good settleability occurs when floc forming bacteria have a competitive growth and storage advantage eg excess food plus time/space available to enable oxidation by DO or nitrate to regenerate food storage capacity.

The operating environment also is influenced by plant configuration and sludge age:

- Compartmental (>substrate gradient).Complete mix (diluted RBCOD concentration)
- BNR with metabolic selection for floc formers but NH_3 and low DO/substrate issues.

The micro-operating environment of the floc is also influenced by floc size and diffusion:

- Diffused air aeration and low F/M ratio result in medium-high floc size > 250 µm
- Flocs>150 µm exhibit substrate diffusion resistance as filaments can grow outside
- Filamentous bacteria with low cell maintenance needs scavenge endogenous nutrients.