BULKING SLUDGE CONTROL—
PROGRESS, PRACTICE AND PROBLEMS

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ABSTRACT

Since bulking sludges are the primary cause of failure of activated sludge systems, the first obligation of the designer is to minimize the possibility of such an occurrence. This paper traces the evolution of bulking control concepts from the earliest date when batch and semi-continuous selectors were employed, to more recent experiences with anaerobic, anoxic, oxic and high F/M biological selectors. This paper also summarizes recent results obtained from 12 USA facilities employing various selectors. Preliminary conclusions support high to low F/M gradient as a dominant selector factor. Whether the system is aerated or not, the available oxygen in the initial contact zones (ICZs) should be substantially less than the oxygen demand in the zone to ensure that anaerobic functions occur within the cell mass. In addition, F/M gradients should be provided in each environment.

KEYWORDS

Activated sludge; Bulking control; Filamentous; Oxic, anaerobic, anoxic or aerated high F/M selectors.

HISTORICAL REVIEW

With few exceptions, soluble BOD₅ removal in activated sludge facilities is not an operational problem. Most process failures result from loss of suspended solids and the resulting BOD (endogenous respiration) from these suspended solids. Disregarding overloaded facilities, basic design problems or improper operation, such failures can most often be traced to the presence of a bulking sludge. The problems of bulking sludges (SVIs > 150 ml/g) have been endured ever since wastewater plant designers modified Ardern and Lockett’s (1914) batch reactor to a continuous flow design.

Donaldson (1932a,b) characterized the filamentous growth causing bulking sludge as “the weeds of activated sludge,” an apt term. He suspected that spiral flow, diffused aeration caused back mixing or short circuiting in the ‘plug flow’ rectangular basins, changing the substrate regime to that of a more completely mixed mode. This mode, he correctly conjectured, encouraged the development of a bulking sludge. As a solution, he suggested the use of baffles to compartmentalize the aeration...
basins. Some 1950s facilities in the United States, such as Baltimore and Columbus, OH., have successfully employed this practice.

However, in the early 1960s, the use of completely mixed activated sludge (CMAS) systems was popularized. Its use provoked an increased occurrence of bulking sludges in wastewater facilities receiving readily biodegradable organics. This departure from the design principles derived from Donaldson’s observations required almost two decades to correct.

From the late 1940s to 1952, Davidson worked on the application of aerobic (trickling filters and activated sludge) and anaerobic processes for the treatment of strong distillery wastes. Davidson (1949) piloted a precursor to the anaerobic contact process using 18-24 hours retention. He also tested the first directly coupled anaerobic-aerobic process (reported in Albertson, 1987), functionally indistinct from the well-known Bardenpho/Phoredox (Barnard, 1976) and A/O process (Spector, 1977). Davidson (1959) tested and patented an anaerobic-aerobic treatment process and in his 1949 studies of this process was able to produce an SVI as low as 34 ml/g on this readily biodegradable distillery wastewater that is notorious for causing bulking sludges.

In the 1950-1960s, the wastewater engineering profession was not ready to accept the idea of depriving an aerobic culture of oxygen and Davidson’s concepts were, for the most part, ignored. Heide and Pasveer (1973) found that short-term, unaerated, contact of the return activated sludge (RAS) or mixed liquor with the influent wastewater resulted in bulking sludge control and noted that the soluble BOD₅ was rapidly removed in the unaerated zone. These results reinforced the Davidson concept.

Meanwhile, other investigators were working with dissolved oxygen (D.O.) control. Bhatia (1967) found that operating the initial stages of an eight-stage biological plant at zero D.O. would control bulking, but that there was a loss in treatment efficiency. Ryder (1974) reported that operating the initial stages of the Reno-Sparks plant at low D.O. resulted in control of bulking sludges. In summarizing the performance of biological phosphorus plants, Garber (1972) noted that the SVI was less than 100 ml/g in these treatment operations. In the initial contact zone (ICZ) of these plants, the D.O. was, or approached, zero in the characteristically long, plug flow tanks.

Koller (1966) reported on the benefits of semi-continuously fed aeration basins to control bulking, and Pasveer (1969) confirmed Koller’s work in his tests to control the SVI by semi-continuous feeding of a full-scale oxidation ditch. Pasveer’s later collaboration with Heide (1973) on batch studies provided further confirmation of Koller’s work.

The British Water Pollution Laboratory (1969) demonstrated that staging of the aeration zones reduced the SVI. In his series of seven papers on bulking sludge control, Chudoba et al., (1973) demonstrated that compartmentalized, aerated reactors provided a high degree of bulking sludge control. Rensink (1974), too, confirmed the observations of earlier investigators regarding the benefits of compartmentalization and batch feeding to control SVI.

Tomlinson (1976) reported a British survey of 65 activated sludge plants. While the CMAS plants had a much higher SVI than that of the long rectangular plants, there was no correlation to the overall ratio of food to mass (F/M) in the plants studied. However, there was an excellent correlation between SVI and the calculated F/M in the first ‘theoretical’ compartment of the rectangular aeration basins. The first compartment volume was estimated from a dispersion model.
SUMMARY OF BACKGROUND EXPERIENCE

The ICZ is commonly called the zone of biological population selection or, simply, the selector. This is the zone of interest for bulking control and where quantification of operating conditions is required. There has been a distinction made between anoxic and anaerobic ICZs. An anaerobic zone has been defined in the Spector patent reference as an ICZ that receives a wastewater influent and a return sludge with a weighted average NOxN concentration of less than 0.5 mg/l (col. 3, lines 46-51). Total influent concentrations greater than 0.5 mg/l NOxN would then constitute an anoxic zone, even though the ICZ NOxN may have been reduced to near zero. For the sake of differentiation in reporting data, these definitions will be used here, recognizing that the biomass may be unaware of this distinction. Anoxic selectors have been and are now often employed for bulking control. Some of the quantification criteria for the ICZ, shown in Table 1, may be subjective or not wholly supportable, but they have been or are in common usage. For example, to microbiologists, anoxic — not anaerobic — means devoid of available molecular oxygen.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic (A_n)</td>
<td>no added oxygen or air, D.O. → 0.0</td>
</tr>
<tr>
<td></td>
<td>total influent NOxN &lt; 0.5 mg/l</td>
</tr>
<tr>
<td>Anoxic (A)</td>
<td>no added oxygen or air, D.O. → 0.0</td>
</tr>
<tr>
<td></td>
<td>total influent NOxN ≥ 0.5 mg/l</td>
</tr>
<tr>
<td>Aerated (A)</td>
<td>addition of oxygen or air</td>
</tr>
<tr>
<td></td>
<td>D.O. ≥ 0.0 mg/l</td>
</tr>
<tr>
<td>Oxic (O)</td>
<td>addition of oxygen or air</td>
</tr>
<tr>
<td></td>
<td>D.O. ≥ 1.0 mg/l</td>
</tr>
<tr>
<td>Hi F/M</td>
<td>≥ 3 kg BOD_5/kg MLSS·d in ICZ</td>
</tr>
<tr>
<td>Lo D.O. (A_l)</td>
<td>≤ 0.3 mg/l D.O. in ICZ</td>
</tr>
<tr>
<td>Hi D.O. (A_u)</td>
<td>≥ 2.0 mg/l D.O. in ICZ</td>
</tr>
</tbody>
</table>

Since there is a continuing and widening search for a universal bulking sludge control approach, it is not surprising that the background data are diffuse and difficult to correlate. Often, the reasons why similar wastewaters may or may not result in bulking are obscure and this further complicates the search. Some wastewaters do not readily cause bulking regardless of the process design.

The development of process control technology for bulking sludges has evolved from a number of different concepts, all of which have had some degree of success. The broadest based data are from Tomlinson, representing long-term results from 65 operating facilities. Although it was necessary to determine the theoretical F/M in the ICZ of the rectangular reactors and to approximate the back mixing effect, Tomlinson's data confirmed the results of Chudoba and many others who had shown the benefits of higher F/M ratios in the ICZ. These investigators found that higher F/M ratios in the ICZ, anaerobic or anoxic, whether aerated or not, continuous, batch or semi-continuously fed, produced lower SVIs.

A comparison of several background studies from 1959 to 1988, summarized in Table 2, supports this position. In some cases, it was not possible to accurately determine the F/M; other studies reported a range of F/Ms and SVIs. However, the data base as a whole showed high F/M in the ICZ to be a dominant factor in controlling SVI.
Lending additional support to this position is Gabb et al., (1988), who reported that about 27 of 33 nutrient removal plants in South Africa had bulking problems; similar problems have occurred in North American plants. These plants were unaerated and either anoxic or anaerobic in the first zone. However, the typical South African and early North American designs do not have an F/M gradient in the anaerobic, anoxic or oxic zones. As a result, many of these designs are single compartments for each environment and with relatively low F/M in each zone.

TABLE 2. PRIOR ART CONTINUOUS FLOW EXPERIENCE WITH BULKING SLUDGE CONTROL CONCEPTS.

<table>
<thead>
<tr>
<th>Author</th>
<th>Selector Mode</th>
<th>Feed Mode</th>
<th>ICZ Mode</th>
<th>D.O. mg/l</th>
<th>F/M lb/lb/d</th>
<th>SVI ml/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davidson, 1959</td>
<td>AN</td>
<td>Continuous</td>
<td></td>
<td>0.0</td>
<td>1.0</td>
<td>34</td>
</tr>
<tr>
<td>Bhatia, 1967</td>
<td>AL</td>
<td>Continuous</td>
<td></td>
<td>0.0</td>
<td>&gt;2.5</td>
<td>&lt;120</td>
</tr>
<tr>
<td>British W PRL, 1969</td>
<td>A</td>
<td>Continuous</td>
<td>Unkn</td>
<td>0.0</td>
<td>0.8</td>
<td>&lt;75</td>
</tr>
<tr>
<td>Milbury, 1971</td>
<td>AL</td>
<td>Continuous</td>
<td></td>
<td>0.0</td>
<td>&gt;2.0</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Chudoba, 1973</td>
<td>AL</td>
<td>Continuous</td>
<td></td>
<td>&gt;0.5*</td>
<td>&gt;2.5</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Heide &amp; Pasveer, 1973</td>
<td>AN/Ax</td>
<td>Continuous</td>
<td>and Batch</td>
<td>0.0</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Rensink, 1974</td>
<td>A</td>
<td>Continuous</td>
<td>Unkn</td>
<td>3.6</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>Tomlinson, 1976</td>
<td>A</td>
<td>Continuous</td>
<td>Unkn</td>
<td>&gt;2.0</td>
<td>&lt;100</td>
<td></td>
</tr>
<tr>
<td>Spector, 1977</td>
<td>AN</td>
<td>Continuous</td>
<td></td>
<td>&lt;0.7</td>
<td>&gt;3.0</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Chudoba &amp; Wanner, 1988</td>
<td>A_H</td>
<td>Continuous</td>
<td></td>
<td>≈1.0</td>
<td>12.0</td>
<td>&lt;50</td>
</tr>
</tbody>
</table>

*Based on private communication with Dr. Chudoba.

RECENT EXPERIENCES

The approach to controlling SVI is following a number of indistinct paths involving anaerobic, anoxic and aerated ICZs. The only consensus is that there should be a definitive high to low F/M gradient or floc loading in the initial zone(s) that removes SBOD₅. A practice recommended by Wanner and Grau (1988) is to provide F/M gradients in anaerobic, anoxic and oxic zones to ensure control of bulking. This recommendation evolves from the IAWPRC hydrolysis model (Ekama and Marais, 1986), which indicates a secondary bulking can occur in the oxic zones due to slow SBOD₅ release by hydrolysis of particulate BOD₅. This slow release of SBOD₅, but with a very low concentration of SBOD₅ and low F/M, would favor filamentous growth. On the other hand, high D.O. - high F/M oxic selectors are not reliable due to technical and economical problems of oxygen transfer. The selectors discussed in this paper may be considered to be various modes of semi-aerobic processes. In other words, floc centers are likely devoid of oxygen in the high F/M zone, even in the presence of 1.0-1.5 mg/l D.O. in the liquid phase.

Newark, OH. The new 347 l/s (8 MGD) treatment plant utilizes an A₉-Aₓ-Oₓ flow sheet for SVI control, nitrification and denitrification. The original plant has had a long history of poor treatment performance due to bulking sludge and foaming episodes. Significant industrial discharges were at least part of the cause. The new plant was brought on-line in June 1988. The SVI has decreased from 100-400 ml/g to 80-200 ml/g, and averaged 124 ml/g. No adverse bulking in the final clarifiers has occurred in the new plant. The SVI first increased in the colder months, but decreased below 100 ml/g when waste activated sludge (WAS) was not returned to the primary clarifiers.
The plant’s three-stage $A_N$ selector currently operates with a F/M of 1.59, 0.79 and 0.53 kg BOD$_5$/kg MLSS-d, respectively. The 14-month average clarified effluent quality of the plant is as follows: 2.7 mg/l CBOD$_5$, 3.8 mg/l TSS, 1.0 mg/l NH$_4$N, 2.4 mg/l TKN, 8.3 mg/l NO$_3$N and 4.1 mg/l TN. Longer term data are needed to determine whether or not the higher winter SVI values were an aberration.

Southerly WWTP, Columbus, OH. The new 4950 l/s (114 MGD) treatment plant receives 40-45% of its organic load from a brewery. The original plant had experienced periodic, but serious, bulking problems. The new plant is designed as an $A_X^{-}A_N^{-}O_X$ flow sheet with internal recycle of NO$_3$N to the ICZ for denitrification. There are 10 compartments in each of the 16 - 274m x 7.9m x 4.6m deep basins. The design of the initial three stages of the $A_X$ selector are loaded at an F/M of 6, 3 and 1.5 kg BOD$_5$/kg MLSS-d, respectively, and it is operating at 70-85% of full organic load, 90-110% of hydraulic design. Long-term pilot studies and the first year of operation have demonstrated an excellent and stable SVI. A stable foam on the ICZ has had high concentrations of *Microthrix parvicella*. However, the foam dissipates when it passes into the oxic zones.

The performance characteristics of the Southerly WWTP are shown in Figure 1. The SVI and performance had been increasingly more stable since the July 1988 startup. Phosphorus removal is not required and the effluent objective is less than 10 mg/l NO$_3$N. The plant has operated under both anoxic and anaerobic conditions without aeration and at a low D.O. of 0.3-0.6 mg/l in the ICZ with no definable performance differences.

![Daily SVI - ml/g](image)

**Fig. 1. Performance characteristics of Columbus Southerly WWTP**

Jackson Pike WWTP, Columbus, OH. The modified plant of 2600 l/s (60 MGD) has been operating as an $A_X^{-}O_X$ process using a two-stage selector with a F/M loading of 5.0 and 1.1 kg BOD$_5$/kg MLSS-d, respectively. The D.O. is less than 0.6 in the initial two zones. The first year of operation of the upgraded plant has produced a high quality effluent with excellent bulking sludge control. However, due to the low SBOD$_5$/TBOD$_5$ ratio in the influent wastewater, SVIs were generally less than 150 ml/g prior to plant modifications. The D.O. in the original plant was also near zero for 25-35% of the aeration length and this possibly contributed to bulking sludge control. Phosphorus removal is
minimal and NO$_3$N concentrations are high (10-15 mg/l) in the effluent as well as in the ICZ influent. Aeration and high NO$_3$N in the ICZ would discourage biological removal of excess phosphorus.

The SVI history and the average clarified effluent quality of the partially upgraded plant is illustrated in Figure 2. The SVI variations are greater at Jackson Pike, but future improvements in aeration control may reduce the range of SVI values.

![Daily SVI - ml/g](image)

Vineland, New Jersey - Landis Sewerage Authority. The Landis plant was designed as an $A_n$-$O_x$ facility with an initial anoxic F/M of 1.0 kg BOD$_5$/kg MLSS-d at maximum monthly loading conditions. At current monthly loadings, the ICZ loading is 0.75 kg/kg-d. The retention time in the ICZ is 0.36 hours based on plant flow, return activated sludge and internal recycle (Q + RAS + IR). The plant receives 70% of its loading from fish packing, wine production and other food processing facilities and has a high SBOD$_5$:TBOD$_5$ ratio. These conditions would indicate a potential to produce a bulking sludge in a conventional plant.

The plant has been able to maintain the SVI in the range of 90-130 ml/g until September 1989 when it increased to 260 ml/g. No apparent reason for the bulking condition has been defined. The dominant filamentous organism reported is type 0041 and chlorination is being used to control the SVI. The monthly average clarified effluent quality is 7 mg/l CBOD$_5$, <5 mg/l TSS, <0.4 mg/l NH$_4$N, and 3 mg/l TN. Even though there is 20-30 mg/l of NO$_3$N removal by denitrification in the anoxic zone, influent TP is reduced to 1.5-3.3 mg/l.

Davenport, IA. The Davenport plant consists of eight CMAS cells with submerged turbine aeration, which can be operated in a CMAS mode or a series mode of two to six compartments. A series mode was employed to reduce bulking, but sludge bulking incidents exceeding 300 ml/g SVI still occurred. The bulking conditions limited the 1735 l/s (40 MGD) design peak flow to 868-1084 l/s (20-25 MGD). In late 1987, the plant initiated D.O. control experiments in the first stage of aeration while operating two trains of three basins each. In one month, the SVI had decreased from over 300 ml/g to less than 100 ml/g when operating at near zero D.O. in the initial basin. Further studies found that reinstating full aeration induced bulking. No air in the ICZ resulted in a very low SVI of 40-50 ml/g, but lead to
excessive dispersed floc in the effluent. Bridging filaments, types 0675, 1701, 0041 and Nocardia sp. are present in low quantities at 80-100 ml/g SVI, which provides optimum treatment.

The experimentation has evolved to an operating procedure of aerating the ICZ for 4-12 hours/day. When the SVI is too low, the aeration period is increased and vice versa to operate in the target range of 80-100 ml/g. The 2 1/2-year SVI history of the plant is shown in Figure 3.

Because of the successful operation of the selector, the Davenport plant is now capable of operating at a flow capacity up to 1820 l/s (42 MGD). The average 26-month clarified effluent quality is 7.4 mg/l CBOD₅ and 13.5 mg/l TSS. The F/M loading in the ICZ is 0.64-1.16 kg BOD₅/kg MLSS·d. The selector mode is Aₓ/Aₙ followed by two to five stages of Oₓ depending on plant operation.

Hatfield TWP, PA. The new 293 l/s Hatfield advanced wastewater treatment plant employs the Schreiber low load process to treat mixed industrial and domestic waste. The original CMAS facility was prone to severe bulking. The new flow sheet is Aₓ-Oₓ using internal recycle for partial denitrification. The anoxic selector is single stage and has an average F/M of 0.13 kg BOD₅/kg MLSS·d. The SVI in the last 15 months ranged from 46-71 ml/g, averaging 55 ml/g.

During the two-month period when the internal recycle pumps were inoperable, the SVI was 55 ml/g, the same average as the months preceding and following this period. The clarified effluent averaged 3 mg/l CBOD₅, 6 mg/l TSS, 1.4 mg/l NH₄N, 9.5 mg/l TN and 1.3 mg/l TP over the last 15 months. The D.O. in the oxic zone is typically maintained at 0.5-1.0 mg/l to encourage further denitrification. Temporary loss of nitrification in the system reduced effluent TP to <0.5 mg/l, which also periodically occurs in the Aₓ-Oₓ mode.

Middletown, OH. The existing Middletown wastewater treatment plant has had a history of chronic bulking problems. Extensive pilot studies were carried out using the plants fully aerated configuration, an Aₓ-Oₓ flow sheet, which produced the lowest SVI, and an Aₓ-Oₓ selector design. Further pilot studies were then carried out using the four-stage, aerated, high F/M selector (Aₓ-Oₓ) concept advocated by Chudoba and Wanner (1988) and based upon Kroiss (1985).

Fig. 3. 30-Day Moving Average SVI at Davenport, IA
The four-stage, high F/M (12, 6, 4 and 3 kg BODs/kg MLSS-d, respectively), medium D.O. (1.0 mg/l) selector was able to reduce the SVI to less than 100 ml/g in three weeks after startup and averaged 65 ml/g SVI at 3000-4000 mg/l MLSS. The following month the SVI averaged 47 ml/g. The microscopic analysis showed that the filamentous species in the main plant was dominated by *N. limicola* II and type 1851 and, to a much lesser extent, types 0675 and 0041. The pilot plant had similar species, but lesser quantities and much larger and better settling flocs.

**Star Valley Cheese Coop., Thayne, WY.** The cheese production facility employs a sequencing batch reactor (SBR) to process the strong wastewater (SBODs of 600-2000 mg/l) in an *A_n*-*O_x* mode. While over 90% of the dairy wastewater treatment facilities have reported bulking problems, the Star Valley SVI is generally 40-80 ml/g and as low as 25 ml/g. The SVI increased to 300 ml/g when the plant was overloaded 200-400% for three to five days and the D.O. was zero to 1.0 mg/l at the aeration cycle. An increase in the SVI was generally observed when organic overloading prevented the D.O. from reaching 4-5 mg/l at the end of the oxic cycle.

The effluent BODs and TSS are 6-8 mg/l and 10-15 mg/l, respectively. Phosphorus accumulation in the MLSS has been noted and would be available for nutrient shortage periods. Phosphorus and nitrogen content of MLVSS, not effluent concentrations, are the best measures of nutrient sufficiency since there is Bio-P removal and NDN occurs. *Nocardia* sp. is a continuing problem but has been reduced significantly by a change in the plant’s cleaning detergent.

**Tree Top, Selah, WA.** The apple and other fruit juice wastes produced by the plant have been treated in a 12-day flow-through CMAS aerated lagoon for several years. The resulting MLSS of 500-1200 mg/l did not settle and the SVI was always greater than 1000 ml/g. Dominant filaments were types 1701, 021N and 0041. Nutrient supplemented pilot studies using two *A_n*-*O_x* reactors with one and two hours *A_n* and a semi-continuously fed *A_n*-*O_x* reactors were conducted. All units were able to produce an SVI of 40-70 ml with the *A_n*-*O_x* unit producing the best clarified effluent. There was 90% removal of the SBODs in the unaerated ICZ without phosphorus release. For reasons unknown, some dispersed floc was present in all supernatants.

Initial operation of the modified, full-scale CMAS unit with four-hour unaerated mixing zone and a 5:1 recycle (MLSS:Q) has reduced the SVI to less than 150 ml/g. This has resulted in two phases of sludge, one of which settles very poorly, and the other phase, very rapidly. The ICZ F/M ratio is 1.8 kg/kg-d and nitrification does occur. No reasons for the dispersed solids have been found.

**OWASA (Chapel Hill, NC).** The 350 l/s (8 MGD) Orange County Water and Sewer Authority nutrient removal facility represents a significant design departure from the conventional process arrangement. This dual biological trickling filter-activated sludge (TF-AS) plant is illustrated in Figure 4. This plant arrangement evolved out of studies by the University of North Carolina and OWASA on the *A/O*, five-stage Bardenpho and various OWASA tests.

In this OWASA process, fermented primary sludge liquor and return activated sludge are contacted without aeration for a period of four to eight hours prior to mixing with trickling filter effluent. The MLSS nitrify rapidly and are denitrified in subsequent steps. A full-scale, two-week control test produced the following grab sample results: <4 mg/l SBOD5, 5.5 mg/l TBOD5, 0.21 mg/l SPO4P and 0.46 mg/l TPO4P. The composite tests for a nine-day study produced values of 3.7 mg/l TBOD5, 0.17 mg/l O PO4P and 0.39 mg/l TP. These results were much better than data obtained by the earlier *A/O* and Bardenpho pilot tests.

The SVI of the OWASA process has varied widely, from 60 to 300 ml/g. The initial contact of trickling filter effluent is maintained at a D.O. of 0.7-1.5 mg/l, and the F/M is about 0.8 kg BOD5/kg MLSS-d in...
Bulking sludge control

the initial, aerated contact zone. Thus, OWASA's first contact zone is neither a high F/M - low D.O., nor a high F/M - high D.O. selector, and this could be the reason for varying SVIs. There is a possible correlation of high SBOD₅ to high SVI of the flow entering the first oxic zone. Nitrification is also occurring in the initial zone at the high F/M selector.

Fig. 4. The OWASA process with fermentation of waste primary sludge

Tri City WWTP, Clackamas County, OR. This 368 l/s (8.4 MGD) plant was designed to operate as an NDN (Aₓ-Oₓ) facility in summer and to be completely oxic during the high flow Fall-Winter-Spring rainy season. To counteract solids washout in winter, the plant was operated in a step feed arrangement. The Aₓ-Oₓ flow sheet produced excellent control of SVI, but the plant has bulked periodically, but not continuously, in the oxic step feed mode. When the anoxic basin was partially aerated, the sludge bulked as indicated in Figure 5. The F/M in the single anoxic compartment ranged from 0.6-1.3 kg BOD₅/kg MLSS·d. The 1986-89 clarified effluent quality averaged 7 mg/l CBOD₅ and 9 mg/l TSS. The NH₄-N levels were less than 1.5 mg/l and TN reduction was 60-65%.

Fig. 5. SVI profile in Aₓ-Oₓ and step feed Oₓ modes at Tri City, WWTP

Eastern Service Area WWTP, Orlando, FL. The 520 l/s (12 MGD) facility employs the five-stage modified Bardenpho (Phoredox) process in an Aₓ-Aₓ-Oₓ-Aₓ-Oₓ mode. This facility has been on-line successfully since 1984 providing a very high degree of CBOD₅, TSS, TN and TP removal. The TP removal is alum assisted. During an intensive 12-month study, the average plant filtered effluent was 1 mg/l CBOD₅, 2 mg/l TSS, 0.5 mg/l NH₄-N, 2.5 mg/l TN and 0.5 mg/l TP. The F/M loading in the single anaerobic
compartment in the ICZ ranges from 0.35-0.80 kg BOD/kg MLSS-d. The average SVI was 127 ml/g and ranged from 89-177 ml/g with a DSVI range of 80-150 ml/g.

**Discussion of the Data.** There are no clear-cut conclusions to be drawn from the operating data of the plants summarized in Table 3. However, plants such as Southerly, Davenport, Tree Top, Middletown and Hatfield, which have had a history of bulking sludge, clearly reduced or controlled the problem with a selector concept. Star Valley, using a SBR, has consistently maintained a low SVI and it would have a maximum F/M gradient. However, the full-scale, continuous flow selector at Tree Top has not performed as well as the batch fed selector pilot studies and also has a lower F/M initial contact than may be desirable.

**TABLE 3. SUMMARY OF RECENT BULKING SLUDGE CONTROL PROCESS DESIGN**

<table>
<thead>
<tr>
<th>Plant</th>
<th>Process Mode</th>
<th>ICZ D.O. ICZ F/M</th>
<th>SVI - ml/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hatfield, PA</td>
<td>AOX</td>
<td>0.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Tri City, OR</td>
<td>AOX</td>
<td>0.0</td>
<td>0.6-1.3</td>
</tr>
<tr>
<td>Southerly, OH</td>
<td>AXN-AXN-OX</td>
<td>0.0</td>
<td>4.5, 2.3, 1.0</td>
</tr>
<tr>
<td>Vineland, NJ</td>
<td>AOX</td>
<td>0.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Jackson Pike, OH</td>
<td>AX-AX</td>
<td>±0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Davenport, IA</td>
<td>AX-AX</td>
<td>±0.4</td>
<td>0.94</td>
</tr>
<tr>
<td>Tree Top, WA</td>
<td>AXN-OX/OX</td>
<td>0.0</td>
<td>∞</td>
</tr>
<tr>
<td>Star Valley Coop, WY</td>
<td>AX-AX</td>
<td>0.0</td>
<td>∞</td>
</tr>
<tr>
<td>Newark, OH</td>
<td>AXN-AXN-OX</td>
<td>0.0</td>
<td>1.6, 0.8, 0.5</td>
</tr>
<tr>
<td>ESA, FL</td>
<td>AXN-AXN-OX</td>
<td>0.0</td>
<td>0.35-0.8</td>
</tr>
<tr>
<td>Middletown, OH</td>
<td>AXN-AXN-OX</td>
<td>1.0</td>
<td>12, 6, 4, 3</td>
</tr>
<tr>
<td>OWASA, NC</td>
<td>AXN-OX/AX</td>
<td>±0.7</td>
<td>0.3-0.8</td>
</tr>
</tbody>
</table>

(1) High SVI during fully aerated experiments; SVI = 125-210 ml/g
(2) Pilot studies, batch fed for AXN-AXN and OX tests.
(3) Full-scale; continuous fed; SVI is not definable.

OWASA has produced an interesting contrast in performance. When NO3N is very high, there is very little SBOD5 remaining in the conditioned RAS due to denitrification and Bio-P reactions. Under these conditions, the SVIs were low. SVIs were high, however, when the SBOD5 in the conditioned RAS is high entering the first oxic zone. This would be consistent with reported bulking observations elsewhere relating to adverse effects of SBOD5 and acetates entering the initial oxic zones.

The Hatfield results are inconsistent with the F/M gradient theory. The low F/M in the ICZ in conjunction with the anoxic selector removing SBOD5 is adequate to control the bulking problem which occurred in the original CMAS plant. However, the process has been able to accumulate excess phosphorus in both AX and AXN modes and thus operates in a Bio-P selector mode.

With the exception of Hatfield, the plants that have bulking conditions and employ a selector have an F/M of less than 2 kg BODs/kg-d in the ICZ and generally less than 1 kg/kg-d. The Southerly, Jackson Pike, Hatfield, Davenport, Newark and Middletown selectors have provided for bulking control on wastewater with a history of bulking problems. It is possible that increasing the F/M in the ICZ in those plants with moderate bulking could reduce the SVI. However, physical limitations imposed by full-scale facilities may preclude opportunities to refine the information.
The use of high F/M selectors (>3 kg/kg-d) possibly negates the effects of aeration and the presence of NO$_3$N. The premise of SVI control is based on the removal of low molecular weight (MW) organics by non-filamentous species prior to the first oxic zone, where filaments would be competitive for SBOD$_5$. The food rich, high F/M zone provides such an opportunity for favored species, which may or may not also accumulate phosphorus in the oxic environment. A high to low F/M gradient in each environment — $A_n$, $A_x$, $O_x$, etc. — provides the optimal opportunity for non-filamentous species.

It would appear that dissolved oxygen or NO$_3$N concentrations are not a good measure of the conditions within the biological floc. Mueller et al., (1968) presented data relating to the D.O. concentration and resulting penetration of oxygen into the cell floc and noted that the cells’ interiors may be oxygen starved in the presence of appreciable D.O. in the liquid phase. Biryukov and Shtoffer (1970) presented similar information and also showed that the D.O. penetration into the floc was a direct function of the stirring rate and inverse function of the biological respiration rate.

Due to the very high oxygen demands at F/M levels of greater than 4 kg/kg-d and MLSS of 2.5-4.0 g/l, the flocs would generally be anaerobic, even in the presence of 1.0-1.5 mg/l D.O. and appreciable concentrations of NO$_3$N. However, as the F/M is lowered, a larger fraction of free and bound oxygen becomes available to the high surface area filamentous organisms. At some point, low D.O. and NO$_3$N in an ICZ may provide adequate support for filamentous growth. At one F/M extreme is a CMAS unit, well known to support filamentous growth under nearly all possible operating conditions. At the other end is the SBR with maximized F/M gradient and, seemingly, our best means of controlling SVI.

**SUMMARY AND CONCLUSIONS**

This study provides several examples of bulking sludge control practices using different selector designs. These results add to our understanding how selectors can control filaments and provide direction for future work.

1. Recent full-scale US selector data generally support the premise that a high to low F/M gradient is a dominant factor in bulking sludge control.
2. The employment of high F/M (>4 kg/kg-d) in the ICZ probably assures that the cell floc centers pass through an anaerobic conditioning stage, whether aerated (D.O. ≤ 1.0 mg/l) or anoxic, and that this conditioning is a factor — and possibly a necessary step — in controlling filamentous growth.
3. A F/M gradient is probably beneficial in all environments ($A_n$, $A_x$, $O_x$) to maximize the opportunity to control bulking.
4. The contact of MLSS and SBOD$_5$ at low F/M should be avoided in all environments to minimize bulking possibilities.
5. In spite of all we learn and understand, some sludges will still bulk.

**ACKNOWLEDGEMENT**

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REFERENCES


